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RÉPUBLIQUE FRANÇAISE

MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR, DE LA RECHERCHE ET DE L'INNOVATION

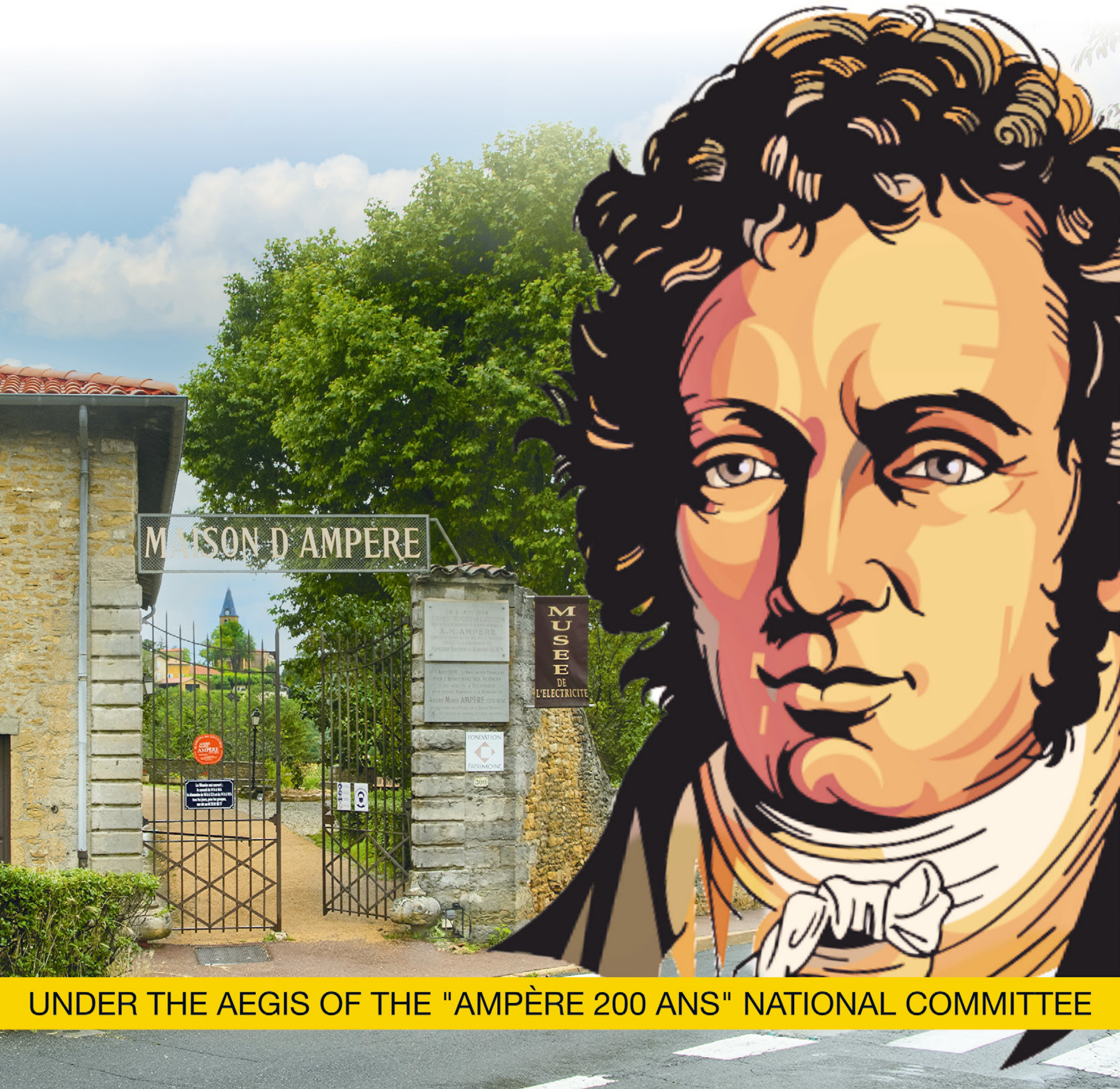
Ampère 200 ans

see

Ampère Maison Musée

Under the patronage of Madame Frédérique Vidal, Minister of Higher Education, Research and Innovation

With the sponsorship of Monsieur Gérard Mourou, Nobel Prize in Physics 2018



UNDER THE AEGIS OF THE "AMPÈRE 200 ANS" NATIONAL COMMITTEE

Why « Ampère 200 ans » ?

"The experimental investigation by which Ampere established the law of the mechanical action between electric currents is one of the most brilliant achievements in science. The whole theory and experiment, seems as if it had leaped, full grown and full armed, from the brain of the "Newton of Electricity". It is perfect in form, and unassailable in accuracy, and it is summed up in a formula from which all the phenomena may be deduced, and which must always remain the cardinal formula of electro-dynamics ».

James Clerck Maxwell, «Treatise on Electricity and Magnetism » (1873)

The name «Ampere» exists and lives on in the world today. The ampere (A) was confirmed by the 26th General Conference on Weights and Measures held in Versailles in November 2018 as one of the seven base units of the international system of units.

But who today knows André-Marie Ampère, the scientist behind the discoveries that have marked the history of science and electricity and whose scientific work cannot be dissociated from the progress we enjoy in the daily life of every household?

The Société de l'électricité, de l'électronique et des technologies de l'information et de la communication (SEE, Society for Electricity, Electronics and Information and Communication Technologies) and the Société des Amis d'André-Marie Ampère (SAAMA, Society of Friends of André-Marie Ampère) are the guardians of an exceptional cultural and scientific heritage, the former being the owner of Ampère's family home in Poleymieux-au-Mont-d'Or and the latter being in charge of the upkeep of the house and the operation of the Ampère Museum within it. They have been guarantors of the memory of the scientist for over 90 years.

It thus seemed legitimate to honor Ampère for the 200th anniversary of the discovery of the laws of electrodynamics. Through the Ampère 200 ans initiative, the SEE and SAAMA aim to make Ampère's work known, to recall his merits, his influence and the influence of his work, and to promote the field of electrical sciences by paying a national and international tribute to the scientist.

The commemorations, which take place in Paris and in major provincial cities and abroad (Geneva, Montreal, etc.), are an opportunity for many scientists, industrialists, researchers, professors, students and pupils to meet and communicate in order to share with the public their thoughts on the importance of electricity in the modern world, on the advances it has made in industrial and everyday life, and finally, to present the challenges for the future and the implications for our society in terms of sustainable development and the training of young people.

Through this initiative we aim:

to contribute to Ampère's notoriety and to give this scientist as an example to our youth so that he is recognized and honored for his talents, as a discoverer and inventor and for the eminent place he occupied in the formidable evolution of the physical sciences in the 19th century;

to contribute to giving electricity a positive image among the younger generations in a context of sustainable development and energy transition towards carbon neutrality, a matter of increasing importance in a large number of sectors (buildings, transport, industry, medicine, etc.). ■

Ampère 200 ans

The aim of the «Ampère 200 ans» commemorations is to make the general public aware of the importance of Ampère's discoveries and their applications. The «Ampère 200 ans» events include exhibitions in museums, conferences, activities in schools and universities, and other events that allow the general public to learn more about electricity and the illustrious man André-Marie Ampère. A website «ampere200ans.fr» has been created for this occasion.

Numerous events were held, some of them remotely in the health context imposed by the Coronavirus pandemic: a national competition aimed at schools and colleges as well as higher education, temporary or travelling exhibitions in campuses, libraries and museums, installations or workshops such as during the Science Festival, the production of booklets, videos and a play, etc., We may mention in particular:

- A general public session of the French Academy of Sciences, relocated to Lyon at the Academy of Sciences and Belles Lettres and the Ecole Normale Supérieure, in February 2020

- A national Ampère 2020 day on November 23, 2020 with a detailed presentation published in the REE magazine below.

- Conferences and exhibitions in schools or universities (CentraleSupélec, Polytechnique, INSA and Ampère Laboratory in Lyon, ESME Sudria-Lyon)

- Presentations at international conferences: SEE MATPOST in Lyon, CIGRE, CIRED and EPE.... Afcas and CONFREGE in Canada,

- Days on the «electricity professions» during the industry week in November 2021 in various cities.

- The commemorative exposure of a «Historic Site» plate of the European Physical Society with the SFP at the Museum Ampere and a «Milestone ampere» plate of the IEEE at the College of France with the valorization of the table of experience of Ampère..

Various events

On electric/sustainable mobility with conferences and:

- A SEE day on electric mobility

- Support for the Watt'Elles rally and presentations at the «Eco Race» in Albi in October 2021

- Inauguration of the new electric vehicle charging point installed at the Maison d'Ampère

Exhibitions, inaugurations or open houses with the electrical industry and, with the City of Lyon, a conference on the occasion of the renovation of the Place Ampère in January 2020. ■

One of André-Marie Ampère's animated experiments that can be discovered at the Maison d'Ampère - Musée de l'Électricité in Poleymieux au Mont-d'or.

The « Maison d'Ampère – Musée de l'Électricité » at Poleymieux au Mont-d'Or.

« Maison d'Ampère
Musée de l'électricité »

The Ampère family home, where André-Marie spent his childhood and studied brilliantly with his father, without attending school, had an exceptional destiny. The property in Poleymieux-au-Mont-d'Or (Rhône) where it is located, about twenty kilometers from Lyon, was sequestered for the benefit of the Nation in 1793, when the Revolution condemned the father of the future scientist to death. Restored to the family two years later, it fell to Ampère in 1812, after the death of his mother. He sold it ten years later when he settled in Paris.

