Possibilities of using energy provided from nuclear fusion in the near future.

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Abstract. Nuclear fusion is an idea that has been theorized since last century, but recently projects have been carried out to demonstrate the economic viability of this energy generation method. This paper will discuss these projects, analyzing their results and looking at the possibilities of having nuclear fusion as a common source of energy in the next few years.

***Index Terms*— Nuclear fusion; Fusion research; ITER; Tokamak; Inertial confinement; Magnetic confinement; SPARC; Stellarator; Nuclear Fusion Economics; Laser driver; Fast Ignition; Wendelstein 7-X.**

I. INTRODUCTION

AT present, the use and development of renewable energies has taken a major role in society's growth. The National Academy of Engineering grand challenges and the United Nations Sustainable Development Goals have addressed the necessity of an evolution in the energy obtention methods and have shown its relevance. In this context, the constant study and innovation in the field of energy production by nuclear fusion and the enormous capacities (in terms of economy, energy quantity and quality, and environmental impact) place this kind of energy supply as the one that will give a certain energy independence to the world.

When the topic of nuclear energy is discussed, nuclear fission is the first concept that comes to people's mind, connecting it with a technology that grew rapidly after the Second World War. The biggest differences between these two methods is that nuclear fusion does not produce radioactive waste and generates a lot more energy. Nuclear fusion is a nuclear reaction in which two nuclei of light atoms, usually hydrogen and its isotopes, join together to form another heavier nucleus[1]. This nuclear fusion reaction releases energy if the mass of the nucleus of the atoms is less than the mass of the iron, or absorbs it if the mass of the nucleus is greater than the one of iron[2]. As hydrogen is the lightest and most abundant element, it represents a great advantage over other elements. Fusion with hydrogen releases a large amount of energy in the form of gamma rays and also the kinetic energy of the emitted particles. This large amount of energy allows matter to enter the plasma state. If this plasma state of the particles were controlled, the energy production process would be successful and also it may be possible to say that fusion energy could become a commercial form of energy obtaining process.

Although the idea of generating energy from nuclear fusión was born nearly in 1940, today, sixty years later, no one has designed a functional reactor yet[3]. Nowadays, this process presents two major difficulties: one, to limit the chain reaction so that all the proton-neutron plasma does not react simultaneously; the second one, to ensure that no

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The present manuscript is part of the research activities in the Inglés II lesson at Universidad Tecnológica Nacional, Facultad Regional Paraná. Students are asked to research into a topic so as to shed light on a topic of their interest within the National Academy of Engineering's Grand Challenges or the United Nations' Sustainable Development Goals frameworks. If sources have not been well paraphrased or credited, it might be due to students' developing intercultural communicative competence rather than a conscious intention to plagiarize a text. Should the reader have any questions regarding this work, please contact Graciela Yugdar Tófalo, Senior Lecturer, at gyugdar@frp.utn.edu.ar metal atoms from the plant walls will enter the plasma. There are numerous countries and organizations that are working to find a way to build a mega-device (reactor) strong enough to resist the high temperatures and to control this difficult process[4]. Even if there are a lot of bright minds working on it, the solution appears to be far away. As well as this, most of the prototypes have only been designed in order to demonstrate the possibility of turning this theory into a reality[2].

The main objective in this paper is to explore the basis of the production of energy by nuclear fusion and analyze whether in the future it will be possible to use nuclear fusion reactors for energy production. It will be necessary to study the current projects that are working on the creation of a reactor for commercial use, and how its developers have decided to overcome certain obstacles.

In order to achieve this aim, the present work is organized as follows. First of all, readers are going to be introduced to the historical context. Secondly, this paper is going to address the obstacles that make it impossible to generate energy by nuclear fusion nowadays step by step. Thirdly, progress in the subject and how scientists are trying to overcome obstacles is explored. In the fourth place, economic possibilities surrounding the idea of a commercial and functional reactor is going to be discussed. The next section introduces some projects that are being developed at this moment. Finally this paper is going to explore the future of this technology.

II. HISTORICAL CONTEXT

The utopian idea of using nuclear fusion energy has stayed in people's minds since the Second World War.

Since the ‘50s scientists and countries have been working on the first concepts about how to create a commercial and useful way to produce it. One example of the power of the nuclear fusión were the infamous “hydrogen bombs” created in 1953. Over the years, the technology used grew strong enough to have some experimental prototypes in the ‘70s. Those prototypes could not work in a continuous way; in fact, they were built just to establish the structural necessities for future reactors [4].

