Building the way to fusion energy

Construction of the ITER tokamak, arguably the largest scientific project ever, is well under way in the south of France. *Nature Physics* spoke with ITER's Director-General, Bernard Bigot, about the challenges ahead — a conversation about physics, engineering, politics and culture.

How did you become involved in ITER?
After the official launch of ITER in 2007 with the creation of the ITER Organization (IO), we've been in what I call a learning phase. The IO, a very complex organization, had to be built from scratch. As the owner of the ITER project, the IO has to deal with assembling the ITER machine and the coordination of the seven partners, or Domestic Agencies — the European Union, China, India, Japan, Korea, Russia and the US — all working on the production of different components of ITER. Over the first few years the IO and its partners have had to learn how to work together on technically complex issues, and assess the final design of the ITER device. It became apparent that the management of the project was not appropriate for it to succeed on time and on budget. In a 2013 management assessment report several weak points were uncovered, and the IO launched a call for a new Director-General. The search committee approached me, feeling that due to my experience and the fact that I'm quite well known within the fusion community — and the worldwide energy community in general — I couldn't decline. I knew that it was quite a challenge, but the ITER members were convinced that I could contribute to this project. First, in conjunction with all of the stakeholders I came up with an action plan that set the project on the right track towards delivery. Since then we have been working intensively on implementing this action plan successfully.

The general opinion seems to be that the IO was too decentralized. Is it fair to say that the IO is a more cohesive organization now?
I would use the word integrated to describe the IO. What is important is not to centralize, but to integrate the different parties, so that decisions can be taken efficiently and effectively. The ITER machine consists of several specific complex components, which by themselves are each extremely challenging. For example, there is the 800 m^3 vacuum vessel that needs to sustain a very low pressure and low temperature, but should also be capable of sustaining a large neutron flux at high temperature. There are the huge superconducting coils at very low temperature — the largest ever built. You also have the cryogenics; ITER is going to be the largest cryogenic plant in the world for producing liquid nitrogen and liquid helium.

These complex endeavours require an integrated project culture to be successful. Until recently, many people involved did not have the impression that they were part of a global project. Each group was concentrating on delivering their own part on time. Now we've transformed the IO into a project-oriented organization, with a very important central integration office. This didn't exist before.

Is your approach of integration being felt already?
Some time ago, some of the suppliers told me very openly, and very candidly, that they already feel the change. It's a change in the culture of the project. What I want is for all of the parties, which means the IO central team and the staff of the seven Domestic Agencies, to act as a single team. Everybody has to feel part of the project. For me, this is an absolute requirement for the IO to perform well and make this project a success. But a culture change always takes longer than we would like.

What really pleases me is that a lot of people have now become really fond of the ITER project. They believe that it is a project worth dedicating their time, energy and knowledge to. And now they see a new organization that better fits the project-oriented approach. People are willing to move on and adapt fast; I feel we are on the right track.

ITER is a huge project and the seven partners should all work together. But somehow, the work has to be divided. How is that done practically?
Let me first emphasize that the project is so large because the physics involved requires that we have such a large facility. You could never produce a large amount of fusion energy with smaller-scale devices. Fusion occurs in the Sun because the Sun's mass is 300,000 times that of the Earth. The same holds for magnetic confinement technology: if you don't have coils that are large enough and strong enough to produce a sufficiently high magnetic field, the fusion reaction will never be sustained. That's why people need to work together. For one nation alone, the scientific, industrial and financial investment would be too much — and it would all take too long.

So we do need to divide the work over the seven members (representing half of the world's population), but the difficulty is that the division is not made on scientific grounds, *per se*. Science itself is very dynamic and flexible, and difficult to plan long-term. The work is divided industrially. For example, in 2005–2006 the agreement between the seven parties was that one part of the vacuum vessel would be made in Korea and another part in Europe; part of the coils would be made in China; the casing in Europe; some other part would be made in Russia, and so on.

From the beginning there has been this split in procurement for the seven members. They agreed to take full responsibility to deliver, and now it's up to them to find the best way to do that under the supervision and coordination of the IO's central team. And that's where the real difficulty lies: some have the money, some have the industrial capacity, but at the end of the day, the IO has to approve and validate production and be sure that all of the components will fit together on ITER's assembly site. Right now, manufacturing worth €7 billion is in progress worldwide.

The advantages of fusion are obvious, especially to physicists and scientists in general. But why has it taken such a long time to get started with ITER?
The main reason is that it's a long-term investment, for which we need the absolute cooperation of the most scientifically and technologically advanced nations to ensure that we will succeed. As all of the members have their own decision and financial appropriation mechanisms, it takes time. Moreover, this project is the first of its kind — nobody has ever built such a machine. The up-scaling is nearly ten times that of the largest facilities operating at present — such as the Joint European Torus (JET) in Culham, UK, the Korea Superconducting Tokamak Advanced Research (KSTAR) project

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in Daejeon, Korea or the Experimental Advanced Superconducting Tokamak (EAST) in Hefei, China. The design, planning, investment, engineering, construction and collaboration protocols are thus also exponentially more complex.