It took a century for the Poleymieux property to regain the memory of its prestigious former owner; it was on the advice of Paul Janet, a member of the French Academy of Sciences and then director of Sup'élec, that two wealthy American businessmen, Hernand and Sosthène Behn, bought the property in 1928 and donated it to the French Electricians' Society, which then entrusted it to the Society of Friends of André-Marie Ampère, created to perpetuate the memory of the illustrious Lyonnais. The Museum of Electricity was inaugurated on 1st July 1931.

The Maison d'Ampère, labelled «Maison des illustres» (Illustrious House) by the French Ministry of Culture, plays a leading role in the communication process on André-Marie Ampère and his work. Composed of 14 rooms, a projection room and an activity area, it devotes several rooms to the life of the scientist and his discoveries in the field of electrodynamics, but also in chemistry and mathematics. The «Maison d'Ampère - Musée de l'Electricité» traces the history of electricity and its applications from the discoveries

Study of photovoltaic energy during the discovery workshops.

Rooms of La Maison d'Ampère - Musée de l'Électricité, in particular during the activities of the Discovery Workshops.

in antiquity to the most modern applications, including the production and distribution of electricity.

In addition to free or guided tours, the Museum offers a programme for school groups of all levels, «Discovery Workshops», which welcome classes accompanied by their teachers, with whom a half-day or full-day programme of activities is organized. The «Discovery Workshops» are mainly open to secondary school students, but also to primary school, vocational training and engineering school classes, i.e. more than a thousand «discoverers» per year; they are also open to families during the holidays. Their content evolves with new installations (photovoltaic panels, wind turbine, mini-hydro power station, «electrically assisted bicycle» station) and technical innovations by offering the first computer workshops for learning coding and robotics. The museum also presents advances in sustainable energy (wind, solar, hydroelectric, hydrogen fuel cells). The museum also participates in European Heritage Days and at the Science Festival.

Finally, the Museum is also a venue for companies, academic groups or researchers wishing to combine a meeting with a visit to the Museum or to organize a day of exchanges with a cultural programme and/or leisure activities (walks, visits to the village of Poleymieux, etc.). The Ampère room, with a capacity of 50 people, offers all the necessary facilities for this type of event. ■

Views of the "Salle Ampère" used for seminars, meetings and other activities.

The « Ampère 200 ans » Commemoration

François Gerin
President of the «Ampère 200 ans» National Committee
President of the SEE

Ampère Day 2020, Monday, the 23rd November 2020, celebrated the bicentenary of André-Marie Ampère's discovery of the first laws of electrodynamics in 1820 (following the experiments of Hans Christian Œrsted, in early 1820).

It seemed important to us to bring together in this document of the REE the speeches, lectures and round tables that marked this historic day, and that more than 450 people followed assiduously at a distance. Their authors and the participants in the round tables were glad to prepare their summaries with the help of Alain Brenac, Editor-in-Chief of the REE, and Bernard Ayrault, member of the editorial board. Thank you all very much. This document summarises all the presentations and the recordings of the day which are also available on the website www.ampere200ans.fr

In addition, the 3EI journal presents a series of more detailed articles of the presentations.

"Ampère 2020", which became "Ampère 200 ans" at the beginning of 2021, is not only the recognition of the talents and work of Ampère, but also a collective action aimed at young people; its objective is in particular to improve the image of jobs in electricity and to promote technical careers, with the help of all the partners of this commemoration.

Together with the SEE and SAAMA, the «Ampère 200 ans» National Committee brings together many active partners, in particular the Associations of Physics and Chemistry Teachers (UdPPC) and Preparatory Classes (UPS) and the General Inspection of Education and Youth. We are planning actions to promote science and technology and restore the image of electricity. These will be organised in the main cities with the participation of associations such as IESF, SFP, UFE, Gimelec and SERCE. ■

Lectures

Round table discussions

Speech by Madame Frédérique Vidal
Minister of Higher Education, Research and Innovation

Mr.President of the SEE, Dear Mr Gerin,

Mr Professor, Dear Gérard Mourou

Ladies and Gentlemen,

While the name of Ampère is highly familiar to us ever since the entry of the electric current into the international system of units, the man and his work remain largely unknown to the general public, even though their heritage is present everywhere in our daily lives.

I am therefore pleased that the Société de l'électricité, de l'électronique et des TIC, and the Société des amis d'André-Marie Ampère, have endeavoured to resolve this paradox by launching the Ampère 2020 Commemoration, this day being one of the highlights. Your commitment to the organisation of this event honours your role as transmitters of scientific knowledge and I would like to thank you for having maintained this event in spite of particularly difficult circumstances.

It is in this very context of the health crisis that we are going through that an initiative like this makes even more sense: at a time when all eyes are on research and when hope is confronting mistrust, I think it is essential to remember everything that we owe to science and to scientists. And there could be no better example than that of André-Marie Ampère to illustrate the beauty and the fertility of the quest for knowledge.

200 years ago, André-Marie Ampère presented to the Académie des Sciences his hypothesis on electric currents and their interactions, thus providing an explanation for the Œrsted experiment. This discovery, which shattered all the existing theories, laid the foundations of electrodynamics.

This plunge into our scientific past reminds us of two essential things: the first is that «there is not basic research on the one hand and applied research on the other. «There is research and its applications, bound to each other just as the fruit of the tree is to the branch that bears it», to quote a great contemporary biologist of Ampère. Not only did Ampère's work revolutionise physics, it paved the way for the electric motor, to the second industrial revolution, and beyond that, to modern comfort and future innovations in energy production, storage and distribution).

Science is a continuous process, to which each researcher brings his or her contribution, in time and space. The works of Ampère are inseparable from those of Hans Christian Œrsted, Faraday, Maxwell...right up to those of today's opening speaker, Gérard Mourou.

Today, it is essential to continue this lineage. To honour Ampère is to give prestige back to electricity, a science which is losing ground among young people, at a time when jobs in energy transition are gaining a new sense and ambition, from the laboratory to the factory. It also means giving a different image of scientists, far from the cold, cloistered, exclusive rationality that is sometimes attributed to them. For Ampère was a free and passionate spirit, who never allowed himself to be confined within the limits of a single discipline, nor even by reason alone. As this Day will show, his scientific legacy goes well beyond electrodynamics. Mathematics, chemistry, philosophy, metaphysics, even language, are indebted to this man who contributed to the discovery of three halogens, who coined neologisms like cinematics and cybernetics and who established a classification of all human studies. An encyclopaedic and romantic man, a man of reason and a believer, he had faith in the unity of science and even more in humanity. «Perfecting myself and men is the idea I always have before my eyes», he wrote.

Recovering attractiveness and trust is at the heart of the research programming law that has just been passed in Parliament after more than a year and a half of work, reflection and debate. Thanks to the unprecedented resources it invests in our research, and to the legitimate recognition it gives to the scientific community, I am convinced that science will regain the place it deserves in our cultural and democratic life, in our economic and industrial strategies, in our responses to the major challenges of our time, in our relationship with the world. With this text, we can, if we all embrace it together, make the next decade the decade of research. Opening the celebration with this tribute to the great universal scholar that was Ampere, whose heart was as open as his mind, I believe it could not begin under better auspices.

Thank you all and congratulations for this beautiful day. ■

Opening Address

The «Journée Ampère» 23rd November 2020

Gérard Mourou

Nobel Prize in Physics 2018
Sponsor of the Ampère 200 ans commemorations

It is a great honour for me to be the sponsor of all the events commemorating the 200 years of the creation of electrodynamics by André-Marie Ampère (1775-1836). Ever since I was a child, with a father who was an engineer and a grand-father a technician who both worked for EDF, I have been aware of and became very interested in everything related to electricity, and therefore to the genius we all admired, André-Marie Ampère.

In July 1820 the physicist and chemist Hans Christian Œrsted (1777-1851) published a memorable experiment showing the effect of an electric flow on the magnetised needle of a compass, which clearly indicated the existence of an interaction between electrical and magnetic phenomena. A week after the presentation of this experiment at the Académie des Sciences, André-Marie Ampère was the first to give a rigorous explanation on 18 September 1820 and to draw up the first laws of electrodynamics and electromagnetism. These seminal findings by Ampère opened up new fields of research into electricity and the applications that followed; their development enabled the expansion of industry and the material comforts that we all enjoy so easily today in our daily lives that most of us have forgotten the foundations and techniques underlying them.

Moreover, the ease with which electricity is used nowadays does not encourage general interest in it: digital techniques and related tools are omnipresent and fascinating. This is no longer the case with electrical phenomena, but these new techniques would not exist without Electricity!

Electricity is also an area that has become unfamiliar to many people, especially young people. It is clear that they are not strongly attracted by it. Engineering schools, in particular, notice a deep disaffection in this branch of physics in favour of other more prominent subjects such as those dealing with the environment or the circular economy in connection with the preservation of our future and the world of nature...

But what kind of world would we live in today if all these advances or inventions had not allowed electricity to preserve these invaluable resources, which would otherwise have disappeared: the fundamental laws of electricity have led among other things to the electric motor which has progressively replaced the steam engine with all the advantages we know, and there is not a company, a home or a vehicle that does not have an appliance or components that operate with electricity or with batteries....

