Will fusion be ready to meet the energy challenge for the 21st century?

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Abstract. Finite amount of fossil fuel, global warming, increasing demand of energies in emerging countries tend to promote new sources of energies to meet the needs of the coming centuries. Despite their attractiveness, renewable energies will not be sufficient both because of intermittency but also because of the pressure they would put on conventional materials. Thus nuclear energy with both fission and fusion reactors remain the main potential source of clean energy for the coming centuries. France has made a strong commitment to fusion reactor through ITER program. But following and sharing Euratom vision on fusion, France supports the academic program on Inertial Fusion Confinement with direct drive and especially the shock ignition scheme which is heavily studied among the French academic community. LMJ a defense facility for nuclear deterrence is also open to academic community along with a unique PW class laser PETAL. Research on fusion at LMJ-PETAL is one of the designated topics for experiments on the facility. Pairing with other smaller European facilities such as Orion, PALS or LULI2000, LMJ-PETAL will bring new and exciting results and contribution in fusion science in the coming years.

1. Introduction

The energy challenge is critical for today’s world. This is motivated on one hand by the finite amount of fossil fuel and by the emerging of new economies and new countries with growing populations and energy demand. At the same time there is a strong appeal towards the reduction of all means of energy productions which produce large amounts of CO$_2$. Global warming appears to be the threat of the century. This is why the European Union has taken a strong commitment to reduce its CO$_2$ production in the coming years and to develop energy production greenhouse gas free. [Fig. 1]

2. The flaw in renewable energies: not enough material

Renewable energies will probably play an important role in this new energy balance but their intrinsic efficiency in terms of space occupation, and their intermittency pose serious problems for intensive production of energy coupled to stable distribution network, at least as long as mass storage is limited. A simple common sense idea, often forgotten: In renewable energies one always insists on the renewable «source of energy» (wind, water, sun) without ever addressing the question of the means to make this energy useful: dams for hydroelectricity, wind-turbines for the wind, and solar cells of thermal devices for the sun.
These devices consume space and matter. This space and matter consumption, in a finite world have a substantial impact on the available reserves of space and matter.
It has been shown that this limitation may be a key issue, and not only for so called «critical materials» such as Rare Earths which can be replaced or recycle, but also for non-specific materials such as steel, copper or aluminum. A similar analysis for space can be carried out.

Despite all the common idea that new renewable energy sources are “free” and “practically unlimited” in a sense that no one owns the sun nor the wind, the fact remains that in order to capture these energies, one needs an immense construction effort. This, unfortunately, is neither free nor unrestricted in the material sense. As shown by Vidal, Goffé & Arndt Ref. 1 projected renewable energy deployments would very soon outstrip the current global production of several key materials. [Fig. 2]

3. Developing nuclear energy fission and fusion : a priority for the energy mix

In this context, the development nuclear energy appears as a necessary task to be addressed in order to satisfy the demand of energy of tomorrow’s world, at least in a transient stage. Fission nuclear energy has a long history and especially France has developed a strong industrial sector. Promising vision of nuclear fission include the generation 4 (GENIV) type of nuclear reactors which will be able to burn depleted uranium and to minimize the amount of ultimate long live waste. Plutonium becomes a resource instead of being a waste.
In the longer term, nuclear fusion seems to be even more attractive promising a production of energy with no limit on fuel materials and limited long term nuclear waste – only fission products - in the production cycle. However this attractive goal faces scientific and technical challenges which will not be easily overcome and require advanced investigations. In parallel, the common points between different possible routes and the possibility of joining forces appear as strong assets.

In recent years several important results have been achieved in the field of nuclear fusion. In 1997 the European tokamak machine JET, in Culham, succeeded in generating 16 megawatts of fusion power, i.e. 70 percent of input power. Last year, at NIF, the high-foot implosions were able to demonstrate a significant alpha-heating of the thermonuclear fuel, thereby really entering a new physical domain in the physics of imploded plasmas [Fig 3]. These achievements are really significant and show how substantial progress understanding nuclear fusion has really been made.

Figure 3 - The experimental results have matched computer simulations much better than previous experiments, providing an important benchmark for the models used to predict the behavior of matter under conditions similar to those generated during a nuclear explosion, a primary goal for NIF. (source LLNL)

At the same time, these results show that the path to energy production by nuclear fusion is still not a straight road, and the development of fusion-based reactors is not at hand. Europe and France in particular are in the front-line of research on nuclear fusion. France has the honor of hosting two leading research facilities for the study of nuclear fusion.

4. ITER the priority path for fusion in Europe

The first one is the ITER facility currently under construction in Cadarache in the south of France. ITER will be an advanced tokamak machine which is designed to achieve the plasma energy breakeven point, and aims at producing more power than it consumes: for 50 MW of input power, 500 MW of output power is the target. ITER will also allow studying the conditions of a burning plasma, the radiation flux from the plasma and the effects on the materials composing the machine. Therefore it will pose the basis for the development of future reactor demonstrators. ITER is an international enterprise, including Europe, USA, Russia, China, Japan and India, but France plays a particular role being the host country for the reactor.

