LET´S CATCH THE STAR

POTENTIAL PATHWAYS TO FUSION ENERGY

Projects, initiatives, and approaches

Compilation and initial assessment of current start-up concepts worldwide

FUSION FOR FUTURE

www.fusion-for-future.de

> "Predictions about the future, apart from a few statements, have always underestimated the speed of technical progress."

Michio Kaku, 2012: The Physics of the Future – our Life in 100 Years

By Aniceto Goraieb

NUCLEAR FUSION HAS BEEN TAKING PLACE FOR BILLIONS OF YEARS DIRECTLY IN OUR SOLAR SYSTEM AS WELL AS IN DISTANT GALAXIES.

All the elements known to us, except hydrogen, have formed in this way in several generations of stars. In contrast to nuclear fission, two light elements are "fused" into a heavier one. A very small part of the mass is converted into pure energy.

Albert Einstein provided the basis for the understanding with the relationship $E = mc^2$, where m stands for the mass and c for the constant of the speed of light (about 300,000 kilometers per second).

THE FUSION CONSTANT PLAYS AN ESSENTIAL ROLE IN NUCLEAR FUSION. IT CONTAINS THE THREE VARIABLES:

Pressure, time, and temperature (energy).

If one of the sizes is smaller, the others must be correspondingly larger. Our sun gets by with relatively low temperatures because it is very large and very dense (massive), so the time that the energy lingers in it is large (in terms of confinement time) and the pressure due to the gravitational force as well.

> “If the process of the sun is used, this is done according to the same rules, different ‘machines’ have been developed for this purpose, which can lead to a marketable design of fusion reactors.”

Aniceto Goraieb & Markus Lemmens

AGENDA OF THIS PAPER:

- The Reactor Concepts
- The Fuel
- The Company´s Worldmap

BACKGROUND & INTENTION

Similar to a Delphi study, this short paper has been discussed with scientists and other experts in the field during summer and fall of 2021. According to the assessment of the participants, a qualitatively determined approximation value is formed in order to be able to understand the various start-ups and their respective concepts little better. It is conceivable that several iterative discussion loops can be drawn in this way. We consider the organization of an expert meeting in spring 2023 in New York or San Francisco.

After looking at the start-ups, the currently recognized and ongoing or under construction international major projects (JET, Wendelstein, ITER, etc.) could also be studied in the same way.

The aim of this approach is to build a bridge between innovative start-ups and established large-scale research projects and to promote synergies through knowledge and technology transfer in the field of fusion research.

In accordance with the company philosophy of the company KBHF (message: "Fusion for Future"), we would like to participate in a successful market launch of the technology in the future. Here we can be a facilitator that supports networking. Basically, we at KBHF work conceptually in the field of so-called deep technology and therefore also pursue a medium- to long-term knowledge and technology transfer (development time between 15 and 20 years).

A first Internet search was carried out, and publicly available information on fusion start-ups and their respective initiatives was collected, which are listed in a table in no particular order. This table serves as a quick reference for the reader. The evaluations are based on the collected opinions of the aforementioned scientists and experts in the field. We are happy to share this source of information by individual request. Please drop an email note and we will answer asap (goraieb@kbhf.org).

In this flyer you will find basic facts to enrich The Company´s Worldmap.

THE REACTOR CONCEPTS

KEYWORD “MAGNETIC CONFINEMENT”