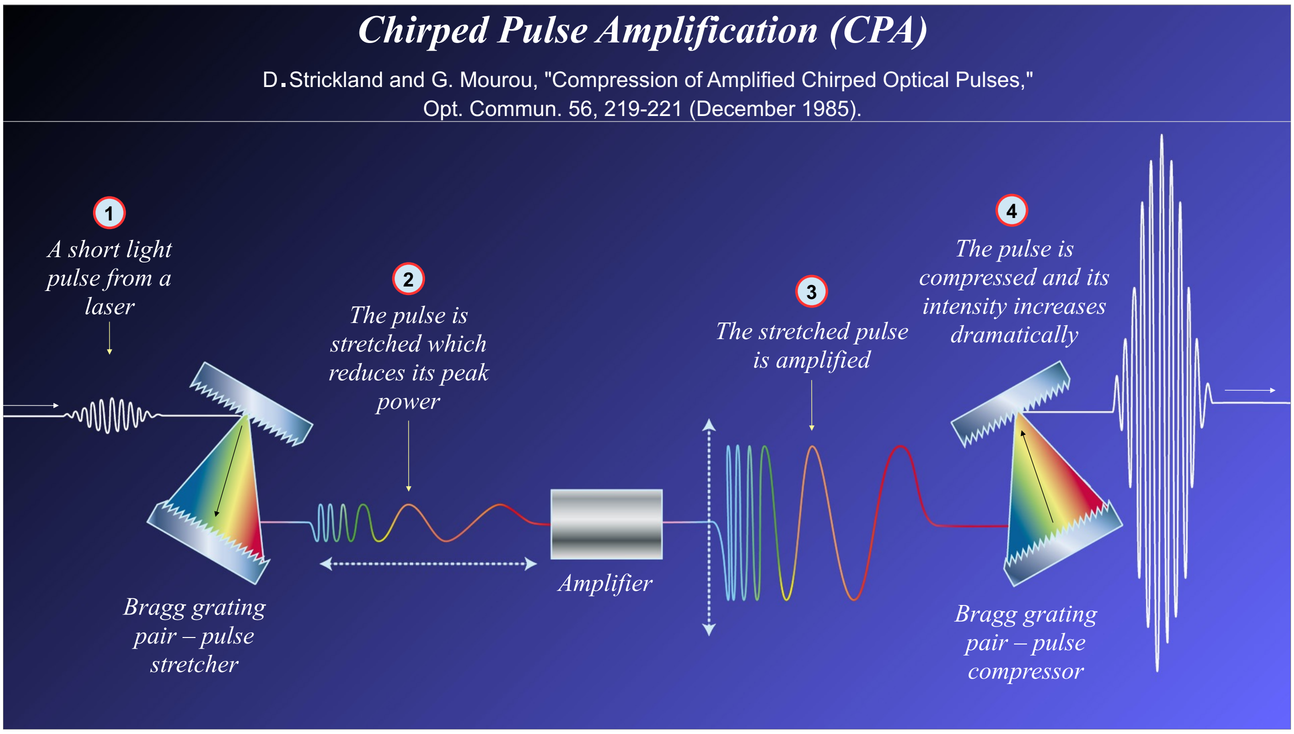
We are, in fact, at the crossroads of two worlds:

• the world of today and tomorrow for which the use of this electricity is vital both to our lives now and also to meet the challenges that lie ahead, giving a perspective for the future. We need to convince young people of this and of course all our fellow citizens must be made more aware; actions of communication and popularisation should lead to a new image of both the techniques and their implication in environmental issues.

• the other world comes to us from History written by remarkable men. They have allowed us to know all these developments and benefit fully from these discoveries.

• Throughout his life Ampère, that genius, embodied scientific curiosity and a taste for innovation so as to make science progress and serve Humanity: multi-skilled, like Leonardo da Vinci, he was a great physicist, mathematician and chemist, but also philosopher, poet, polyglot and a Romanticist.

> **"Throughout his life Ampère, that genius, embodied scientific curiosity and the taste for innovation so as to make science progress and serve Humanity"**



Ampère has always been one of the most fascinating and endearing scientific characters.

Ampère's work paved the way for Maxwell's theory (1831-1879), which unifies electricity, magnetism and light, a brilliant intuition that Ampère had in 1801. Maxwell thereby concludes that light is an electromagnetic wave.

My own work focuses on a special light, the extreme light that won me the 2018 Nobel Prize in physics, shared with my former student Donna Strickland.

I have conducted my research mainly in the field of ultra-short optical pulsed lasers, in the order of a femtosecond, that is one millionth of a billionth of a second, and we have invented a technique of Chirped Pulse Amplification (CPA) generating ultra-short pulses, even shorter than the femtosecond, and of very high intensity (see figure above). We can thus obtain considerable power (measured in petawatts, i.e. 1 joule during a femtosecond), allowing us to explore previously unattainable fields of physics. A first application of our CPA technique with femtosecond lasers is to remove matter without peripheral damage; the best-known example is in ophthalmological surgery, to correct the sight of millions of people every year.

I am also considering the possibility of using fission to produce clean and abundant energy, using thorium, or the transmutation of waste to reduce their radioactive life to just a few months.

I also propose the clearing of near-earth space of its debris, by deorbiting them with ultra-intense laser pulses focused on them.

What continues to make me dream is really all the future applications of our invention. What drives us is not the hope for a Nobel prize but our passion for research and our curiosity that we need to satisfy.

So, on this very rich Day of Commemoration, I learned a great deal about Ampère, and also about all the applications presented in this document which resulted from his discoveries.

Ampère created and launched electrodynamics, direct current, and I think permitted advances towards electromagnetism, where by increasing the frequencies the performance is greatly improved; this leads to much smaller systems, as shown by the presentations on the progress of the international ITER project and the work on the SOLEIL synchrotron.

I like to draw parallels between on the one hand electromagnetism, with its heroes Ampère, Fresnel, Œrsted, Maxwell, and on the other hand light, the advent of coherent light and the laser with Einstein, Townes, Maiman, two phenomena which, like electricity, have brought about a profound transformation in our society.

Naturally, I have been enthusiastic about this commemorative event to present or rediscover the work of Ampère and to promote Science among the young and the general public, in particular Electricity, and also to let us dream of the prospect that this work offers us for the future. ■

André-Marie AMPERE
(1775-1836), the genius and the tears

Xavier Dufour
Professor of mathematics and philosophy

The celebration of André-Marie Ampère's stunning discoveries in the field of electromagnetism, made in September 1820, must not leave aside the many facets of a brilliant autodidact, at the junction of Encyclopaedia and Romanticism. Officially a mathematician, willingly a chemist, occasionally a naturalist but always a philosopher, Ampère was also a man of heart, sensitive and mystic, whose life was marked by cruel ordeals.

A romantic youth

Born into a Lyon family in the Saint-Nizier neighbourhood, Ampère grows up in the rural setting of the Monts d'Or near Lyon and teaches himself the most diverse disciplines: an insatiable reader of the Encyclopaedia, he devours classical authors and books on botany, mathematics, composes poems and writes a treatise on squaring the circle at the age of thirteen. At 18, he masters the Lagrangian Mechanics perfectly. In 1793, his father, who was a Justice of the Peace, is guillotined at the end of the siege of Lyon. The young man falls into depression for a year before returning to his frantic activity, which even leads him to invent a universal language. At the age of 21, he meets Julie Carron who he marries in 1799 and who later gives him a son, Jean-Jacques, future writer and academician.

Appointed professor of physics at Bourg-en-Bresse, Ampère gets himself noticed by the scientific community after his two treatises in mathematics. Very soon after his transfer to Lyon high school, he witnesses the death of his wife who leaves him widowed at 28. Distraught, he mixes with young intellectuals marked by the trauma of the Revolutionary period, in particular the thinker Pierre-Simon Ballanche and Claude-Julien Bredin. In 1804, the three friends founded a circle of reflection, the «Christian Society», where philosophy and religion are discussed. A short-lived circle, from which some friends Ampère made there will support him all his life and a circle which historians will later recognise as one of the «hidden sources of Romanticism» (A. Vialatte).

Paris, between science and philosophy

Appointed assistant teacher in mathematics at the Ecole Polytechnique in 1804, Ampère often meets with the Paris scientific elite, led by Laplace, while also being deeply interested in the philosophy of Maine de Biran. The latter lays the foundations of a spiritualism based on the primacy of the will, in opposition to the prevailing materialism which reduced human faculties to a combination of passive sensations. Sharing the spiritual orientation of this doctrine, Ampère tries to complete it with a realistic doctrine of knowledge. With his theory of the abstraction of 'noumenal relations', he tries to show that science does indeed reach the structure of physical reality.

At the same time, he becomes enthusiastic about chemistry, discovers chlorine and fluorine, establishes the «Avogadro-Ampère» law of gases and founds a theory of chemical reaction on the need to distinguish between atoms and molecules (1814). In 1820, he revolutionises the world of physics in just a few days and founds a new science, electrodynamics. The famous *Mathematical Theory of Electrodynamic Phenomena,* (1826) a synthesis of his works and deduced only from experience, makes allegiance in its title

> **"With his theory of the abstraction of 'noumenal relations', he tries to show that science does indeed reach the structure of physical reality"**

to the Newtonian conception of science then in force. But in fact, differing from the main theories it paves the way to new physics, which are also embodied by Fresnel and Arago.