From the 1970s until today the advance in the creation of an effective system to generate and contain the massive power expelled by the fusion of two atoms has taken only small steps.

III. PHYSICAL OBSTACLES TO NUCLEAR FUSION GENERATION

In order to explain the obstacles that have made nuclear fusion impossible, it is crucial to describe the aspects that rule the fusion process: fusion needs to reach enormous temperatures and a specific time to occur. It is also necessary to have a reduced space where the fusion can be controlled. The idea of generating energy by fusion has always been in the background within the economic and environmental spheres due to the obstacles described below.

A. The Coulomb Force and Elastic Collisions

It is necessary to remember that the kind of nuclear fusion this paper is going to describe consists in clashing a Deuterium atom (heavy hydrogen isotope) with a Tritium atom (super-heavy hydrogen isotope) [9, Fig 1].

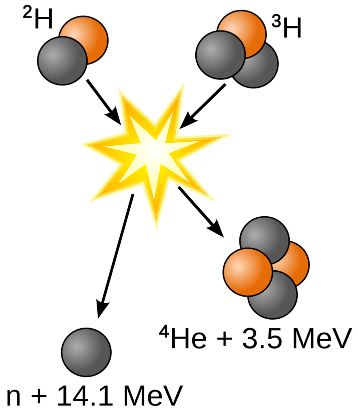

Fig. 1. Merging of a deuterium with a Tritium. As a result, you get Helium, a neutron and energy. Credit: All credits for the unknown artist who created this image.

The principal requirement to merge a deuterium atom with a tritium atom is to overcome the Coulomb forces.

This force is an electric interaction dependent on the charge and the separation between two charged particles, as shown in [1, Fig 2]. Deuterium and tritium are both positive particles so this force turns into a repulsion one. The particles try to separate as much as they can from each other. The magnitude of the repulsion generated between those two atoms make previous methods of particle acceleration useless.

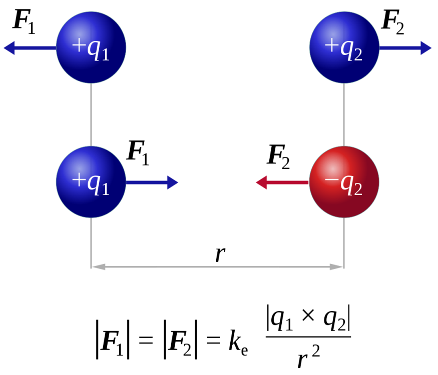

Fig. 2. Illustration of the Coulomb equation. The electric force is proportional to the electric charge and inversely proportional to the square distance. Credit: Dna-Dennis (wikipedia user and contributor).

It is necessary to reach a specific temperature that makes the merging between Deuterium and Tritium possible. This temperature is over 50 millions of celsius degrees and it is called “Ignition temperature”. After the two atoms reach this temperature they are capable of overcoming the repulsion caused by the Coulomb forces. All this process is known as Thermonuclear Fusion or Hot Melt[5].

The other relevant aspect is that not all the collisions of those particles produce a fusion, which is only possible in a confined space or under some specific conditions. In the sun, the high temperatures and pressures make this process possible and nearly infinite, but on earth it is impossible to produce it under natural conditions. For example, even if the “ignition temperature" is reached, most of the particles will collide in an elastic way. If this occurs, the reaction is going to be uncontrollable and ineffective. In most of the cases, collisions in these conditions will not produce a nuclear fusion, even if they are happening at the ignition temperature. This means it is necessary to drive the collisions by reducing the space when particles will collide.

B. The need for an efficient confinement system

As stated above, fusion takes place at a high temperature, and it requires a reduced and controlled space to occur on the earth. Since 1970, prototypes have always presented the same problems: the materials of the confinement cameras give way due to the unreal temperatures. Nowadays, there is not a material capable of withstanding the very high temperatures needed for fusion to take place. The majority of known materials such as steel, titanium, and other metallic alloys will be destroyed in fractions of a second. Moreover if the plasma produced touched the confinement walls, the material that composes the isolation camera would be degraded, turning it into a radioactive isotope.

If an event like the one mentioned before happens all the potential of being a massive and clean source of energy will disappear. This particular problem coupled with the high temperatures required have had scientists very busy over the years and have precluded the creation of a completely functional reactor.

IV. A SOLUTION: CONFINEMENT METHODS

As stated in section III, the plasma made in the reactor's camera needs to be isolated. At this point, it is necessary to describe two current methods of generating nuclear fusion.

