People behind PASQuanS

"Clearly, Europe is at the forefront of quantum science, and atomic quantum simulation in particular. But it is a challenge for Europe to translate this scientific leadership into a technological leadership."

Peter Zoller
Austrian Academy of Science OEAW, Austria
PI, Theorist

Could you briefly describe your institutional and personal role within the PASQuanS project: Which specific project activities are you involved in?
I am a theoretical physicist working in atomic physics and quantum optics. PASQuanS pursues building scalable quantum simulators with atomic platforms, and identifying and implementing applications of quantum simulation. I have always understood myself as somebody who, as a theorist, is close to experiment, trying to think of novel fundamental physics and technological applications we can do in light of experimental progress in the lab. In the early days, our main focus was to devise new concepts and proposals for quantum hardware, as are today in the focus of PASQuanS.

The emphasis has now shifted towards programming quantum simulators in our labs, which are scalable, although non-universal quantum, devices, both from a basic science and application point of view. This applies in particular also to our Innsbruck quantum environment and experiments on trapped ion quantum simulators.

Which results have already been achieved on your end and what will be the next milestones?
We have written a number of publications, which try to look ahead and identify, what is possible with near future atomic quantum simulators, in particular in light of the increasing programmability of these quantum devices. These ideas range from variational quantum simulation, where quantum circuits are programmed on atomic simulators from solving the quantum many-body problem, to applications like optimal quantum sensors, e.g., as better atomic clocks; or novel measurement protocols like our randomized measurement toolbox, which allows us to get much deeper insight into the role of entanglement in quantum many-body physics.

In the early days it often took many years to realise such ideas in the lab. However, the remarkable experimental progress in control of engineered atomic quantum systems has led to a much shorter cycle of theoretical proposal and experimental realisation. This points to the accelerating progress in building atomic quantum simulators in the lab.

For you personally, what has been most fascinating about the project so far and how do you think PASQuanS will impact future research and developments in this field?
There are too many fascinating projects and too many frontiers to elaborate here in detail, but a highlight has been the local and non-local collaborations with the experimental PASQuanS partners, and to see that in trapped ion experiments our new physics idea works in an amazing way. PASQuanS represents a group of international leaders and top researchers working on a plurality of atomic platforms. This has been an extremely stimulating scientific environment, and should be considered a highlight and success story of the EU Quantum Flagship.

Quantum technologies are a field of strong international competition. Where does Europe stand and how can the translation of basic research into applications be successful?
Europe is, and has been extremely strong in quantum science. Many of the fundamental ideas on the theory side, and many of the first and seminal experiments have been done in Europe. Clearly, Europe is at the forefront of quantum science, and atomic quantum simulation in particular. But it is a challenge for Europe to translate this scientific leadership into a technological leadership. While in the US big tech companies get involved with serious financial commitments, it is part of European culture to act much more cautiously.

You have a strong personal research focus on quantum optics and quantum information. If you had to explain both terms to a non-scientific audience in a few sentences – how would you describe them?
The roots of quantum information science reach back to the early 1990's. These were the days when first quantum algorithms and applications were discovered where quantum computers and quantum simulators would provide a "quantum advantage" in solving problems not only of interest in physics, but in a much broader context with impact on society. In the 1990's the central question was: "How to build a quantum computer or simulator?" And atomic physics provided an excellent starting point to answer these questions. Atomic physics had learned how to prepare, trap and laser cool single atoms, and arrays of atoms, and the tools like manipulation with laser light were developed.

Historically, many of these tools in atomic physics were driven by the field of high-precision measurement, one prominent example given by the (optical) atomic clock. Thus, for us theoretical physicists working in atomic physics and quantum optics it soon became obvious that we could develop the tools and concepts to quantum computers and simulators with atomic platforms. Based on the amazing experimental progress, today these ideas are reality in the lab, and PASQuanS is a prime example for this atomic physics and quantum optics success story.

Together with Ignacio Cirac, you have developed a model of a quantum computer as early as in 1995. If you had been asked about your expectations for the year 2020 back then, what would you have said? Have your expectations come true and, if not, what do you think has hampered the expected achievements in the meantime?
Let me first say, it is amazing for me to see that the original idea from 1995 has resulted in small-scale functioning quantum computers existing in our laboratories today, successfully competing with other platforms. And even companies have been built around these ideas. Maybe it was obvious to us as theorists that this should work, but in reality, this turned out to be a long road of experimental ingenuity, hard work and engineering, and credit should go to my experimental friends for actually achieving this goal. While small-scale quantum computers are today a reality, the scalable, fault tolerant quantum computer we are dreaming of is still far in the future.

But there is significant new physics and relevant applications which we can actually “do” in the coming years with intermediate-scale quantum devices already existing in our labs today. I want to add here that Ignacio Cirac and I have been very lucky that many of these early day ideas and concepts actually made it into the lab: this includes quantum simulators for Hubbard models with optical lattices, or the dipole blockade behind the Rydberg quantum simulators, as we see today in PASQuanS.

Everyone is talking about the “Second Quantum Revolution” – with research results of the last centuries now turning into a new generation of quantum technologies and, ultimately, products on the market. In your opinion, which fields of application have been the most promising so far and what can be achieved in the next decade?
The next decade will still see analogue quantum machines, as we have in PASQuanS. But the cross-over from analogue to digital – the latter meaning “universally programmable and fault tolerant” – will be a continuous transition. Analogue quantum simulators of today have the unique feature of being scalable to large atom numbers, i.e. to a regime beyond the capabilities of classical computations. In the next decade we will progress to more and more

digital versions, where we programme increasingly complex quantum circuits from the basic building blocks provided by analogue quantum simulators. While all of us can list a number of applications for these “noisy intermediate scale quantum devices” addressing interesting and fundamental questions in many-body physics, real-world applications like quantum chemistry or the quantum computer are probably still far in the future.

Our goal must also be to find applications with impact beyond those quantum physicists are interested in. One example, which we have been working on, partly also with experimentalists, is to have quantum computers or simulators generate large-scale optimal quantum states to be used in quantum sensing. Here the programmability of simulators, for example as low-depth variational quantum circuits, and their scalability to generate highly entangled states of many atoms, finds application in building optimal quantum sensors, beyond what can be achieved with uncorrelated atoms.