In the meantime, the scholar attains the highest academic positions: professor at the Ecole Polytechnique in 1807, a professor legendary for his wandering thoughts and digressions, and Inspector General in 1808, which obliges him to take long trips around the country, member of the Académie des Sciences in the geometry section in 1814 and professor and chair of physics at the Collège de France in 1824. In the same year he publishes a long article on comparative anatomy to defend Geoffroy Saint-Hilaire's thesis on the "unity of plan" of animal species, bringing a host of arguments against Cuvier's opinion. The debate between Ampère and Cuvier will continue six years later on at the Collège de France.

Emotional and spiritual tribulations

However this genius of abstraction is a passionate man, of an unstable temperament, and lacking emotional insight. His second marriage in 1806 with a calculating woman ends in their separation just after the birth of his daughter Albine. In this context, he who was an apostle for sciences while in Lyon will go through a religious and moral crisis for 12 years, exacerbated by his emotional torments. We can follow the meanders of this crisis in the abundant correspondence between Ampère and Bredin, who remained in Lyon. In March 1814, obliged to break-off an affair, Ampère is even on the verge of suicide. It is not until 1817 that he finds his way back to a calmer faith. In October, a spiritual awakening inspires him to write a meditation with Pascalian overtones: «*Dear God, what are all these sciences, all these reasonings, all these discoveries of genius* [...] *that the world admires and whose curiosity so avidly feeds upon? In truth nothing but pure vanity.*"

Of course, Ampère does not abandon scientific activity, far from it. But the search for partial truths of the positive sciences cannot be enough to satisfy his intelligence: «philosophy», he says «the only really important science», allows a broader view of intellectual activity and the evaluation of each piece of knowledge. Finally, it is up to faith to shed light on ultimate questions. The mysticism of knowledge that makes Ampère one of the last universal scholars reflects the intensity of his spiritual life. «I see only truths, teach me the Truth!" he wrote to Bredin.

"In 1820, he revolutionises the world of physics in a very short time and founds a new science, electrodynamics"

The final years

From 1829, Ampère returns to an old project: convinced of the profound analogy between the laws of the universe and the organisation of intelligence, he embarks on a classification of all human knowledge, the ultimate work of an encyclopaedic mind capable of embracing the most diverse domains in search of a unity that transcends them. Published in 1834 for its first volume devoted to the «cosmological sciences» and in 1836 for the second volume, posthumous, devoted to the «noological sciences» (today called human sciences), this classification is astonishing for its rigorously dichotomous architecture. This is justified by considerations of the psychology of knowledge, another subject which Ampère had developed at length in his philosophical works.

In 1831, the scholar lodges a law student, Frédéric Ozanam, his guest for more than a year. The future professor, a specialist of Dante and famous polemicist of social Catholicism, recounts in his correspondence the domestic conversations, the temperament and wanderings of his host as well as his simple and abandoned piety. Highlighting the scientist's intuitive intelligence, he notes: «The discoveries that have brought him to the position he has today came to him suddenly, said Ampère, without knowing how...»

On June 10, 1836, on an inspection tour in Marseille, Ampère died that very same day. To someone who proposed to him to hear the *Imitation of Jesus Christ*, he is said to have replied: «It's useless, I know it all by heart». A passionate, sensitive and generous scholar died, and it is up to his friend of heart Bredin to draw a final portrait: "Never did a man love the way he loved. I don't know what to admire the most, this heart or this brain...". ■

The author

Xavier DUFOUR, born in 1963, is a physicist engineer (1988), an associate professor of mathematics (1991), a doctor of philosophy (2003). He defended a thesis on «André-Marie Ampère, une philosophie de la connaissance».
Professor of mathematics and philosophy at the Lycée Sainte-Marie in Lyon, he also taught the philosophy of knowledge at the Faculty of Philosophy of the Catholic University of Lyon. He has published articles on the philosophy of Ampère (Sabix), his spirituality, as well as books on the religious fact at school.

Light

A story of friendship between Fresnel and Ampère

Edmond Amouyal

Emeritus Director of Research at the CNRS Laboratoire des Solides Irradiés, Ecole Polytechnique

Augustin Fresnel's wave theory of light and André-Marie Ampère's electrodynamic theory are the fruit of a real collaboration - little known - between two scientists faithful in friendship, generous and brilliant. Those discoveries were two of the greatest of the nineteenth century, and led to the tremendous growth of research and industrial innovation.

Introduction

Ever since the sixth century BC, Greek philosophers have wondered about the origin and the nature of light. But it is only in the XVIth century that significant scientific works will be known, in particular those of Kepler, Galileo, Snell, and Descartes who in 1637 publishes the laws of geometric optics and who considers, just as the Greek atomists did, that light is of a corpuscular nature. Soon after, Grimaldi discovers the diffraction of light. His works and those of Huygens (1629-1695) argue in favour of the wave form of light. At the same time, Newton (1642-1727) challenges the wave concept and his aura was such that for more than a century he imposes his mechanistic approach of the corpuscular theory of light. But in 1801, the wave hypothesis of light is revived with the experiments of Thomas Young (1723-1829) who observes his famous fringes of interference by diffraction through two cracks. He concludes that light is of a wave nature, without demonstrating it, which Augustin Fresnel will do brilliantly in 1815.

Augustin Fresnel (1788–1827)

Augustin Fresnel was born on May 10, 1788 in Broglie (Eure) in the chateau of the Dukes de Broglie. At the age of 16, he joins the Ecole Polytechnique. In 1809, he is a civil engineer for the Eure department. In 1814 he sends his first scientific work entitled «Rêveries» to his professor André-Marie Ampère (1775-1836), to which Ampère pays no attention. Fresnel then turns to François Arago (1786-1853), who encourages him to specialise in optics alone. Fresnel will confirm Young's findings and on 15 Oct.1815 he sends his first thesis on the diffraction of light to the Académie des Sciences.

His hypotheses is that light is of a wave nature, thus attacking Newton's corpuscular theory from the outset. Ampère, a Newtonian like all the scholars of the time, is convinced and seduced by the mathematical rigour of the young Fresnel's demonstration. It was from then on that their friendship and scientific collaboration began, friendship and complicity that they shared with Arago.

Ampère's contribution to Fresnel's wave theory of light

Ampère finds appealing Fresnel's wave theory of light, which explains not only the diffraction and the interferences that Newton does not explain, but also the reflection and refraction of light. Fresnel's theory is strongly contested by Newtonians, first of all by Siméon-Denis Poisson (1781-1840). In 1817, the Académie des Sciences launches a confrontation to compare the two theories on the diffraction of light. Ampère encourages Fresnel to compete, and it is Arago who does the experiment in 1819: the bright spot predicted by Poisson appears, Fresnel and his theory triumph. His thesis submitted on July 29, 1818, is acclaimed by the Académie des Sciences.

> **"He shows, among other things, that the phenomenon is a continuous and not a discontinuous electrical flow, and he is the first to name this flux "electric current"**

The friendship and exchange of ideas between Fresnel and Ampère intensify when Fresnel tackles the problem of the polarisation of light by reflection discovered in 1808 by Malus. Natural light is not polarised: it vibrates in all directions along its path of propagation. It is polarised when it vibrates in a fixed direction. The explanation of Malus and other Newtonians is unconvincing. Fresnel applies his theory by hypothesising a longitudinal luminous wave, vibrating in the plane of propagation of light. But this does not explain the results of his experiments. Ampère then suggests to Fresnel that he should consider a revolutionary hypothesis, that of a *purely transverse luminous vibration*, that is, perpendicular to the plane of propagation. No scientist of the time, including Arago, will endorse this ground-breaking hypothesis. In 1820 Fresnel publishes a complete review of his wave theory of light. He will call this phenomenon *straight polarisation* to distinguish it from the circular and elliptical polarisation phenomena he is the first to explain.

Ampère and electrodynamics, Fresnel's contribution

The year 1820 is also a great year for Ampère and physics. On September 11, 1820, Arago reproduced the experiment of Hans Christian Œrsted (1777-1851) at the Académie des Sciences. In 1819, Œrsted observed that the magnetised needle of a compass placed in the vicinity of a conductive wire connected to a Volta battery was deflected when the wire communicated with the battery. This experiment clearly shows that there is an interaction between electrical and magnetic phenomena. Neither Œrsted, nor Arago, nor the other scholars really have an explanation. On September 18, 1820, in a flash of genius, Ampère would give one in seven days! It starts from the simple idea that electricity and magnetism are the manifestation of the same phenomenon, and that magnetism is due to the electrical phenomenon. Ampère discovers dynamic electricity, or «*electrodynamics*». He shows, among other things, that the phenomenon is a continuous and not a discontinuous electrical flow, and he is the first to name this flux «*electric current*». He will also introduce the concepts of electrical voltage and current intensity.

The scientific collaboration between Ampère and Fresnel was not one-way. Fresnel will make suggestions to him. The most important one is about the nature of electric current. Ampère thinks that electric currents are macroscopic and that they circulate on the surface of the magnet around its axis. Fresnel will submit to him the idea of microscopic currents that manifest themselves inside the magnet around the metal particles of this magnet. At the end of 1823 Ampère will eventually adopt this brilliant and visionary hypothesis of Fresnel's. Two notes by Fresnel from 1821 will be found in Ampère's papers after his death, one of which deals with the «*particle currents hypothesis*», that is, currents linked to the molecules of the magnet and which manifest themselves in the core of the molecule. We know today that these are the electrons of atoms..