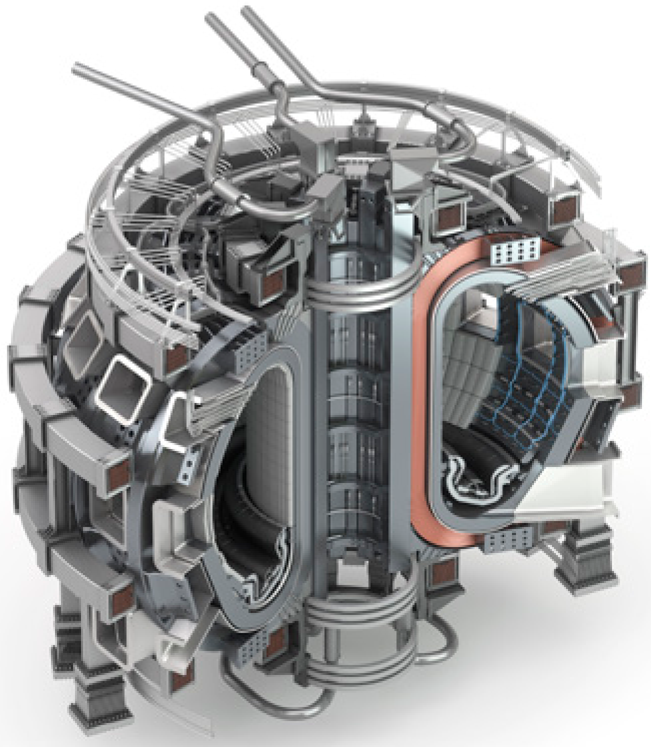
Due to the very high temperatures, an aggregate state is created, which is called plasma. This plasma is electrically conductive, so it can be contained with the help of magnetic fields, which also keep the plasma from coming into contact with the walls of the reactor. Various coil systems are used for this purpose. Examples of this are the **MIRROR MACHINE**, the **TOKAMAK**, and the **STELLARATOR**.

- **In the MIRROR MACHINE, particles are repeatedly reflected back and forth in a straight tube, sometimes referred to as a “sausage”.** The coils at the ends of the “sausage” represent the constriction and are intended to prevent too many particles from escaping. By collisions between the particles, particles are then continuously "kicked out" again. The mirror effect can be improved by using additional field coils, or the effect can be used on one side of the machine to create a kind of “plasma cannon”. This latter technique would seem to be well suited for use in nuclear rocket propulsion.

- **With the TOKAMAK, on the other hand, the coils are arranged in such a way that the plasma is held in suspension in a ring-shaped volume, technically called a torus, but looking like a "donut" or "car tire".** The heating is similar to a transformer with an iron core, but only a part of the required temperature is reached, and the "transformer" has to be restarted again and again. This results in pulsed operation and requires additional plasma heaters, such as microwave or plasma cannons (gyrotrons or particle accelerators). Normal magnets consume too much energy, so superconducting components are used that operate at temperatures close to absolute zero (-270°C). Examples of this design are THE JT-60 (Japan), JET (England)[1] and ITER (France), which is currently under construction. High-temperature superconductors (HTS) are used to achieve higher magnetic power with simpler operation. An offshoot of the conventional tokamak design is the spherical tokamak, often compared with a cored apple. Its compacter design can lead to a massive cost reduction compared to the classic TOKAMAK concept. Examples are NSTX-U in USA, START, MAST and the new STEP project at JET in Culham, UK.[2]

- Another option for a magnetic confinement is: The ring-shaped volume of the STELLARATOR resembles a bicycle tire. In contrast to the tokamak, the twisted magnetic field of the stellarator is completely generated by external magnets, and the inner core “transformer” is omitted, which makes this approach particularly flexible in its design. The biggest advantage over other fusion machines is that stationary, non-pulsed operations are possible. This significantly reduces the thermo-mechanical load on the structure. However, the magnetic structures used today are extremely complex, and this also applies to components that are required to use heat and breeding, see below. Wendelstein-7X currently uses this approach in Germany, and developments in Japan are similarly advanced, but research is also being carried out worldwide on smaller machines.[3]

[1] JET still uses normal instead of superconducting coils, as the technology was not yet mature at the time of the machine’s construction.
[2] https://en.wikipedia.org/wiki/Spherical_tokamak
[3] Further information can be found here: https://de.wikipedia.org/wiki/Stellarator



Thermonuclear reactor ITER | TOKAMAK
(International Thermonuclear Experimental Reactor)

ANOTHER WAY TO ENABLE THE FUSION PROCESS IS TO USE THE VARIABLE PRESSURE.