A. Magnetic Confinement

It is actually the most advanced and used method for obtaining fusion. It consists in using the Lorentz force (magnetic force felt by a charged particle) through a magnetic field to prevent the plasma particles from touching the walls of the reactor, which could take place because of gravitational or inertial action[6]. In order to achieve this, scientists have developed a device that makes this possible: the tokamak.

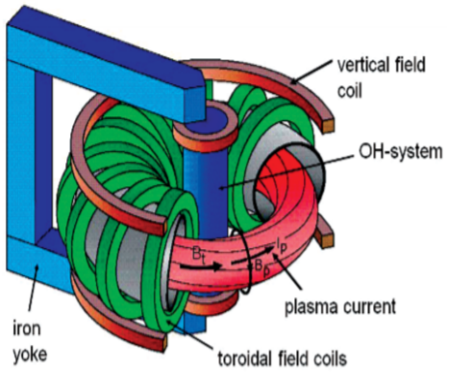

Fig. 3. Principle set-up of a tokamak with circular cross-section. This is the basis of designs for nuclear fusion reactors. Credit: All credits for the unknown artist who created this image for the research article "Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility".[19]

The tokamak is one of the concepts and devices developed to carry out the magnetic field that will keep the plasma isolated inside the reactor. It consists of a vacuum chamber with a toroidal shape (doughnut shape). On the outside surface of the chamber, conductive cables wrap up the toroid making a coil through which an electric current passes, forming a magnetic field stronger in the inside than in the outside (torus effect)[11] which allows the particles to circulate in a spiral way without touching the tokamak's walls.

B. *Inertial Confinement*

Inertial Confinement is also known as Inertial Fusion Energy (IFE) and is one of the alternatives to magnetic isolation method. Since it is based on the fast generation of energy before the ignited plasma has time to expand, it is an easy way to produce fusion.

Initially, there is a deuterium-tritium spherical capsule[8] of few millimetres in size and at a low temperature. It is powered by a driver[9], which consists of a large array of lasers aimed at the fuel. This energy compresses the fuel to high densities and heats it up to the temperatures needed to create the plasma. This results in a mini nuclear explosion in the centre and the heat generated spreads outwards, heating the plasma it encounters and igniting it. All this has to happen before the compressed plasma expands and cools down, which happens in 10 nanoseconds (10^{-8} s). If during this time more energy is produced than that invested in compressing and heating the capsule, the result of the experiment is favourable.

This phenomenon is best shown by [7, Fig. 4]:

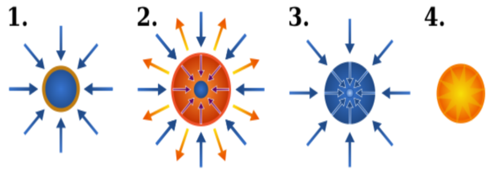

Fig. 4. Nuclear fusion sequence by inertial confinement. Credit: Benjamin D. Esham (bdesham) Wikipedia user and contributor.

1. The radiation rapidly heats the surface, generating a plasma.
2. By means of an action-reaction effect, the plasma expands outwards and the fuel is compressed.
3. The capsule implodes reaching densities of more than 200g/cm3 and temperatures of 100 million degrees.
4. Nuclear fusion takes place in the centre and is transmitted to the adjacent compressed fuel, producing more energy than is consumed in the process.

V. THE ECONOMICS OF NUCLEAR FUSION.

Most of the obstacles mentioned in section III have been overcome with the solutions that the two different confinement methods achieved, but, at the same time, these solutions have strongly impacted the costs of nuclear fusion.

In fact, these two methods are actually research and development projects, so they present particular technological complications that poses further obstacles to the development of nuclear fusion energy on a commercial scale. In order to solve these issues, researchers around the globe are delving into possible approaches.

A. *Inertial Fusion Energy's economic issues.*

In an Inertial Fusion Energy (IFE) power plant the cost of fuel will be effectively zero[14], because a millionth of a kilogram of deuterium and tritium can release the energy equivalent to over ten kilograms of coal, thus the cost of IFE electricity comes from the initial capital investment in the construction of the plant, the human resources, miscellaneous supplies and equipment. More than half of the remaining capital costs is for a single piece of equipment, the driver.

The driver's cost can be estimated if the size needed for a given IFE power plant can be predicted. In [14, Fig. 5] there is an example made by various studies in 1995 for the cost of heavy ion accelerators of many sizes.

