Ricky's Afterthought:

Nuclear Fusion: the Holy Grail of the Energy Crisis!

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"Electricity through fusion will be with us within 20 years" boasted Professor Peter Thonemann, my boss at the Physics Department at the University of Swansea where in 1968 having completed my PhD in gas discharges at Imperial College, London, I moved to South Wales and started a Post-Doctoral Research Fellowship. It was the kind of throwaway remark he would make as we had coffee in the spacious room high up on the 6th floor in the department overlooking the magnificent expanse of Swansea Bay, a site earmarked for a possible future wave energy converter. The fusion process entails raising the plasma, comprising of light isotopes of hydrogen such as deuterium ^2H (D) and tritium ^3H (T), to very high temperatures so that they fuse to form the heavier element helium (^4He) and a fast neutron. The mass of the products is smaller than the original, the difference converted to energy in the emerging fast neutrons via Einstein's mass energy equivalence, $e=mc^2$. The question is of course, can one reach high enough temperatures of the order of 150 million °C for sufficient time for fusion to occur before the isotopes escape the confining magnetic fields keeping these away from the wall of the vessel?

Prof Thonemann was Head of the Department having carried out his DPhil at the Clarendon Labs at Oxford where he met Dr Tuck. Their subsequent work centred around magnetic confinement in plasmas which in essence is at the heart of the work carried out so far on research into fusion with attempting to keep the ionised particles away from the walls of the confining vessel.

For many scientists Prof Thonemann was regarded as the father of fusion and spent most of his career working on this topic at Harwell and then Culham Labs near Ditcot not far from Oxford and was associated with the work on ZETA, (Zero Energy Toroidal Assembly)[1]. The announcement of the appearance of energetic neutrons from fusion in the 1950's was, to say the least, a bit premature but it is fair to say that work on ZETA continued and led to the toroidal type of fusion reactors, called tokamak, currently being experimented on at the UK's Atomic Energy Authority at Culham under the JET scheme (Joint European Torus) and at ITER in France.

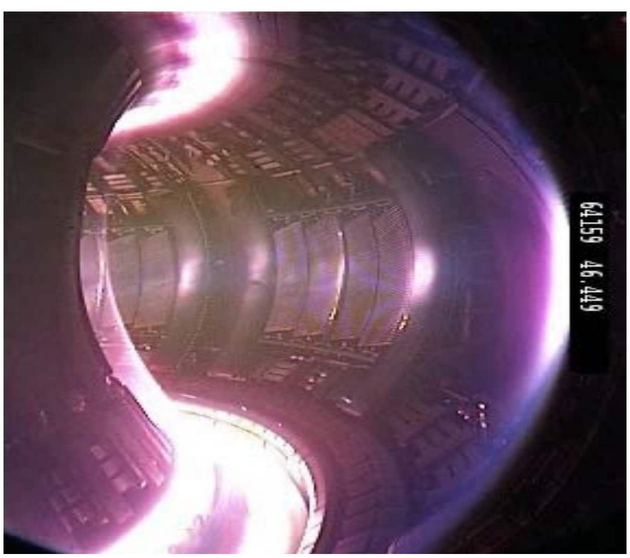
In the mid-sixties Prof. Thonemann became Deputy Director at Culham and within a short period of time he accepted the Head of Department position in the Physics Department at the University of Swansea. I was one of his first researchers tasked to study the collisions of energetic particle with the walls of a linear pinch device. The fear was, and still is, that once these particles escape the confinement afforded by the magnetic fields, they would collide with the cold walls and lose all their energy.

Status quo in Europe

It has becomes a joke to talk about fusion being 20-30 years ahead[2]. A few month ago there was a press release stating that Eurofusion scientists and engineers at the UK's Atomic Energy Authority JET facility at Culham had achieved a record breaking 59 MJ of sustained fusion using deuterium and tritium for a duration of 5 s and that was hailed as a great success as it was double what they had achieved in 1997. Well, for fusion to solve the energy crisis the tokamaks of the future must produce sustainable power not for 5 sec or 5min or 5h or 5 days or 5 months but continuously. That is, the fusion-generating plasma must remain away from the walls by its magnetic confinement and that has always been the main challenge. Nobody has ever suggested that producing a simulated sun in the laboratory would be easy. The proponents of fusion power claim that the supporting technologies such as extremely powerful magnets, high performance computing and machine learning and advanced manufacturing techniques give confidence that we are much nearer achieving a working reactor that was thought possible a few years ago. Is that wishful thinking or do the experiments point to fusion being at the "end of the tunnel" so to speak, at least a very long tunnel indeed?