Conclusion

Fresnel and Ampère paved the way for the theory of James Clerk Maxwell (1831-1879), which unifies electricity, magnetism and light, and which concludes in 1864 that light is an electromagnetic wave. But, in 1900, Max Planck reintroduces the corpuscular aspect in theoretical physics, considering that at the scale of atoms, energy takes multiple amounts of a minimal quantity which he calls *quantum of energy*. In 1905, Albert Einstein (1879-1955) will advance the concept of energy quantum associated with the electromagnetic waves of light, the light quantum which will be named *photon* in 1926, and he applies it to interpret the photoelectric effect, unexplained by the wave theory of light. For Einstein, light is dual, being both a wave and a particle. In 1924, Louis de Broglie takes on Einstein's idea of duality and formulates the brilliant hypothesis of the wave nature of the electron, and he will extend this idea to all matter.

With their discoveries on waves leading to modern electricity, the works of Fresnel and Ampère have passed through the ages. It was their friendship and genuine scientific collaboration that helped them to face the scepticism of their contemporaries. Their discoveries have opened up new fields of research and innovation. They are at the origin of the tremendous growth of industry and still contribute to our daily well-being. ■

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Ampère,
The « Newton of electrodynamics»

Hélène Fischer
Senior lecturer in physics at Université de Lorraine

As early as 1802, Ampère has the dazzling intuition that magnetism and electric current are two different facets of the same phenomenon. In 1820, his life was shaken by the results of Œrsted. Ampère was then subject to a real creative frenzy, endlessly trying to explain those results and prove that his childhood dream of reforming physics was true.

At the end of the eighteenth century, the concept of electricity was subject to debate. There are several theories on the existence of one or two electric flows, and several opposing opinions to explain whether electrical phenomena are achieved with or without contact. The Newtonian theory, with its strong formal analogies between the laws governing gravitation, electricity and magnetism, is appealing and gives the impression of an unshakeable edifice. This conception of physics also leads to consider any phenomenon as an entity completely independent of others, which rules out any reciprocal action between «electric fluids» and «magnetic fluids» in particular. Thus, the magnetic effects of lightning intrigue but remain unexplained.

During that time, at the beginning of the nineteenth century, a movement of thought emerges in the Germanic countries, *Naturphilosophie*, which offers a Romantic vision of nature. Scientists there oppose the Newtonian philosophy and affirm the profound unity of nature and the phenomena observed, despite their diversity: they assume the existence of two fundamental forces which are at the origin of all the properties of matter, manifesting themselves in different forms, and which can be converted into each other. It is therefore no surprise that the possibility of a unity between electric and magnetic phenomena becomes conceivable! Naturally, Newtonians regard the supporters of this conception of the world with superiority and contempt: the Dane Œrsted (1777-1851), greatly influenced by Naturphilosophie, is mocked in Paris in 1803 when he presents the work of Ritter (1776-1810) demonstrating the identity of behaviour of a battery and of a magnet. From this misadventure he sees the need for more scientific rigour based on experiments.

Following Volta's invention of the battery (1745-1827), Œrsted proposes a hierarchy between the various forms of electricity: ordinary electricity, galvanic electricity and finally magnetism. He is convinced that only the neighbouring forms of electricity could interact, and in April 1820 he has the idea of bringing a magnetised needle close to a wire in which flows a galvanic current. The observation of the deflection of the needle does not surprise Œrsted, as he is profoundly convinced of the unity between physical phenomena. In July 1820, he publishes his discovery in a thesis that becomes rapidly famous around Europe.

In September 1820, the account of Œrsted's work presented by François Arago (1786-1853) at the Académie des Sciences is received very coldly for two reasons: on the one hand, in the absence of the notion of current, it is impossible to understand that the battery without the wire has no effect on the compass. On the other hand, it is possible to accept conceptually that the needle can orient itself perpendicularly to the wire, and not longitudinally as Newtonian physics predicted! Arago is then forced to reproduce Œrsted's experiment at the Académie.

Numerous experiments are then carried out throughout Europe aimed at researching further into «electromagnetic» effects, but only Jean-Baptiste Biot (1774-1862) and André-Marie Ampère (1775-1836) attempt to account for them by mathematical laws. They then produce two competing theories: Biot, joined by many physicists, hypothesises a temporary magnetisation of the electric wire, which links the unknown, the galvanic currents, to the known, the magnetic flows.

> **"In order to convince the community, Arago is forced to reproduce Œrsted's experiment at the Académie"**

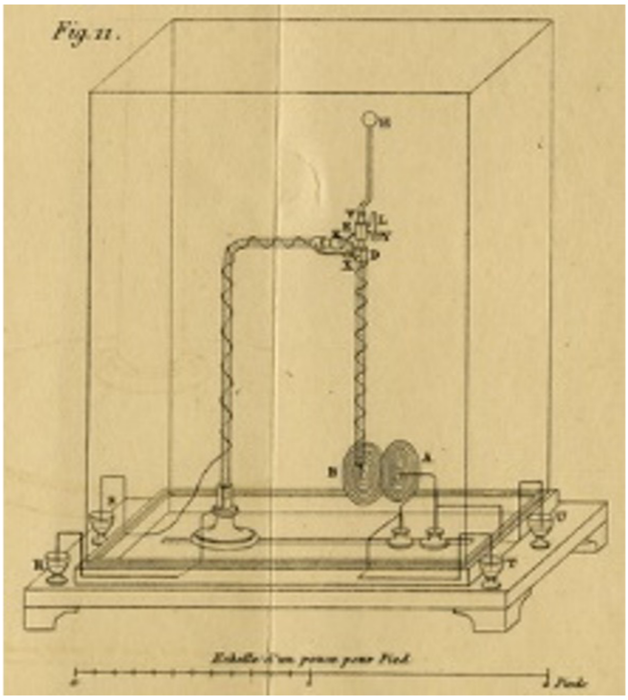
Œrsted's discovery is then reduced to a purely magnetic interaction explained within the framework of the Newtonian theory.

On the contrary, Ampère has the impression that the Earth's magnetism is due to internal electric currents responsible for the orientation of the compass. He presumes the existence of currents in magnets and supposes interconnections between electric currents. But how can such a dazzling intuition be explained?

Since his youth, Ampère, a passionate self-taught man, has been influenced by the Romantic philosophy of Germany. As early as 1801, he publishes a significant thesis aimed at unifying electricity and magnetism: he wants to reform physics by imagining a fluid filling all space, and also a unique and universal attraction to explain the various physical phenomena. In September 1820, Ampère saw Œrsted's experiment as a demonstration of his own strong conviction and the opportunity to write the corresponding mathematical laws, with the idea that posterity will remember him as a great man.

For 5 months, he then enters a period of frantic creativity to justify his intuition by experimenting, and to write a new theory of magnetism based on interactions between currents. With incredible fervour, he designs many ingenious experimental devices, which allow him to show that a spiral of current behaves like the electrical image of a magnetic pole, and that two spirals with current passing through them behave like two magnets that attract or repel each other depending on the direction of the currents that cross them. He imagines a magnet as if crossed by loops of macroscopic electric currents in planes perpendicular to its axis. Then, from 1821, he rather believes in particle currents, circulating around each particle of the magnet, always parallel to that of the magnet. Finally, he defines the notion of electric current as the circulation of an «electric fluid» through the entire circuit. The famous little man called after him points in the direction of the induced magnetic effect.

At the same time, Ampère starts looking for a universal mathematical law defining the action between 2 infinitesimal elements of current, neither one oriented in relation to the other. On the basis of certain hypotheses which he will later justify, and of observations established thanks to his ingenious experimental devices, and after abandoning any project of absolute measurement in favour of the development of the «zero method», he formulates a mathematical law unifying electricity and magnetism, and in 1826 publishes his



The decisive experiment: the study of interaction between two spirals.

Théorie mathematique des phénomènes électrodynamiques, deduced only from experimentation and which will later give birth to Laplace's law.

By the conceptual upheaval it creates, Ampère's approach was a real bombshell for the scientific community: at first rejected entirely, it will later gain consensus thanks to Ampère's determination. The devices he designed will not all come into being, but he will keep them in mind allowing him to combine his qualitative experiments with his theoretical formulations, always in search of a logical consistency between the «universal judgment» of theory, and the «particular judgment» of experience, in the words of G.Canguilhem. It is this exemplary scientific approach which will enable Ampère to establish a universal law unifying electricity and magnetism, and which will turn Œrsted's discovery into a scientific revolution leading to electromagnetism. ■

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The ampere unit: from electrodynamics to quantum mechanics

Wilfrid Poirier

Researcher at National Laboratory of Metrology and Testing

The author recalls the complex and eventful history of electric units from the adoption of the metric system to the historical revision of the International System of Units (SI) adopted in 2018.

Modern metrology was born during the French Revolution in response to the citizens' demand for uniform units to improve scientific, industrial and commercial exchanges. The response to this call was the adoption of the metric system in 1793 under the impetus of the Académie des Sciences. This marks a shift towards more universal definitions of units. In 1875, the signature of the metre convention and the creation of the International Bureau of Weights and Measures to maintain the mass and length standards, marked the beginning of the internationalisation of the units. But at that time electric units are not included.