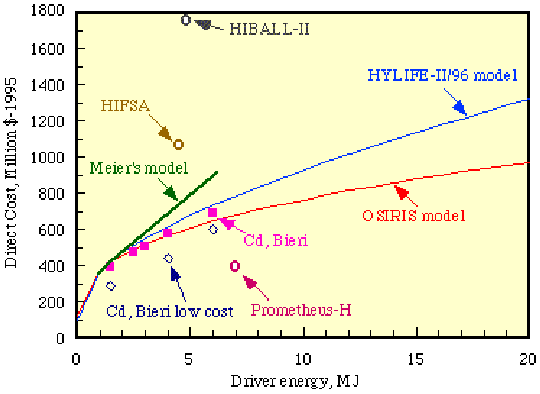

Fig. 5. Energy-cost relation of drivers from many nuclear fusion projects. Credit: All credits for the unknown artist who created this image for the research article "Inertial fusion energy: a tutorial on technology and economics."[5]

The driver's cost could be reduced if a single driver is used for a large number of targets, but bringing the driver down (for maintenance, for example) then presents a major disadvantage because the large number of targets would not produce energy. This can be easily solved by providing two separate drivers with a switch in order to alternate one as the other is in maintenance.

In any case, the economics of IFE can always be improved by reducing driver costs, which also depends on driver energy. Two areas for further research are highlighted from the last condition: improving target designs and optimizing target and target-chamber designs[15]. The first one will reduce the driver's energy and the second one will increase capsule ignition rates (allowing lower capsule energy release and drive energy).

While there are several drivers that promise high enough efficiency for the driver efficiency-target gain product to lead to an acceptable commercial IFE power plant, it would be attractive to have an inertial fusion concept with a higher efficiency-gain product and allow a smaller driver size. That concept may be the Fast Ignition, and nowadays it is the central objective of many of the most important projects.

B. Magnetic Fusion Energy's economic issues.

In terms of costs for the energy production it is a well-known fact that they can be divided in two specific categories: the initial capital for the building of the power plant and other necessary facilities, and the operational cost of the energy plant.

In the first place, the capital for the construction of a fusion power plant represents approximately 73 percent of the initial investment. It seems a very large percentage but it is a similar percentage compared to the capital needed for building a fission or coal plant[16]. It means that the facilities building will represent nearly the same costs the energy companies usually manage.

In the next category, there are all the operational costs, such as the "periodic replacements", the operations in itself, maintenance and others. The periodic replacements represent 16 percent of the normal running of the plant costs[16]. These replacements are divided into two: the replacement of the divertor and the replacement of the "first wall". These two elements face the energy irradiated by the fusion process and the replacement costs depend on their capacity to withstand the wear. Finally an 11 percent of the costs lie in the maintenance, the periodic operation and other extra costs.

Nowadays, the estimated downtime of the reactor, due the replacement of the parts mentioned before and other operations, has reached availability of over 75%[17]. This means that the most optimized geometries for the tokamak have reached, theoretically, the economic feasibility for a commercial use[17].

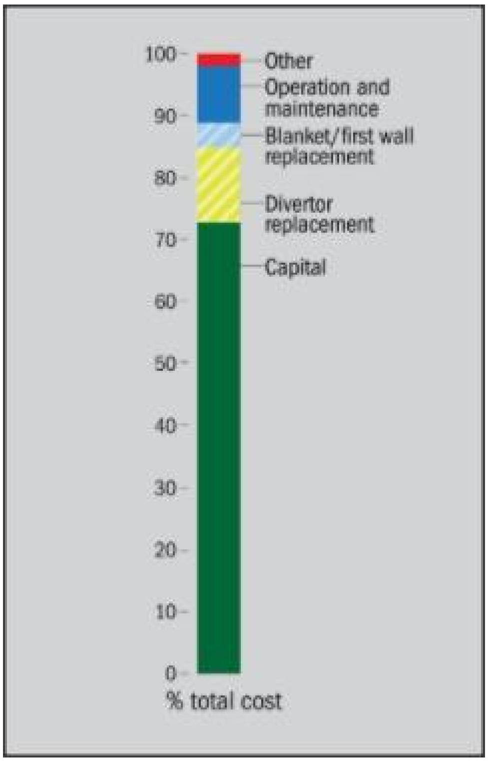

Fig. 6. Representation of nuclear energy production costs, as a percentage of each section. Credit: All credits for the unknown artist who created this image for the research article "*Fusion Energy via Magnetic Confinement: An Energy Technology Distillate from the Andlinger Center for Energy and the Environment at Princeton University.*"[16]

C. A big ally: climate policies.

Countries and people have been fighting for a clean future for a long time. Nowadays in the 21st century environmental protection is, possibly, one of the most important challenges in the international scene. Fusion energy is a low-carbon system of energy production so this method of obtaining energy will not pay special taxes which, for example, coal energy pays. These political, and economic decisions, plus the constant pressure made by the young generations, the environment protection societies and every person that has suffered or is suffering the effects of contamination pave the way for a more friendly ecosystem for this kind of technology. In the near future, it is possible for the costs of fusion energy to considerably decrease the operation costs to be the same as those invested in fission energy, making it more widely available.