Europe including Switzerland, in collaboration with six other countries, has decided to invest heavily in this type of fusion reactor which culminated in the so called ITER (International Experimental Thermonuclear Reactor) Fusion reactor currently being constructed at Saint Paul les Durance in Southern France.

ITER, essentially a scaled-up version of the JET system, is a proof-of-concept which is expected to produce 500 MW of fusion power with an input of 50 MW of electricity for 20 min. The project includes a 400,000t tokamak complex comprising of the tokamak building, the diagnostics building and the tritium building. The tokamak complex is a seven-storey structure that is 120m long, 80m wide and has a height of 73m. The fuel will be D and T.



A view of the chamber where the D-T plasma is created and elevated to high temperatures

Although deuterium is easily extracted from water, tritium is rare and is produced during nuclear fusion. The temperature expected within the $840m^3$ of plasma will be around 150 million ^{o}C. The magnetic field that confines the plasma is produced by induction resulting in a current that flows through the plasma and heats it, akin to ohmic heating. But external heating is also needed to reach the temperatures for fusion and this is provided by either a neutral beam injection and/or high frequency electromagnetic waves. So a combination of toroidal and poloidal magnetic fields established within the core will heat and confine the plasma[3]. The recent announcement from Culham of producing 59 MJ of sustainable fusion power albeit for a short time strengthens the case for ITER.

Thus far $22.6 bn has been allocated for ITER. The EU with the UK and Switzerland contribute around 45% while China, Russia, EU, USA, India, Japan and South Korea each contributing about 9%.

Worldwide investment and major schemes

Judging by the investment that has been allocated to date into fusion one would conclude that policy-makers and entrepreneurs believe that electricity through fusion is certainly on the horizon. Glancing at the headlines in the website of the Fusion Industry Association (FIA) one is astonished at the optimism. These range from "Whitehouse sets sights on Commercial Fusion" and "The holy grail of fusion generation might finally be within our grasp" to the "Compact tokamak is on the verge of energy production" and "European industrial giants join nuclear fusion race". A report was published indicating that many companies have invested up to a total of $2.4bn.

Some of the major schemes follow:

Commonwealth Fusion Systems, a spin-out of MIT has raised $1.8 bn to fund the construction of a pilot plant at their campus. This is supposed to be operational by 2025. In Sept 2021 they announced that in collaboration with MIT's Plasma Science and Fusion Centre they successfully tested a high temperature superconducting magnet delivering 20 T which is the highest magnetic field ever produced and which will be used in their SPARC tokamak-like device to generate fusion power.

A scheme on a similar time frame is that of the Canadian firm General Fusion (Amazon's Jeff Bezos is an investor) who wish to produce a working prototype, the so called "Fusion Demonstration Plant" on a site near the Culham Labs in the UK where they would tap existing expertise, particularly in the procurement of future fusion reactors, and hoping that the reactor will also be operational by 2025. In this process, a super-heated gas called a plasma, consisting of a particular form of hydrogen, is injected into a cylinder which is surrounded by a wall of liquid metal. Hundreds of pneumatic pistons are then used to compress the plasma until the atoms fuse, generating massive amounts of heat. This heat is transferred to the liquid metal, and used to boil water and make steam to drive a turbine.

Microsoft co-founder Paul Allen is investing in Irvine, Calif.-based Tri-Alpha Energy. Other co-founders include Goldman Sachs, Wellcome Trust, and Silicon Valley's NEA and Venrock. The concept here is rather different from the more conventional tokamak design in that the system uses a nuclear fusion design that shoots beams of plasma into a vessel where it's held in place, spinning, by a magnetic field. The design shares some properties with particle accelerators. The researchers have also developed a machine learning tool called "Optimetrist Algorithm" which they will use to choose the parameters for nuclear fusion. This was done in collaboration with Google research. Although the algorithm concentrated in optimising the parameters for their C-2U plasma generator different types of plasmas are envisaged for future reactors.