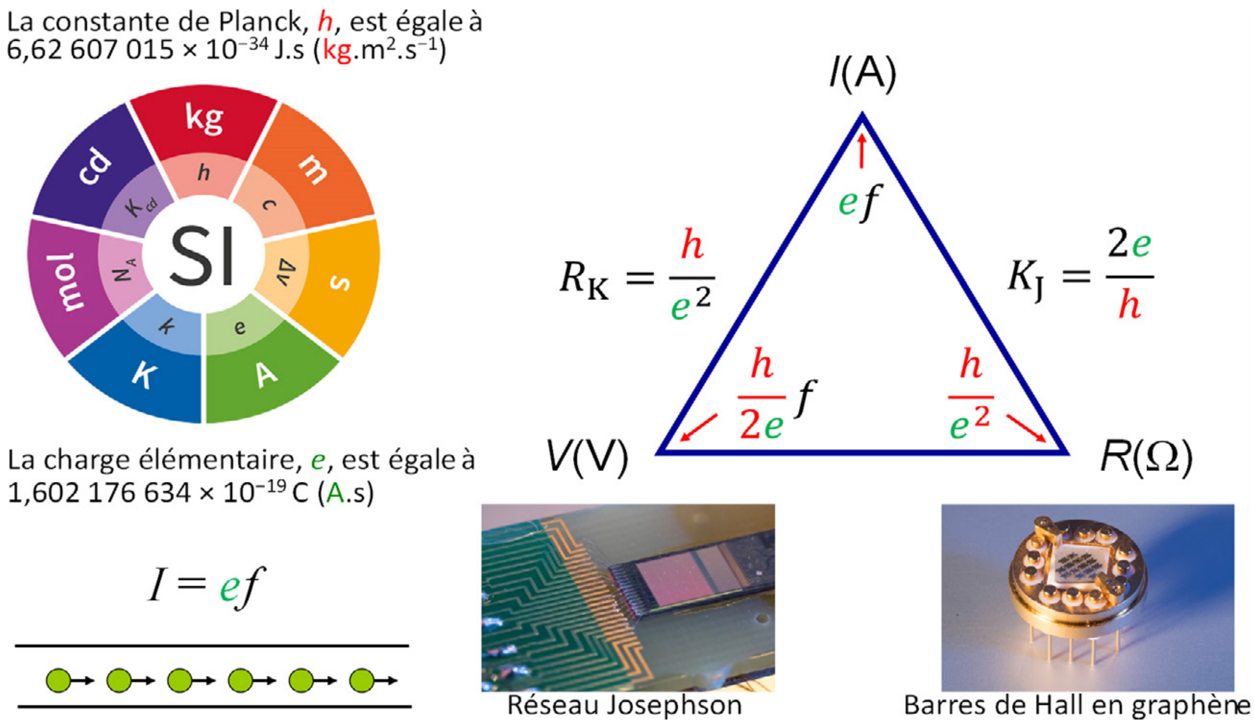
Electricity will not be defined by measured quantities until the end of the 18th century. The strength of the electric current and the electrodynamic properties are discovered in 1820 by Andre-Marie Ampère following the key experiment of Œrsted demonstrating the deflection of the needle from a compass orthogonally to the passage of «electricity» in a wire. It is the starting point for innovations related to electricity, produced by engineers and inventors, which will stimulate a second industrial revolution at the end of the 19th century. Driven by this scientific and technical effervescence, the first international congress of electricians is held in Paris in 1881 during which the first electrical units are defined. André-Marie Ampère being recognised as the founder of electrodynamics, his name is chosen to name the current unit: an ampere is the current produced by one volt in one ohm.

The definitions of the ampere and other electrical units will evolve with new resolutions taken at successive General Weights and Measures Conferences (GWMC). In 1948, the ampere became the basic electrical unit. Its definition, based on its force and the fixing of the magnetic constant of vacuum $\mu_0=4\varpi\times10^{-7}$N/A^2, will remain unchanged within the SI, itself established in 1960, until May 2019. Furthermore, the volt is defined from the watt and the ampere, and the ohm from the volt and the ampere by applying Ohm's Law. This definition of the ampere is the first to be based on the fixing of a natural constant, which makes it more universal. However, being linked to the newton, it requires the realisation of electric units based on complex electromechanical experiments. Since these cannot be performed regularly, the electrical units are therefore stored using national bases of standard components (resistors, Weston batteries, reference to Zener diode) whose instability increases the uncertainties of the measurement.

Considerable progress in fixing the definition of electric units came from quantum mechanics, which notably made it possible to understand the properties of electron transport. Two quantum effects really revolutionised electric metrology. The quantum Hall effect, discovered by Klaus von Klitzing in 1980, demonstrates itself in two-dimensional low-temperature conductors (a few kelvins) subjected to a magnetic field by the measurement of the transversal resistance (Hall) to the values R_K/i, where R_K is theoretically equal to h/e^2, h is the Planck constant, e is the elementary charge and *i* an integer. The Josephson effect, discovered in 1962, occurs in junctions separating two superconductors subjected to a radiofrequency signal f_J. It is demonstrated by the measurement of the voltage at the values nf_J/K_J where K_J is theoretically equal to $2e/h$ and n is an integer. These two effects produce universal resistance and voltage standards whose relative reproducibility is better than 10^{-10}. However, the electrodynamic definition of the ampere needed the determination of R_K and K_J in SI units based on electromechanical experiments with measurement uncertainties higher by two orders of magnitude. This was one of the major reasons for a profound revision of the SI, in addition to the temporal drift of the iconic artifact, the kilogram.

On 16 November 2018, at the 26th GWMC, a historical revision of the SI (Figure 1) was adopted based on the fixing of seven constants, including h and e. It endorses the theories of quantum mechanics and statistical physics [1].

The ampere, symbol A, is the electrical current unit of the SI. It is defined by taking the fixed numerical value of the elementary



SI revised on 16/11/2018. The relationships of the ampère, volt et ohm units with the constants h et e. Photos of the quantum standards for tension and resistance.

charge, e, equal to 1,602 176 634 × 10^{-19} when expressed as unit C, which is equal to A.s, where the second is defined in terms of $\Delta\nu_{Cs}$ (caesium 133 transition frequency). Electric units [2], defined from the constants h and e, can therefore be realised directly using quantum effects without any additional uncertainty. Thanks to the increasing mastery of nanotechnology tools, quantum standards have continued to evolve. Josephson networks could be developed based on a large number of 1 V and 10 V junctions in series. Similarly, networks of Hall bars made from gallium arsenide heterostructures have achieved resistance values ranging from 100 Ω to 1 MΩ. More recently, quantum standards of resistance in graphene, a single layer of carbon atoms organised in a honeycomb network, have shown that they can function at higher temperatures (> 4 K) and at lower magnetic inductions (a few teslas).

Since the revision of the SI, the intensity I of an electric current expressed in amperes may be written $I = ef$, where f is a frequency. Two quantum realisations of the ampere have been developed. The first one aims at the generation of small currents (200 pA maximum) by using quantum effect electronic blocking to manage the passage of electrons one by one through a nanoscale structure.

The second one is to apply Ohm's Law to quantum standards of resistance and voltage. Recently, the LNE has developed a quantum current generator based on this principle delivering currents ranging from 1 μA to 10 mA measured in terms of the product ef_J with a record relative uncertainty of 10^{-8}, thereby improving the realisation of the ampere by two orders of magnitude.

Advances in quantum standards bring new metrological applications: the realisation of the kilogram from h, the realisation of the kelvin and, in the longer term, a universal quantum calibrator to realise the volt, the ohm, the ampere and the farad from the constants h and e. Despite the recent historical revision of the SI, André-Marie Ampère's discoveries remain at the heart of these new developments! ■

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The author

A former student of ESPCI, Wilfrid Poirier received his doctorate in solid state physics in 1997. A researcher at the LNE since 2001, he devotes himself to quantum electric metrology. His work has focused on Hall networks, graphene quantum resistance standards, precision measuring instruments, and more recently the realisation of the new definition of ampere. He received the LNE Research Award in 2018.

Œrsted,
a forerunner of electromagnetism

Laila Zwisler
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In 1820, the Danish scientist Hans Christian Œrsted discovered something new during a lecture, when he allowed an electric current to pass through a conductor above a compass. The current caused the magnetic needle in the compass to twitch slightly. Œrsted had found a link between electricity and magnetism, an effect which became known electromagnetism.

This paper gives an overview of the discovery of electromagnetism and why H.C. Œrsted was looking into the phenomenon. It will also discuss the reception of the discovery, but it will also show the long story of how electromagnetism was embedded in our scientific worldview and technologies. All this made electromagnetism omnipresent in our everyday life.

With this discovery, Œrsted opened a path to future technologies and new knowledge. But, of course, this prospect was unknown in Œrsted's day, where the discovery came as a shock to many prominent researchers, as it ran completely contrary to their theories. The principal character himself was probably not surprised. For some time, Œrsted had been toying with the idea that an electric current could affect a magnet. He wrote about it in 1812 in the book «Ansicht Der Chemischen Naturgesetze»:

"At the same time, experiments should be conducted to try to determine whether in one of the conditions in which electricity is highly bound, one could produce an effect on the magnet, as a magnet. The matter will not be without its difficulties, because the electricity will act on the magnetic body as on the non-magnetic one; perhaps it might however be possible to obtain some information about this by comparing magnetic and non-magnetic needles».