Let's compare ITER with CERN. Now a very large facility, CERN grew in a stepwise fashion: they started with small accelerators and gradually upgraded to larger machines. From day one, ITER will be the largest machine in the world. CERN's core members are European countries. There has traditionally been a lot of cooperation and interaction between scientists across Europe. For ITER, the seven partners involved amount to 35 countries, a mix of very dissimilar cultures. There are substantial differences in the way scientists and engineers with these different cultural backgrounds work and think.

So setting up this large cooperation takes time, but the different nations commit themselves because the reward is well worth the investment. If we succeed in demonstrating that fusion technology can provide a large amount of energy in a very sustainable, economically competitive and safe way, this will completely change the global energy landscape.

■ Before you became Director-General of ITER, you occupied important positions in France's Alternative Energies and Atomic Energy Commission (CEA). France is known to be a country with a strong nuclear energy tradition. Is this an advantage for the operation of ITER?

I do believe that this is advantageous for the project. France has experience with delivering large nuclear projects, with full consideration of the safety requirements. To be clear: ITER does not present the same risks related to safety, waste or proliferation as fission technologies. But ITER is still considered a nuclear installation, and so we need to have the same type of requirements for quality control and safety assessment.

The second point is that, as the head of the CEA for nearly 12 years, I was already accustomed to working in a position of trust with the seven ITER partners. Such trust is very important when you are dealing with an international collaboration project. If people trust each other, they will act in the interest of the project.

The fact that ITER is being built in France is also advantageous because the French population is quite supportive and familiar with nuclear technologies. I notice this when I speak with the local people and the local authorities; the overwhelming feeling is that ITER is the right way to go, and they are ready to help and support. So that's really positive.

■ The ultimate goal of ITER is to demonstrate the possibility of energy production from fusion. But will there be scope for fundamental physics research and to make discoveries in plasma physics?

Oh yes. ITER is a unique machine. It will generate the largest plasma ever on Earth — a long-lasting plasma with very high energy production — so there will be plenty for physicists to explore. On top of that, there are the technological challenges in cryogenics, superconductivity, materials, diagnostics and control processes. ITER will be rich with diagnostic sensors and instrumentation to enable this research and to optimize the design of future tokamaks. This will provide many new tools and situations for physicists to play with — things they've never played with before — so I am absolutely confident that, given the typical imagination and inventiveness of physicists, they will discover a lot.

This is also why, even if ITER will not run scientific experiments in the next few years due to the time required for construction and assembly, the project has to maintain close relationships with the universities and national laboratories of the seven ITER members. With this in mind, we decided to launch the ITER Scientist Fellows' Network at the end of 2015 — this will become a network of the world's top fusion scientists supporting the ongoing scientific analysis of burning plasmas in ITER and the preparations for ITER's scientific exploitation phase.

■ What exactly are the main challenges for ITER from a physics point of view?

There are many challenges. For example, mastering the turbulence that will occur in the plasma, which will have a density about one million times lower than atmospheric density and a temperature of 150,000,000 °C.

There's also the production of tritium. Tritium does not occur in nature, so in future fusion power plants it will have to be produced within the reactor from a precursor: lithium. We have to design and test the best way for producing the tritium and recycling it from the fusion reaction, and for dealing with these gases in a safe way.

There are also materials science challenges. Although there are no moving parts within the reactor, we still need materials that can sustain a long-lasting high flux of neutrons, heat, radiation and so on, so that the equipment will last for a hundred years or more.

There are so many challenges; it's a fantastic field to work in.

■ You already made a comparison between ITER and CERN. People associate CERN with all kinds of spin-offs, like the internet or the LHC Computing Grid. Do you foresee similar spin-offs beneficial for science and society coming from the ITER project?

Yes. A lot of the technology involved needs to advance. I have a good example: ITER requires pulses to heat the plasma, the hydrogen mixture. For this, you need a power pulse that reaches 50 MW in just a few milliseconds. This requires new electronics. A small company in Korea has now developed that technology. The director of the company told me that thanks to the ITER project, they have been pushed far beyond where they were before, and that now their technology is being considered for application in high-speed railways.

Another example concerns superconductivity. Because the power intensities that will go into the superconducting coils are unusual, I expect that a lot of ITER-related industrial research and development will become highly relevant for future energy transportation, medical imaging and other technologies that rely on the use of superconductors.

When CERN started, nobody could anticipate the invention of the world-wide web or the Grid. If we want to explore nature and matter in the most extreme and exceptional conditions, we need to develop new technologies — these will spread out more widely than just within the project they were initially developed for.

This is why the seven members want to be involved in the production of some of the components; they expect their industries to learn and make genuine innovative breakthroughs.