Peter Thiel a venture capitalist and co-founder of Pay Pal is investing in Helion Energy. Their website states, I quote, "Helion's unique pulsed, non-ignition fusion device will generate zero-carbon electricity from D and H-3. This is made possible by combining modern power electronics with the work that was carried out since the 1950's". They also claim that temperatures reached in their plasma were around 100 million ºC. What is impressive is that they secured $0.5 bn and an additional $1.7 bn is pledged should they meet some specific milestones. The hellion team hope to demonstrate electricity from fusion by 2024!

Finally, ETA Technologies based in California, state in their website that their National Laboratory scale prototype combines their proprietary power management technology and advanced accelerator beam driven field reversed configuration (FRC) for compact and efficient operation. Their latest prototype is called Copernicus and although they may start with a D-T fuel they will eventually switch to Hydrogen and Boron. They claim that TAE's patented accelerator technology injects neutral beams for driving current to heat and stabilise the plasma for fusion.

In all these schemes the main goal is producing more electricity from the fusion process than is put in to get the system going. That has not been achieved as yet. I must add, however, that some respected scientists doubt some of the claims that are made in some of the schemes discussed above.

Although in the first instance investing a few $ bn towards fusion may seem a staggering amount, on reflection if one considers the net worth of some of the main contributors, it puts such funding into perspective. For example, the net worth of Bezos, Allen and Thiel were purported in 2021 to be $130bn, $20bn and $7bn respectively.

Smaller fusion start ups

Worldwide there is a host of smaller enterprises that are experimenting with small fusion reactors with outputs of the order of 100MW and are turning away from the vast national and international counterparts such as the ITER. Moreover not all are basing their expectations on tokamak design but there are alternatives such as a linear reactor with a rotating plasma or indeed inertial confinement where the plasma is pressed to extreme densities thus creating conditions for fusion as in the Fusion Demonstration Plant discussed above.

For example, First Light Fusion near Oxford plans to use this inertial method whereby fuel pellets are compressed and heated so fast that they fuse in nsec before the fuel blows apart[4]. The Big Friendly Gun is 22m long and terminates in a 21.5t vacuum chamber which houses a 1 cm plastic tube containing the D-T mixture.

The compression occurs when projectiles are fired at 14.5 km/h towards the fuel pellet. Lithium flowing inside the reactor vessel will then be heated by the fusion-released energy of the neutrons. The heat is transferred to water then turned into steam for driving the turbines to generate electricity. Apparently this is repeated every 30 s. Their goal is a plant producing 150 MW of power by the mid-2030s. This approach is based on getting the physics right and what is more it does not rely on having to confine a plasma as in the case of the tokamaks. Given the engineering complexity of the tokamaks firing projectiles at a fuel pellets present fewer problems but will it work, that is the question?

The investment acquired thus far is very impressive too. They received £23million in 2015 followed by £19 million in 2019 and £34 million last February.

Outlook

The global energy market is worth $3trillion and much of that is fossil fuel fired and if part of that can be replaced by fusion so much the better for the environment. Nuclear fission is displacing part of that but disposing of the radioactive core of the reactor remains the major problem. Renewables are well established and currently are providing a substantial part of the energy we need, however, with decarbonisation of our industries and transport mankind will need much more energy than can be provided by renewables and nuclear fission.

My gut feeling is that fusion systems based on the tokamak reactor design may be the ones that may result in sustainable power generation but I doubt that such systems will be fully operational before 2050. Will we see smaller system operating much earlier? I really doubt it but let us hope I am wrong.

For further reading

1. https://www.swansea.ac.uk/science/news/professorpeprofessorpet-areflectionofhislife.php
2. "The Promise of Fusion" by Helena PozniaK, IET Journal Volume 17 March, pp. 38-41 2022
3. AC Metaxas, 1996, Foundations of Electroheat: A Unified Approach pp. 206-207.
4. https://firstlightfusion.com/