The expectation of the existence of electromagnetism was also in accord with Œrsted's philosophy of life. Œrsted was deeply inspired by the German Romantic school of natural philosophy. According to Romantic philosophy, nature was a living organism embedded with a deep reason. The Romanticists believed that there was a fundamental unity in nature, and that everything in the world was connected. The world was dynamic, and phenomena were to be understood as interactions between opposing forces that were constantly seeking to achieve balance through conflict. For Œrsted, phenomena such as electricity and magnetism were manifestations of this unity. Many Romanticists believed that the path to knowledge went through internal processes, preferably emotional and sensuous. Experiments made no sense to many Romanticists as feelings could not be measured or forced.

Others, like Œrsted, believed that a combination of experiments and intuition was the best road to the truth.

The Romanticist view stood in stark contrast to the mathematical description of nature, which was dominant in physics in the early 1800s, especially in France. The connection between electricity and magnetism was a great surprise because the leading scientists believed that electricity and magnetism consisted of completely different types of particles, which could not possibly affect each other.

The Romantic wave and the French scientists represented opposing knowledge cultures and did not agree on what could count as knowledge or how knowledge was created and represented. The idea of feelings and intuition as the path to true knowledge held little currency in Paris, where scientists preferred to be convinced by experimental proof and mathematical stringency.

French scepticism

In Paris, the news of Œrsted's discovery of an electromagnetic effect was met with scepticism. Was it once again 'Romanticist dreaming', as Pierre Dulong wrote to the Swedish chemist Jacob Berzelius? The electromagnetic effect was not accepted until it was experimentally verified by François Arago.

A number of French scientists, including André-Marie Ampère, threw themselves into the work of investigating the new phenomenon. During this exploration, Ampère got the idea that magnetism arose

Portrait of Hans Christian Œrsted by C. W. Eckersberg (1822) © DTU.

from electrical currents. Hence, Ampère constructed a device in which two wires carrying current attracted or repelled each other. Ampère believed that there were tiny electric currents in a magnet, and that these were what produced the observed effect, which thus had nothing to do with magnetism. With his great efforts, Ampère laid the foundation for many later theories of electromagnetism, and he began the mathematical development of the field. In the following years Œrsted visited Ampère, but Œrsted had mixed feelings about the work and argued that the focus on mathematics led to an incorrect picture of the phenomenon both Œrsted and his discovery gained widespread fame, and it also attracted the interest of the British scientist Michael Faraday. In 1821, Faraday found that a magnet and a wire carrying current could rotate around each other, and ten years later, he discovered induction – that a magnet could create an electrical current in a wire if they were moving relative to each other. In the US, Henry Joseph discovered this effect at the same time as Faraday. Œrsted himself contributed little to the scientific work on electromagnetism after 1820 – perhaps he had already found what interested him. But the fame that accompanied the discovery brought Œrsted such influence, that in his day, he became Denmark's leading scientist. Œrsted and the phenomena he had demonstrated went their separate ways from thereon.

Science as Applied Technology

The discovery of electromagnetism was not just a matter of scientific curiosity or philosophy. It was also a matter of technology and in the early 1800's the dominant technology of the day was the battery. With its galvanic elements one could produce a fairly constant electric current. The scientifically inclined threw themselves at this interesting new source of electricity and expensive batteries were constructed. In this flutter of activity, electrolysis led to notable discoveries of new chemical elements. Hence electricity was mainly seen a chemical advance and not one of physics. Magnetism was a well-known phenomenon and one might say that with all this interest in electricity, surely electromagnetism was soon to follow. But compared to our present day experiments, the batteries were weak, complicated and expensive to run. Therefore to see an electromagnetic effect required a conscious effort. The battery used by Œrsted during the lecture in Copenhagen was small and expensive to run and gave Œrsted little room for manoeuvering. Generally, Œrsted had limited funds. He often struggled financially and in early 1820 he was close to bankruptcy. Without a boundary between his personal finances and those of his affiliated university, his research was hampered by the material situation. Œrsted was bailed out by friends, but he had to find both the time and the money to examine his findings in greater detail.

Breaking the news

Three months after the lecture, Œrsted had access to a better battery and collected a group of distinguished men to witness the proceedings. In a series of systematic experiments, Œrsted explored electromagnetism in many imaginative ways. Generally, Œrsted was a diligent and a thorough experimenter. During the experiments, he found that the electromagnetic effect went around the wire. Œrsted prepared a pamphlet about his experiments in Latin, had it printed and send it to important scientists of the time. In the pamphlet he provided a clear description of the experimental set-up and results, making it easy for others to repeat.

The pamphlet clearly demonstrates that Œrsted's actions were not only compatible with the ideas of the Romanticists, but also with those who believed that knowledge was to be found through reason alone In his scientific work, Œrsted sought empirical confirmation of his hypotheses in the surrounding world. As an individual Œrsted could not be identified with only one school of thought, he united Romanticist ideals with the ideals of the Enlightenment. ■

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From the Ampère's Man to the Tokamak

Round table discussion chaired by **Bernard Bigot**, Managing Director of the ITER Organisation
With the following participants:
- **Alain Bécoulet**, Director of Engineering at the ITER Organisation, « How to create a current of 15 million amperes with ITER? »
- **Jean Daillant**, Managing Director of the Soleil synchrotron, « From Ampère to synchrotron radiation »
- **Daniel Verwaerde**, former Managing Director of the CEA, « Z-pinch and fusion by inertial confinement »

The round table discussion consisted of three consecutive presentations, each followed by answers to some of the audience's questions. The three papers illustrate topical developments based on the fundamental laws of electrodynamics, as formulated by Ampère, and supplemented by Gauss and Maxwell. All three interventions concern high-tech companies and research mobilising considerable human or technical resources and international cooperation. With them important societal issues are at stake: will controlled nuclear fusion ever be the dominant source of energy for mankind? What will be the consequences and applications of a better understanding of the intimate core of matter?

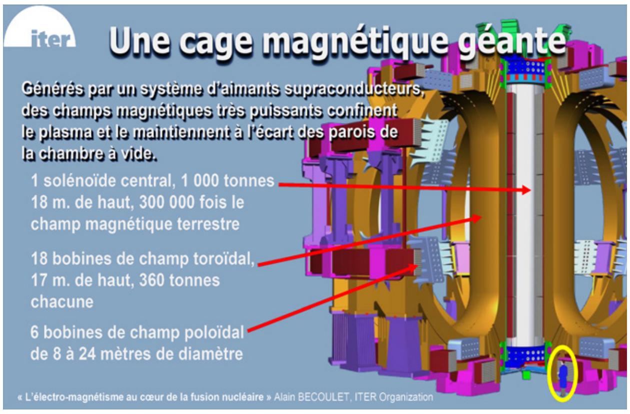
How to create a current of 15 million amperes with ITER?

ITER is an international co-operative project aimed at demonstrating the possibility of industrial production of electric energy by controlled nuclear fusion, by performing on earth some of the reactions taking place in stars such as the sun. As these reactions occur at temperatures in the order of 100 million kelvins, in plasmas in which all matter is totally ionized, the problem of confinement is essential.

The fundamental laws of electrodynamics, as well as the reference to Ampère's Man and to Laplace's Force, are at the origin of the magnetic confinement which consists in keeping the plasma inside a torus by a set of coils with current flowing through them: This is the principle of the Tokamak, which has been studied for 60 years and has proved its effectiveness. Let us just remember that the torus acts as a solenoid closed in on itself in which the magnetic field is created by a series of toroidal coils. In order to avoid the separation in the plasma of negative charges (electrons) and positive charges (nucleons) and to ensure the stability of the plasma, additional coils of axial symmetry are essential: a central coil and also coils called poloidal. The global magnetic field, around which the charged particles rotate, is of a closed helicoidal shape, confined in the torus.

The nuclear fuel chosen consists of deuterium and tritium (the two isotopes of hydrogen) that fuse producing a nucleus of helium and a neutron; this neutron carries a kinetic energy of 14.1 MeV, which will be transformed, in the «usual» way, into electrical energy.

In order to obtain a favourable energy balance, the laws of scale require an enormous power plant, an idea of which is given by the huge dimensions of the coils.



For example, the currents will be 68 kA for coils, which requires the use of superconductors: liquid helium will circulate inside these conductors. The whole machine will be a gigantic cryostat, the size of the Arc de Triomphe, producing a net energy, with, all around it, a vast industrial complex with giant sized electrical and cryogenic installations, not to mention the huge amount of possible production of electricity from the steam which will carry the energy of the neutrons... The plasma current will exceed 15 million amperes!

Assembly began in July 2020 with, for example, the coils being built on-site; the first plasma will be produced around 2025 and, if as expected ITER generates 10 times more energy than it consumes, humanity will benefit from an abundant and virtually unlimited source of energy by mid-century… ■

From Ampère to synchrotron radiation

The Soleil synchrotron, installed on the Saclay plateau, provides a source of radiation used to probe matter, covering a wide spectrum ranging from infrared to X-rays. Four consequences of the Ampère theorem, integrated in the Maxwell equations, are at the basis of its functioning:

- *the electromagnetic field spreads like a wave, at the speed of light.*

- *an accelerated charge produces a wave:* in the Soleil, relativistic electrons (energy of 2,75 GeV) rotating in a storage ring, produce this radiation; the theory shows that centripetal acceleration produces a tangential radiance, travelling forwards, which is used in a 'beamline' that permits specific experiments.