There are several ways to do this:

A plasma can be compressed by a very short but extremely strong pulse of the magnetic field. This can be compared to a neon tube, which contains a plasma that is generated by an electrical discharge, and through use of a coil given an applied electrical pulse, the plasma can be compressed. This arrangement is called the pinch effect. The principle of the hydrogen bomb is also based on a pinching effect, which is caused by an atomic bomb located in the center of the fusion charge.[4]

Related to the latter is inertial fusion. Here, many laser or particle beams are directed at a very small sphere (bead) in the center of the machine, which is then compressed and heated to several thousand bars of pressure. Similar to a small star, the bead implodes, resulting in a sudden release of energy. This machine is also operated pulsed, for the generation of an energy surplus even several times per second. The most important inertial fusion machine is located at the National Ignition Facility (NIF) in the USA, which made a significant step toward ignition in August 2021.[5]

Other approaches to achieve fusion use mechanical pressure. This is similar to a combustion engine, or hydrodynamic pressure in a liquid, which can be induced by sound, for example.

[4] https://www.spektrum.de/magazin/kernfusion-mit-dem-pinch-effekt/824843

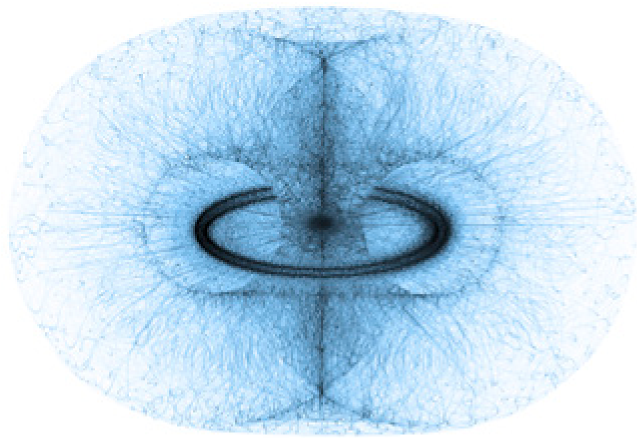
[5] National Ignition Facility experiment puts researchers at threshold of fusion ignition Lawrence Livermore National Laboratory (llnl.gov)

In contrast to this is the concept of so-called "cold nuclear fusion". Ever since two scientists falsely announced their "breakthrough" in 1989, "cold fusion" has had the reputation of being unrealistic. From my point of view, wrongly, because it is quite conceivable that a kind of catalysis reaction could lower the hurdle for ignition. In that 1989 experiment, this was done via a solid in which the atomic lattice's fuel, e.g. hydrogen, is pressed (https://gotec.io/wissenschaft/physik/das-pons-fleischmann-experiment-kernfusion-bei-raumtemperatur). Due to the atomic structure of the solid, the atoms of the fuel move closer together, and the probability of a fusion reaction increases.

Catalysis already works very well with so-called muons, which are particles similar to electrons, but with 200 times the mass. They occur in the high-altitude radiation (cosmic rays) that hits the earth's atmosphere. Their lifespan is only a fraction of a second (2,2 µs), yet they can force several hundred atoms to fuse during this time, depending on temperature.[6] This happens because the atoms of hydrogen use the muon as an electron to form a molecule. Attracted by the extremely large mass, they come too close. This muon-induced nuclear fusion could already take place at room temperature, but unfortunately no way has yet been found to produce these particles that would be effective enough for the construction of a fusion reactor.

Antimatter is also worth mentioning. It is not a fusion in the true sense, but rather a complete destruction of matter and conversion into pure energy, also according to Einstein's relationship $E = mc^2$. At CERN in Geneva, it was possible to produce some "anti-hydrogen atoms" and even catch them in so-called laser traps. If you encounter normal matter, only a huge amount of energy remains, on this technique. Here too, however, the amount of energy needed to start the process is far greater than the recovered energy, which makes this concept unsuitable for a fusion power reactor.

This is a set of rough classifications, as there are certainly more potential variants. And it is possible that humanity will also find other ways in the future, e.g. through the findings from the study of "dark matter" or "dark energy".



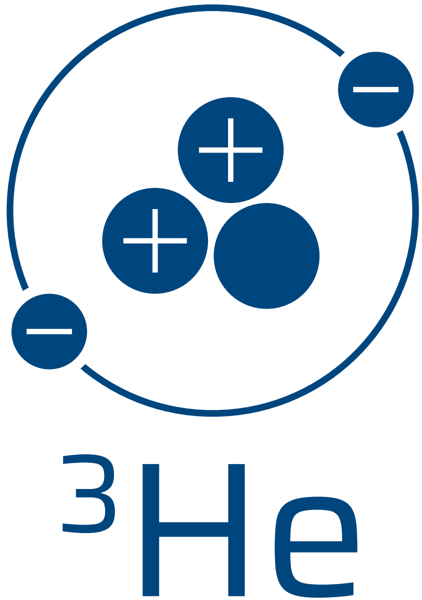
[6] Kalte Fusion – Wikipedia

THE FUEL

AFTER LEARNING ABOUT DIFFERENT CONCEPTS FOR THE REACTOR, WE COME TO THE FUEL: HYDROGEN.