VI. PROJECTS WORKING ON SOLUTIONS

The only ways to truly improve or to give solutions to all of the cases mentioned above are the theoretical work and the experimental projects. Nowadays, with all of the technological advancements, there are many projects that could be the last (or next to the last) step for commercial nuclear fusion plants.

There is a ratio called fusion energy gain factor, expressed with the symbol Q, which is the relation between the gain in energy at fusion and the energy used for the reaction (E-output/E-input). When Q is less than one, the reaction needs more energy than it produces, and when it is greater than one, there is an energy gain in the nuclear fusion process.

Political and private investment has made the construction of these projects possible. This makes the collaboration between countries to achieve nuclear fusion as an economic and clean source of electric energy become visible.

A. National Ignition Facility (NIF).

NIF is a large laser-based inertial confinement fusion research device, located at the Lawrence Livermore National Laboratory (LLNL). NIF aims to achieve fusion ignition with high (or favorable) energy gain.

It is the largest laser and most energetic ICF device built to date, and it was finished in 2009 and in the same year it started to work. NIF researchers worked on the ignition of the fuel pellet inside the hohlraum, but they did not achieve the ignition despite all the efforts made. The NIF officially ended on September 30, 2012.

Scientists kept investigating laser energy, pellet quantity, hohlraum spherical form, and other parameters in order to achieve their main objective. There was a false “scientific breakeven” memo made by Ed Moses in which says that the amount of neutrons produced was 75% more than any previous shot [18]. He also said that the fuel reached approximately 14 kJ against 10 kJ deposited in the fuel, which Q is 1.4; but there was not counting with the total energy that the laser released. With the last definition, the input would be 1.8 MJ and the output 14 kJ, a Q of 0.008.

Since 2013, improvements in controlling compression asymmetry have been made a record in 2018 [19], resulting in 0.054 MJ of fusion energy released by 1.5 MJ laser pulse. Also, NIF has been working since 2016 with Magnetized Liner Inertial Fusion (MagLIF) in order to investigate key aspects, using a single quad of NIF to deliver 30 kJ of energy to a target, whose data return was very favorable and analysis is ongoing by scientists at LLNL.

B. SPARC.

The Sparc project represents one of the latest steps in the development of fusion energy. SPARC Tokamak is a project developed by the Commonwealth Fusion Systems (CFS) and the Massachusetts Institute of Technology Plasma Science and Fusion Center. It is a tokamak designed on the basis of the ITER and other previous fusion projects[18]. It consists of a compact ($R_0=1,85\ m$) D-T Tokamak with a high field of $B_0=12,2$ [T], built using barium copper oxide magnets [20]. The fast ignition SPARC Tokamak promises to be the next big advance, with theoretically Q about 11 [20]-[21]. At present, Sparc is close to reaching Q>2 [20]-[21]. That means the energy the SPARC can produce will be two times the energy it needs just to be operational. It is expected that in the near future this coefficient will increase (reducing energy loss) because of the constant refinement of technology used in this Tokamak. The idea scientists had to improve this tokamak is to reduce as much as they can the size of tokamak and increase the magnetic field. This high field can not be produced with magnets of normal metals. Using normal material for the magnets could overly increase the costs to make the project unavailable. The solution was to use superconductive materials (Nb3Sn) [20]. This material is not a normal superconductor, it is a HTS (high temperature superconductor) that works in an opposite way to the “old superconductors” LTS (low temperature superconductor) [20]. This innovation is the reason for the giant step the SPARC is taking. Compared to the “titans” in the fusion energy environment, as the ITER, BPX, CIT, FIRE and so on, the SPARC design greatly reduces the building and operational price. Only seven years have passed since the SPARC design began, and now the design and experimental phase is believed to be finished. In 2021 the building of the SPARC is going to start, which is expected to pass the *Q=2* limit and in the future reach the *Q=10* with the nominal physics assumption [20].