At Cadarache, CEA is modifying its Tore Supra plasma facility which, once transformed, will become a test platform open to all ITER partners: the WEST project (acronym derived from W Environment in Steady-state Tokamak, where W is the chemical symbol for tungsten). The goal is to equip the tokamak with an actively cooled tungsten divertor, benefitting from its unique long pulse capabilities, its high level of additional power and the unique experience of operation with actively cooled component [Fig. 4]. The divertor is a key component which faces the largest part of the heat and particle fluxes coming from the core plasma during experiments. The current option, in order to avoid erosion is Tungstene but the potential pollution of the plasma and the need for huge heat extractor remains critical issues on the path to success.
5. The Megajoule Laser in France: a key facility for the Nation’s security

At the same time, CEA is running the Megajoule Laser facility on its site near Bordeaux. LMJ, a brother laser to NIF, is already operational for physics experiments although with a limited number of beams, and more beams are currently added to reach the final configuration of 176 beams and over 20 permanent diagnostics. The LMJ has been built with the main goal of contributing to assuring the French nuclear deterrence. [Fig 5]. CEA, in agreement with the Region Aquitaine, has decided to open the facility to academic civilian research for a quota up to 30% of the laser time. In particular a Petawatt laser, companion to the LMJ, PETAL has been developed explicitly as a research instrument for academic research and will be open through the same process as LMJ to the international academic community. [Fig 6].

The first call for proposals for civilian experiments was issued end of 2013 under the management of ILP, Institute for Lasers and Plasmas, which federated the research groups which work, in France, on the physics of laser-produced plasmas. Finally, 4 experiments out of 6 proposals have been selected by an independent International Scientific Committee nominated by ILP. Experiments are planned to start in 2017. These experiments include:

1) The study of strong shock generation by laser plasma interaction in the context of shock ignition studies proposed by Sophie Baton (LULI), Xavier Ribeyre (CEILIA) and al.

2) The study of radiative shocks, of astrophysical relevance, in the laboratory proposed by Michel Koenig and al.

3) The study of primordial magnetogenesis proposed by Gianluca Gregori and al.

and finally

4) The study of the interplay between B-field and heat transport in ICF conditions proposed by Roch Smets and al.

The next call for experiments will appear early next year for a deadline for submission mid-2016. Academic civilian experiments are an important point in the research policy of CEA. At the same time they offer the possibility of starting a research program dedicated to the study of nuclear fusion for the production of energy. Such research program conducted jointly by the European scientific community and by CEA researchers will need to grow and aggregate new teams in the next years in order to be able to cope with the challenges of nuclear fusion. Such “consolidation” implies a large scientific community working in Europe on the subject, larger funds and more technical means, increased dedicated laser time.

One could wonder what can be the role of the European scientific community working in ICF compared to much larger communities such as the US or the Asian communities. What will be in particular the contribution of experiments performed on LMJ-PETAL. Certainly the advancements
done by our US colleagues during the National Ignition Campaign are enormous and there are many things, which we need to learn by collaborating with them.

At the same time, the results of NIF experiments have clearly shown that there are still many difficulties to be overcome to reach ignition. On LMJ, scientists will put most of their efforts to perform direct-drive experiments. Using PETAL as an advanced radiographic diagnostic they will be able to check the uniformity of implosion needed to create the conditions of extreme densities and temperatures required at the center of the fuel pellet.

6. European studies on direct drive ignition

Indeed the difficulties of indirect-drive experiments on NIF seem to re-open the chances for direct drive and, in this field, promising new schemes are appearing, in particular the new approach called “Shock Ignition” introduced by the colleagues of the University of Rochester, which decouple the ignition process from the compression process allowing much more flexibility and potentially higher efficiency.

This seems to be a very interesting path for academic experiments on LMJ, and for the development of a European research program on inertial fusion for energy production.
Such effort, which in Europe has to be created, should not to be seen as an alternative to the main recognized approach of Magnetic Confinement Fusion. Interesting in the last few years, research programs involving both the ICF and the MCF communities are starting and need to be extended. After many years of “confrontation” and cold war between MCF and ICF we are now in a new phase of beginning of collaborations around some points of common interests: the behavior of material irradiated by high radiation and neutron fluxes, the need to develop new diagnostics tools adapted to burning plasmas, the problems of the interaction chamber and the breeding of nuclear fuel. This is certainly a very positive change and CEA will work to further favor it.

Another important element of the European panorama is certainly the presence of several smaller laser facilities. Such “intermediate” laser facilities are indeed essential for the development of a strong European program on inertial fusion for energy (IFE). Of course one cannot imagine realizing experiments on LMJ-PETAL without a proper preparation on a dedicated facility. Therefore all these laser systems are essential: LULI in France, Vulcan and Orion in the UK [Fig. 7], Phelix in Germany, Pals in the Czech Republic. Here European scientists will be able to test the ideas for experiments on LMJ-PETAL, to develop and calibrate diagnostics and, even more important, such facilities will continue to assure the formation of a new generation of scientists working in the field.

Figure 7 – ORION progresses in direct drive implosion experiments. Initial experiments have achieved $>10^9$ DD neutron yield

At the same time, we need to begin addressing other issues related to drivers for future fusion facilities. We need to develop new laser technologies which are able to simultaneously offer large delivered energy, high overall efficiency, high repletion rates. Without such laser systems, inertial fusion energy will probably remain a dream even after it has been scientifically demonstrated. Research programs addressing the required technology developments have already started in France, the LEAP project again in Aquitaine within collaboration between CEA, the University of Bordeaux and the industrial world, but also in other countries, in the UK (Dipole project), in Germany (Polaris program at Jena), in the Czech Republic (at ELI-beamlines in Prague).

7. Conclusion and perspectives for fusion studies

It is clear that the development of such new generations of powerful and efficient laser systems will benefit not only the world of scientific research but also the economic and industrial world via the generated activity, and finally every aspects of society, lasers finally being a pervasive technology in the 21st century. Finally, this is the final point, which I would like to stress: by pursuing the research on Inertial Confinement Fusion, we are not only advancing science but we are providing top-level scientific and technological research. We are contributing to maintaining high technological standard and preserve the interest of our economies and of our industry. We are contributing to the training of new scientists and a new technological leadership for tomorrow’s society.

[Ref. 1] Vidal, Goffé, Arndt, Nature Geoscience 6, 894–896 (2013).