In its process, the sun uses heavy hydrogen, deuterium (D) in a D-D reaction. Simpler is a D-T fusion on Earth, which uses deuterium and superheavy hydrogen, tritium (T). The Deuterium amount in our oceans is huge and will last forever (millions of years). In water about 150 Atoms out of 1 Million are Deuterium, while Tritium does not occur in sufficient quantities in nature, so it must be produced in a D-T fusion reactor through a process called "breeding". Tritium decays with a half-life of about twelve years, resulting in the helium isotope (He3), which lacks a neutron. The sun also produces this "ash" and sends it into interplanetary and interstellar space via solar wind.

Large quantities of it are stored on our moon, among other places. Using D-He3 as fuel would have the advantage of not having to breed tritium, and this reaction produces charged particles that could potentially be converted directly into electricity. Stars like our sun can also fuse carbon (red giant) from helium and iron from carbon (white dwarf) before ending their lives (black dwarf). Elements beyond iron require additional energy to be produced, and they are only produced during stellar explosions, so-called supernovae. When the fusion reactions end in stars that are much more massive than our sun, they implode due to the gravitational pressure and the atoms are either ejected or crushed, creating a so-called "neutron star" or a black hole.



Particles mean radiation, so there are approaches such as p-B11 (hydrogen with boron), they produce virtually no radiation and/or radioactive residues. While the magnetic confinement requires about 100 million degrees for D-T and 600 million degrees for D-He3, the value for p-B11 is 1 billion degrees! However, temperature is just another word for the speed of the particles, in modern particle accelerators these temperatures can already be reached. Reactor concepts that allow an increase in pressure or confinement time could also be advantageous here.

Every plasma needs a coating, a coat. This jacket meets several criteria: it keeps the heat in the reactor (confinement time), protects against radiation (biological shield), decouples the excess heat and, in the case of the use of tritium, breeds this short-lived radioactive element. The inner wall can be made of special steel, graphite, beryllium or tungsten, but there are also concepts that provide for a liquid wall. To "breed" tritium, the neutrons produced during the fusion process are used to leave the plasma at very high speeds, they are first braked in the blanket and then used for breeding. Beryllium or lead is used for braking, lithium is needed for breeding. Blanket concepts with solid materials use beryllium or Be-alloys and lithium ceramics. Blanket concepts with liquids are based on low-melting metal (lithium), metal mixtures (lithium-lead (Li-Pb)), salt mixtures or fluoro-lithium-beryllium (FLiBe).

Finally, there are still differences in heat extraction. Most of the existing concepts convert the heat into steam and generate electricity as in conventional power plants. The coolant for this is water or helium, the latter especially in conjunction with jacket concepts based on a solid. With D-He3 and p-B11, however, the heat is only a small part of the energy, most of which are charged particles that could be used directly for power generation. The major problem that has to be solved is the selection or development of materials that withstand this bombardment of high energy particles. Neutrons are neutral by definition and are directly leaving the plasma but cause significant impact on the matter they hit. Charged particles like protons can be guided by a magnetic field and focused on a target but the surface of these target materials might be evaporated by the high temperatures they cause.

One could say materials represent the final frontier for the commercialization of Fusion. A lot of efforts toke place concerning plasma enclosure, heating, and controlling but the conditions of a continuous burning star are still beyond our experience. The “bottle” for it is a humankind project of its own. The solution approach would affect not only Fusion but also the alternative energy sector and space travel.

Star-Trek-Universe: Zefram Cochrane will develop the warp engine and fly it the first time in 2063.

We all know that he will not be successful without a Fusion energy source. It should be small and light enough to fit in a spaceship.