Nowadays, the advances in magnetic confinement reported by the SPARC describe a possible comercial use in the near future. This project is not an only experimental project, it is focused on the objective to make fusion energy possible and affordable.

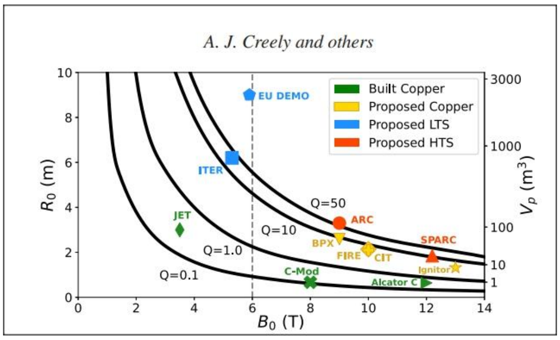

Fig. 7. Logarithmic curves representing the relationship between the magnetic field, the reactor radius and Q coefficient. Credit: All credits for the unknown artist who created this image for the research article "Overview of the spark tokamak."[20]

C. *FIREX-1*

The FIREX-1 is an inertial confinement prototipe focused on the creation of a fast-ion ignition using large power lasers [22]. It is being developed in Japan by Osaka University. The great majority of all the FIREX-1 experiments were looking for a better development of the beams that produce the fusion. Since its creation, scientists have been improving the beam's power in order to reach the ignition temperature and the ability to continue working after the plasma appears [23]. This prototype uses two types of lasers: the GEKKO XII and the LFEX. The environment created by the plasma, as stated in previous sections, is very harsh and the lasers suffer a loss of power [23]. Up to now, the GXII and the LFEX have experimented with 9-12 lasers with an energy between 300-800 J in a pulse duration of 1,5 ps [23]-[24] producing an implosion of about 2 kJ [24]. These results were much better than the results obtained in the previous experiments in 2002 and 2009 [23]. The efficiency ratio is about 10-20%, and it is expected to reach 5 keV by improving the lasers [24]. This information can be concluded from the results of the last experiments in 2011 and 2012. Nowadays, there is no new information about the project, maybe because there are no new important advances in the experiments. On the other hand, lack of information could be connected with an information protection policy, making it is difficult to predict the future of this project or if it will finally become a commercial reactor.

D. *International Thermonuclear Experimental Reactor (ITER).*

ITER is an international collaborative project aimed at demonstrating the scientific and technological feasibility of fusion energy for peaceful purposes. Many countries like Japan, U.S.A, Russia and European Union's members are participating in this project.

It consists of a D-T tokamak of 24 m diameter and 28 m high [25] which has been designed to create a plasma of 500 megawatts (thermal) for around twenty minutes, while 50 megawatts of thermal power are injected into the tokamak. It will result in a Q=10 that means a ten-fold gain of energy. The project began its five-year assembly phase in July 2020, being 2025 the year expected to initiate the experiments with the reactor.

The programmatic objective of ITER is translated into a number of specific technical goals, all concerned with developing a viable fusion power reactor [26].

- ITER should produce more power than it consumes. It means to achieve at least Q>1, keeping the target of Q=10 predicted.
- ITER must extend the pulse duration with profiles of plasma temperature, density, and current in near steady state, using non-inductive current drive which is almost essential for a power-generating reactor.
- ITER will implement and test the key technologies and processes needed for future fusion power plants - including superconducting magnets, components able to withstand high heat loads, and remote handling.
- ITER will test and develop concepts for breeding tritium from lithium-containing materials inside thermally efficient high

temperature blankets surrounding the plasma.

This mega project could make important contributions to the nuclear fusion world. If ITER achieves its goals, the production at a commercial scale of nuclear fusion energy will be very close to becoming a reality.

E. Wendelstein 7-X.

W7-X is the world's largest fusion device of stellarator type at the Max Planck Institute for Plasma Physics. Stellarator is a new form of tokamak devices, shaping the best geometric way to take advantage of magnetic fields. Wendelstein's objective is to investigate the suitability of this type for a power plant.

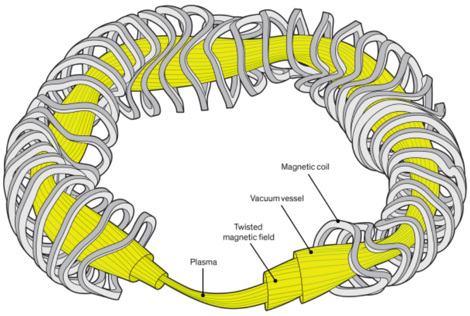

Fig. 8. Stellarator illustrative picture. The stellarator's challenging geometry makes it complicated to build and extremely sensitive to imperfect conditions. Credit: Chris Philpot.