- *a magnet exerts a force on a current:* this effect is used to force previously accelerated electrons into circular motion (in Soleil, by a linear accelerator LINAC and then by a circular accelerator called BOOSTER).

- *a current is equivalent to a magnet:* electromagnets are used in the Soleil, although the present trend is to use permanent magnets.

The Soleil storage ring has a diameter of 120m… and the electronic beam is the size of a hair. Radiation, available in about twenty beamlines, is more brilliant than the sun and allows a wide variety of experiments summarised below :

Molecular rotation	25 µm - 1 mm	Distant infrared
Molecular vibrations	1-30 µm	Infrared
Phonons	0,01 - 0,1 µm	Inelastic scattering
Chemical movements	~ 100 nm	Photoemission
Electronic transitions in solids	10 - 100 nm	Soft X-rays
Atomic levels	0,1 Å - 1 nm	Hard X-rays

Many international and multidisciplinary co-operations characterise the Soleil working environment. Soleil teams work in fields ranging from geophysics to archaeology, from the food industry to astrophysics, from medical imagery to environmental studies.

Significant examples include the discovery of metallic hydrogen (under 4106 atmospheres!), the observation of magnetic vortexes (10^{-8} m) and …the study of viruses.

Z-pinch and fusion by inertial confinement

The Z-Pinch is a cylindrical hollow conductor whose diameter is in the order a centimetre and its walls are less than one millimetre. It can also be made by using conductive wires or a conductive gas. The cylinder, crossed by an intense current, produces a tangential magnetic induction leading, in reference to the 'Ampère's Man', to a centripetal force which tends to crush the conducting cylinder.

Using this design, several spectacular experimental devices have been imagined and then created:

- Sandia's machine in the USA is without doubt the largest Z machine; it consists of discharging several megajoules of electrical energy from a bench of capacitors charged in parallel (it is a Marx generator). With a switching of the order of a microsecond, the instantaneous power reaches 80 TW, or 1000 times the total power available on the French network! The current reaches a maximum of 25 MA.

- another device, proposed by A. Sakharov, consists in achieving the compression by an explosion method. The cylinder channelling the ray r is placed in a constant magnetic induction B parallel to the current; pinching produces a double effect: the induced current opposes the decrease of the magnetic flux, which results in a *B'* increase of the total field. The overall conservation of the flow shows that, if the final ray after explosion is *r'*, the current is amplified by a factor *(r/r')2x(1+B'/B)*. The results obtained by simulation or by experiment (at the CEA Gramat) are complex, because the powers involved create a plasma moving in a centripetal manner.

By combining simultaneously two experiments set up «head to foot», it is hoped to achieve fusion by inertial confinement; the energy is concentrated on a fusible target consisting of a micro-balloon containing the tritium-deuterium mixture. The outer surface, brutally heated (by a battery of lasers), is thrown violently outwards and, by reaction, the density of the central part increases strongly (by about a factor 10^3) to reach the temperatures necessary to initiate the fusion (in the order of 10^7 K).

This is the principle of inertial confinement and that of a possible fusion… but that will be, perhaps, the next stage after those of the tokamaks and ITER! ■

(Notes taken and article by Bernard Ayrault)

Electrically powered vehicles

Round table discussion chaired by **Philippe Watteau**, Managing Director of the Vedecom Insitute
With the following participants :
• **Patrick Bastard**, Director of Research at Renault, « From electrification of vehicles to energy storage »
• **Yann Vincent**, General Manager of Automotive Cells Company, « Accelerate battery manufacturing today in France and Europe »
• **Florence Lambert**, General Manager of CEA Tech Liten. « Future generations of batteries, from R&D to production, with an eco-responsible approach

The round table discussion was conducted on the basis of exchanges between the speakers who spoke about all aspects of the use of electricity in mobility today and the resulting technical or product developments. The part devoted to the answers to the many questions remained limited by time and some answers were given during the exchanges and presentations. The key points identified by the editor have been grouped here according to the main themes raised.

Introduction

- Electricity has been in use for a long time for car accessories.

- Starting mass production for electric motors represents a real revolution. The cost must be brought down (transport from Asia is prohibitive).

Carbon footprint studies should also be carried out on the whole product, taking into account both the design and the use in order to compare the different technical approaches; analyse their respective life cycles.

- The issue of sovereignty is essential: Europe's strength is the high level of its educational system; the electric vehicle (EV) development program must be in phase with the needs (ecosystems).

How to face the competition?

- It is necessary to organise and synchronise operations, especially with the innovators: researchers and industrialists must cooperate («stick together»).

- Aim for long-term European competitiveness. To do this, create «hubs of innovation» and so shorten the time from validation of a concept to its industrialisation.

- Industrialists must be helped by specialists in fundamental physics (e.g. give them access to major instruments) to avoid spending years of research in isolated labs.

- Simulation is paramount to making faster progress. We need to accelerate the whole movement by updating roadmaps to introduce state of the art technologies in the factories (dry process, solid state batteries, ...).

- Share ideas, make the right choices, and protect results.

The question of batteries

- The battery represents a significant part of the cost of the car and its design is strategic. Its development enjoys significant support from the French and German states.

- Automotive Cells Company's battery project draws from the extensive expertise of Total/Saft in products and processes, and from PSA's expertise in mass production. ACC has benefited from capital contributions since August 2020. Its R&D centre is based in Bordeaux with a pilot plant in Nersac in Charente. Production from the first *Gigafactory* is planned to begin in 2023, followed by a new plant every year.

Innovations for electric vehicles

Switching to all-electric is a complex problem: it's not just about replacing a combustion engine with an electric one. We must develop the technical solutions while remaining competitive!

- **Motorisation:** Should car makers convert to production of electric motors ? For Renault the answer is YES because we must be wary of new entrants: changes in technology are always a great opportunity for them!

The electric motors for traditional applications now on the market are very different from the needs of electric mobility or they are specialised motors (e.g. rail), made in small series. So a specific design is needed. Although the electric motor has obvious intrinsic advantages over the combustion engine, it must be optimised in terms of cost, performance (efficiency) and durability. Several technologies are possible.

- **Connection to the power grid:** the connection of the EV to the grid for a large part of its life can be a plus (depending on the demand on the grid). The perspective of the V to Grid makes it an interesting complement to the development of RE. Bidirectionality is an opportunity to exploit: with 50% of RE in the energy mix, 10% bidirectionality could make electric storage unnecessary. Carbon-free production in France is clearly an asset.

- **Standardisation of charging stations** is a key issue. This is being dealt with but the situation is still imperfect (multiple badges) and the payment by the user (Plug and Charge) will have to be simplified to relieve the client of this worry.

Installation of new charging points must continue at a steady pace, and the question of fast recharge batteries must be tackled.

- **Charging by induction** while on the move is an interesting alternative which is dealt with by large-scale European projects involving local and regional authorities.

- **Electronics in the power chain:** This question is less known to the general public but it is also an important challenge concerning 3 key elements of the power chain: charger, inverter and CC converter. The objective is to design components compatible with mass production; create a real industrial sector in Europe.

Several strategies are possible (Renault for example designs some of these devices) and it should be noted that this niche represents a real chance for European products.

Big laboratories in Europe (including the CEA) with a good expertise in power components are a great asset for European industry.

Battery recycling: is the circular economy on the way?

- ACC has not yet integrated this activity into its program, the priority today being the deployment of plants to establish European sovereignty. But recycling will become a vital activity, in particular for the supply of raw materials. In 2035, the number of batteries to recycle will become equivalent to the number of new batteries produced!

- Improve components to allow the battery a second life: easy to dismantle, with smart cells which store the cell's past record.

- The cell design must integrate the need for recycling: aim for 95% thanks to the expertise of chemical engineers. In particular, reduce the dependence on cobalt for batteries (a market sensitive to the geopolitical situation of some countries).

- Several competing roadmaps currently coexist. The priorities are saving raw materials and using better solvents.

- Life cycle analysis (LCA) at Renault is taken into account from the beginning of the design. More rigorous calculations for LCA are required because the current debate tends to underestimate the benefits of EV.

- It is important to convince the public that electric mobility will be much better than the use of combustion engines, at least as long as the electricity used is sufficiently carbon-free.

How about hydrogen ?

- Be careful not to oppose technologies! Hydrogen can play a complementary role in the EV sector, for intensive charging for example.

- It may be better adapted for use in heavy transport, by rail or sea, and for decarbonising European electricity production.

- It may also be of interest to developing countries, the European model cannot be exported everywhere

Some answers to questions from participants

• «*Will the network support an influx of EV*?» Yes, no problem, even if the whole European fleet was electric we would just need a 15% increase in production of electricity.

• «*What do you think about the sodium-ion cells that the CNRS is working on?*» It's for the long term, we're at a very low TRL.

• «*A photovoltaic roof on EV. What should we think of it?*»

It's being studied, it is mainly a question of cost (what added value?)

• «*Will the lifespan of electric motors be sufficient?*» Yes this type of engine has a great advantage in this respect

• «*Will the number of battery cycles be increased?*»

We are already at a thousand cycles at least, but it is better to speak in terms of MWh exchanged with the engine.

• «*We talk about EV for private cars, but are heavy-vehicles also concerned?*» There are some interesting experiments. ■

(Notes taken and article by Alain Brenac)

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For information on the «Ampère 200 ans» commemoration and to consult the many documents associated with this operation, please access the site:

www.ampere200ans.fr