LET`S HAVE A FUTURE GLANCE

For space travel, space stations or even colonizing foreign worlds water and its elements are essential, so the best would be if it could directly turn water in oxygen and hydrogen! Deuterium is a hydrogen isotope and can be separated for the energy production using nuclear Fusion. So why don't we skip the "steam machine" and aim towards a power plant that emits hydrogen and adds pure oxygen to our atmosphere? We could use it in future also for terraforming Mars or other planets, like in the SciFi "Total Recall" (1990). The so called "violet" hydrogen can be stored, used in regular gas power plants and in trucks or cars, by direct burning (gas-turbine, piston-engines) or be converted in electricity using fuel-cells. **This would make FUSION much more attractive and gain public acceptance.**

For this variant, however, the temperatures in the reactor jacket would have to be further increased and a considerable development effort is still required. This requires an indirect long-term technology transfer from science to industry, also called "Deep-Tech". Highly specialized micro businesses in form of start-ups or spin-offs could take over to reach the goal. "Spin-Ins" like KBHF with their relationship to public research organizations could help to make this a collective endeavor.

Jules Verne anticipated the moon landing for about 100 years, although the technology was not the same, it was the result. In reference to one of the greatest science fiction authors of all time, I am mentally guided by the term "Verne factor"; it should help to determine the (temporal) proximity of the described technology. Its amount corresponds to the years estimated for implementation to market maturity. The Verne factor results in the result of all received expert forecasts divided by the number of participants. The larger the (annual) number, the longer it takes to realize. The time forecast can be changed positively if the examined start-ups (through interviews, their own book and magazine articles or blogs) issue further information that suggests a market opportunity in the short term.

THE COMPANY´S WORLDMAP

COMPANY	LOCATION	CONCEPT	WEBSITE
Commonwealth Fusion Systems	Massachusetts, USA	TOKAMAK	https://cfs.energy
TAE	California, USA	Two plasmas Accelerator	https://tae.com
Tokamak Energy	Oxford, England	TOKAMAK	https://www.tokamakenergy.co.uk
Helion Energy	Washington, USA	Two plasmas Accelerator	http://www.helionenergy.com
Type One Energy	Nevada, USA	STELLARATOR	https://www.typeoneenergy.com
HB11	Sydney, Australia	Laser Fusion	https://hb11.energy
CTFusion	Seattle, USA	Magnetic Confinement	https://ctfusion.net
First Light Fusion	Oxford, UK	Inertial Fusion	https://firstlightfusion.com
ZAP Energy	Seattle, USA	Pinch Effect	https://www.zapenergyinc.com
General Fusion	Burnaby, British Columbia, Canada	Mechanical compression	https://generalfusion.com
LPP Fusion	New Jersey, USA	Pinch Effect	https://lppfusion.com
HyperJet Fusion Corporation	Virginia USA	Inertial Confinement	http://hyperjetfusion.com
Horne Technologies	Colorado, USA	Inertial Confinement /Pinch Effect	https://www.hornetechnologies.com
Miftec	California, USA	Pinch Effect (Z-Pinch)	http://miftec.com
Renaissance Fusion	France and USA	STELLARATOR	https://stellarator.energy
Innoven Energy	Colorado, USA	Inertial Fusion	https://innoven-energy.com
Compact Fusion Systems	New Mexico, USA	Compression by liquid metal (FRC)	https://www.nuclearfusionsharktank.com/compact-fusion-systems
Princeton Satellite Systems	New Jersey, USA	Fusion propulsion based on FRC	https://www.psatellite.com
Helicity Space	California, USA	Fusion Propulsion	https://www.helicityspace.com
Proton Scientific	Tennessee, USA	Inertial Fusion & Electron Beam	http://protonscientific.com
EMC-2	New Mexico, USA	Similar to mirror machine	http://www.emc2fusion.org
Fuse Energy Technologies	Montreal, Quebec, Canada	Z-Pinch, magnetic compression	https://www.fusionenergybase.com/organizations
NK Labs	Cambridge, USA	Muon-catalyzed fusion, laser heated	https://www.nklabs.com
Kyoto Fusioneering Ltd.	Kyoto, Japan	TOKAMAK	http://www.kyotofusioneering.com/en
Marvel Fusion	Munich, Germany	Laser-driven Fusion	https://marvelfusion.com

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