The confinement method used is magnetic confinement; the device will test an optimised magnetic field for confining the plasma. It will be produced by a system of 50 non-planar and superconducting magnet coils. It aims for higher density plasma and temperatures of 60-130 MK. The superconductive coils create a field of 3 T.

The project consists of three operations: OP 1.1 was to conduct integrated testing of the most important systems as quickly as possible and to gain first experience with the physics of the machine, and it concluded successfully in 2016. OP 1.2 continued to test the divertor uncooled, which is a device within a tokamak or a stellarator that allows the online removal of waste material from the plasma while the reactor is still operating. Finally the OP 2 will be to test the cooled divertor, which will be in operation by 2022 for pandemic reasons.

Nowadays, W7-X is one of the most promising projects related with nuclear fusion energy at commercial production for their achievements. The only disadvantage is that the stellarator has particular environmental conditions to operate, but until today it seems to not be a problem yet. Beyond that, stellarator optimization [24] is also a current research which scientists at Max Planck Institute are working on.

VII. CONCLUSION

In conclusion, this paper has finally shown at least four different types of nuclear fusion designs. It started with the simple magnetic and inertial confinement nuclear fusion devices, showing their economic and physical issues. Since then, many other kinds of devices have emerged like W7-X, whose fundamental working is a combination with magnetics principle but a different tokamak device, the stellarator in this case.

Also, there are projects not mentioned as examples in this paper like TAE which works with a FRC (field-reverse configuration) principle, or HyperJet which works with Magnetized Target Fusion (the hybrid combination between magnetic and inertial confinement method). It means that there are multiple configurations for a nuclear fusion plant design, and it could be more in the future that will be more effective than the older ones, because that is the way science and progress works.

Many of the projects mentioned above are going to be finished in 5, 10 or 15 years, and maybe their goals could not be achieved before 2045, but it is not a reason for giving up. It is a fact that there is a very high possibility for commercial nuclear fusion to be giving energy to the world before the end of the century; it is just a question of work, research and time.

REFERENCES

[1] I. Palermo, *"Diseño nuclear de un reactor de fusión por confinamiento magnético con envoltura regeneradora líquida de doble refrigerante He/LiPb (DCLL)."* Universidad Nacional de Educación a distancia, Madrid, España. 2014.

[2] O. Planas. 2019, October. ¿Qué es la fusión nuclear? Available: https://energia-nuclear.net/que-es-la-energia-nuclear/fusion-nuclear

[3] M. Schoijet. 2005, November. "La energía nuclear de fusión: Aspectos históricos." *RIDAA*, Volume 11, Number 22. Available: https://www.opli.net/opli_magazine/eo/2013/laser-fusion-experiment-yields-record-energy-at-llnl/

[4] J. M. Perlado Martín. 2010. “La fusión nuclear como fuente masiva de energía.” *Ingeniería y territorio*. Number 90. Available: https://dialnet.unirioja.es/ejemplar/252277

[5] P. F. Peterson, Professor. 1998. “Inertial fusion energy: a tutorial on technology and economics.” University of California, Berkeley. Available: https://web.archive.org/web/20081221233137/http://www.nuc.berkeley.edu/thyd/icf/IFE.html

[6] J. B. Martinell, “*Los prometeos modernos o el esfuerzo para controlar la fusión nuclear.”* Universidad Nacional Autónoma de México, 2013, ch 4: EL USO DE CAMPOS MAGNÉTICOS PARA CONFINAR UN PLASMA.

[7] F. R. Villatoro. 2011, April. HiPER – La fusión nuclear por confinamiento inercial en Europa. Available: https://francis.naukas.com/2011/04/27/hiper-la-fusion-nuclear-por-confinamiento-inercial-en-europa/

[8] J. B. Martinell, *“Los prometeos modernos o el esfuerzo para controlar la fusión nuclear.”* Universidad Nacional Autónoma de México, 2013, ch 6: EL CONFINAMIENTO INERCIAL Y SUS PERSPECTIVAS.