Let's discuss politics. Now that the construction of ITER has taken off, what are the political challenges ahead?
From the start, the expected construction time until the first ITER plasma was 10–12 years. But in the meantime, the project has been plagued with difficulties and delays. It is essential that we keep the trust of the policymakers of the seven Domestic Agencies by showing that the project is properly managed, and by producing the first deuterium–tritium plasma as soon as is technically possible, avoiding any delays arising from coordination difficulties. So the most difficult challenge in this respect is more managerial than technical or industrial.

Recently, some US leaders of Congress made it clear that unless they are convinced that the project is well managed, they may not be ready to put more money into ITER. It's a big task for me to convince everyone that the new action plan we agreed on is dependable and appropriate for completing the project, and that there is no other way to move forward. Some members may not like it, because they have to delegate and deputize some of the responsibility to the Director-General of the IO — the Director-General is now fully empowered to take any technical decision.

In a large project such as ITER, there are always changes. Manufactures and suppliers may discover, along the way, that there are other ways to proceed — many of the things they do are world firsts. We need to be able to adapt and properly manage these changes. Previously there was no efficient way to change an order; we wasted a lot of time arguing and discussing changes.

Right now, there are nearly 2,000 engineers, contract supervisors, safety inspectors and others employed by the IO. The basic operating cost is nearly €200 million per year. So every wasted day due to delayed decisions has a cost of around €1 million. A smooth and timely decision process is absolutely key.

But of course, I understand the politician's concerns: they want the project to deliver soon.

Do you think there might be some unexpected surprises that could undermine the success of ITER?
Unexpected things can always happen. With a plasma at 150,000,000 °C, delivering a power of 500 MW, materials may not be able to sustain the extreme conditions or there could be disruptions in the plasma current, which is generated and controlled by massive coils that need to be positioned with millimetre precision.

But I am confident that the engineers will be able to solve that. They have the experience of building smaller tokamaks, and now with all the tools that are available — simulations, 3D modelling — we can evaluate all of the necessary properties.

Of course, we have to remain humble and be aware that difficulties are very likely. This is why we have to carry out risk analyses, to determine how we can mitigate risks and to be sure, through quality control and anticipation of potential problems, that we are able to resolve any possible difficulties.

When will ITER have its first plasma?
Right now, one of the most important commitments of my action plan is to deliver a new, updated baseline schedule for the time it will take to manufacture and assemble the various components of the ITER machine, based on our current knowledge. We are working very hard on that. We want to come up with a reliable, fully committed resource-loaded timetable. Before all of the relevant information has been assessed, together with suppliers and the Domestic Agencies, I will not commit on a date. I want the date I will give to be the final date. I want to be serious — we have to keep people's trust.

How do you see the energy landscape for the near future? What should we focus on before fusion energy becomes a reality?
When I was the head of the French CEA, this question was always on my mind. At present, 85% of the world's energy comes from fossil fuels. We are also wasting a lot of energy; we could save a lot. The important effort we have to concentrate on first of all is saving energy, developing technologies that consume less energy but provide the same service. It's not only a technology issue, but also a societal one.

But saving energy is not enough. Predictions are that in the future the average world energy consumption will be 2.5 tonnes of oil equivalent per person per year (half of the current European consumption), which will lead to a 50% increase over present consumption levels. So in the future we will need more energy, whatever savings we achieve. Where will we find this energy? Renewable energies can provide part of it, but in my opinion it will be very difficult to supply over 50% of the world's energy demand from these sources, due to diffuseness, intermittency and storage problems — with renewable energies, it's difficult to have a high power density readily available to meet the needs of industrial centres or cities, for example. I do wish to stress, however, that we do have to develop renewable energy technologies as much as we can. Great progress has been made in the past ten years — in solar and wind energy, biomass transformation and so on, as well as in storage technologies.

We still need a way to produce massive and continuous energy flows. There are not very many alternatives. Fossil fuels will not run out tomorrow, but we have to reduce our consumption as much as possible so that we can rely on them for a bit longer and also reduce the risks of climate change. The only available alternative at present is nuclear fission — for the countries that can master the technology. I believe nuclear fission is still a technology worth continuing with during this century while we wait for nuclear fusion. But if exploited, safety has to be the first priority.

What would you consider to be the ideal energy landscape for the future?
In the long term, when nuclear fusion technologies are well established, my view is that we will rely on renewable energies and fusion energy, and there will be no further need for large nuclear fission programmes. Nuclear fission comes with specific risks, whereas with fusion there is no real risk on the same scale. Secondly, fission produces long-term radioactive waste, which is not the case for fusion. So I believe that when fusion energy technologies are demonstrated to be economically competitive and viable for producing energy in a sustainable way, fusion will be the winner.

You are very busy now with running ITER, but do you have time to do some science yourself?
Frankly, no. I'm working every day from seven in the morning until midnight, so I cannot produce science myself. I have great respect for the people who do scientific research and I'm delighted to read and absorb new science, to discuss it with scientists — I believe I have the proper background for that. But you have to accept that the work has to be shared and divided: now my duty is to manage the project, and I devote all my time to this management. I was expecting to retire, and maybe to start new scientific projects. It's a bit of a shame, but that's life — you cannot do everything at the same time. ❐

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