[9] Lawrence Livermore National Laboratory - How ICF Works. Available: https://lasers.llnl.gov/science/icf/how-icf-works

[10] Lawrence Livermore National Laboratory. Inertial Confinement Fusion: How to Make a Star. Available: https://lasers.llnl.gov/science/icf

[11] F. Wagner - Physics of magnetic confinement fusion.St. Petersburg Polytechnic State University - St. Petersburg, Russia Available: https://www.researchgate.net/publication/40901505_The_Physics_of_Magnetic_Confinement

[12] S. Entler et al. 2018, March. “Approximation of the economy of fusion energy.” *Energy.* Volume 152. Pages 489-497. Available:https://www.researchgate.net/publication/324024237_Approximation_of_the_economy_of_fusion_energy.

[13]C. Bustreor, “Fusion energy economics.” 64th Semi-annual ETSAP meeting, Seoul, Republic of Korea, 4-5 November 2013. Available: https://iea-etsap.org/workshop/seoul_nov2013/bustreo_fusion%20economics.pdf

[14]P. F. Peterson, Professor, “*An Assessment of the Prospects for Inertial Fusion Energy*”. University of California, Berkeley, 2013, ch 3: Inertial Fusion Energy Technologies

[15]P. F. Peterson, Professor, “*An Assessment of the Prospects for Inertial Fusion Energy*.” University of California, Berkeley, 2013.

[16] C. B. Chou, Janam Jhaveri, et al and the Andlinger Center for Energy and the Environment, “*Fusion Energy via Magnetic Confinement: An Energy Technology Distillate from the Andlinger Center for Energy and the Environment at Princeton University*.” Princeton University 2016 ,ch 4: Economics.

[17] M. Slowikowski, “*Fusion reactors: types, economics, impact.*” Available: https://newpowerpost.com/types-of-fusion-reactors/

[18] M. Koga, Y. Arikawa, H. Azechi, et al. 2011, October. “Present states and future prospect of fast ignition realization experiment (FIREX) with Gekko and LFEX Lasers at ILE”. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated.* Volume 653, Issue 1. Pages 84-88. Available: https://www.sciencedirect.com/science/article/pii/S0168900211001872

[19] S. Le Pape, L.F. Berzak Hopkins, L. Divol, A. Pak "Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility". 2018. Available: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.245003

[20] A. J. Creely, M. J. Greenwald, S. B. Ballinger, et al and the SPARC Team. 2020, October. “Overview of the spark tokamak.” *Journal of Plasma Physics* , Volume 86 , Issue 5.

[21] R. Mumgaard; Sparc team, “Spark and the high-field path.” APS Division of Plasma Physics Meeting 2018

[22] H. Azechi, K. Mima1, Y. Fujimoto, S. Fujioka, et al. 2009, September. “Plasma physics and laser development for the Fast-Ignition Realization Experiment (FIREX) Project”. *Nuclear Fusion.* Volume 49. Available: https://iopscience.iop.org/article/10.1088/0029-5515/49/10/104024

[23] H. Shiraga, S. Fujioka, M. Nakai, T. Watari, H. Nakamura, Y. Arikawa, H. Hosoda, T. Nagai, M. Koga, H. Kikuchi, Y. Ishii, T. Sogo, K. Shigemori, H. Nishimura, Z. Zhang, M. Tanabe, S. Ohira, Y. Fujii…H. Azechi. 2012, September. “Integrated experiments of fast ignition targets by Gekko-XII and LFEX lasers.” *High Energy Density Physics.* Volume 8, issue 3, Pages 227-230. Available: https://www.sciencedirect.com/science/article/abs/pii/S1574181812000134

[24] Unknown Writer. 2013, August. “Laser fusion experiment yields record energy at Lawrence Livermore's National Ignition Facility". *Opli.* Available: https://www.opli.net/opli_magazine/eo/2013/laser-fusion-experiment-yields-record-energy-at-llnl/

[25] T. Klinger et al. 2019, July. “Overview of first Wendelstein 7-X high performance operation.” *Nuclear fusion.* Volume 59, number11.Available:https://iopscience.iop.org/article/10.1088/1741-4326/ab03a7.

[26] J.B.Lister§, B.P.Duval. X.Llobet. “THE ITER PROJECT AND ITS DATA HANDLING REQUIREMENTS” - CRPP-EPFL, Association EURATOM-Confédération Suisse, 1015 Lausanne, Switzerland W.Spears. Available: https://accelconf.web.cern.ch/ica03/PAPERS/TH601.PDF

[27] S. Chiocchio. “ITER AND INTERNATIONAL SCIENTIFIC COLLABORATION*” - ITER JWS, Boltzmannstrasse 2, D-85748 Garching, Germany. Proceedings of EPAC 2006, Edinburgh, Scotland. Available: https://accelconf.web.cern.ch/e06/PAPERS/FRYCPA01.PDF