

Chapter 10

Knowledge and Technology: Sharing With Society

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10.1 A Core Mission of CERN

Education and basic research are large costs to society, which governments, in general, accept as a necessary long-term investment. Still, it is fair to ask how this investment can be used to the best overall benefit for society.

Many excellent reports and talks [1–5] describe how basic research, motivated by “curiosity” — the desire to extend our understanding of nature — contributes as much to innovation as do the applied sciences, which focus on solving specific problems. Both stimulate industry and advance technology.

Consider the core technologies of high energy particle physics. Accelerator applications range from killing bacteria and treating cancer, to welding and cutting, hardening materials, reducing harmful gas emissions from thermal power plants, and much more. Particle detectors are not only ubiquitous in medical imaging; they are also used, for example, by volcanologists and archaeologists to image sites of potential interest. Computer simulation toolkits developed for particle physics have become essential in other fields, including medicine, aerospace, and nano-science.

Complex instruments and cutting-edge technologies are required for the construction and operation of accelerators and intricate detectors, as well as for managing the wealth of data they produce. When existing technologies are inadequate to meet requirements, developments are triggered that often give rise to technological innovations. Most famously, the World Wide Web, which was invented at CERN in the late 1980s to allow automatic sharing of information for scientists, has revolutionized global communication with enormous social and economic impact. Three decades later, data-handling and analysis needs for research at the LHC continue to push forward the evolution of worldwide distributed grid computing, bringing benefits to bio-computing and health sciences, astrophysics, environmental studies, and others.

One of the missions of CERN is to disseminate the results of its research and technological development, to trigger and prepare possible applications outside particle physics and to be a forum for the exchange and scrutiny of ideas for this purpose. Since its origins, CERN has shared knowledge with students, visitors, collaborating institutes and industrial partners [6]. Today, the Organization and the collaborating universities and institutions are together enhancing their efforts in knowledge-transfer and education, aiming to trigger innovation and improve the understanding of basic research as a motor for new and relevant technologies.^a

Knowledge-transfer mechanisms

The commitment to formalizing the transfer of knowledge acquired at CERN has grown steadily over the decades, with an increasing availability of services and support for inventors and external partners, and for multidisciplinary ventures [7]. During this time, a number of knowledge-transfer mechanisms have been implemented in order to profit from the worldwide network of competencies in universities and high-tech industries in the Organization's Member and Associate Member States. The following gives an overview of these mechanisms together with illustrative examples.

Knowledge transfer through people

CERN's 12000 user-scientists are the most important knowledge-transfer mechanism, together with the educational programmes for students, fellows, and technical trainees. The Laboratory is a hub for knowledge sharing, with visiting researchers, teachers and industrial partners taking expertise back to institutes, universities and industry. Via training, education, and large-scale collaboration, CERN propagates this culture of knowledge sharing, which is considered one of its major contributions to society.

Training and education form one of CERN's core missions. A prominent example is the Summer Student Programme for physics and engineering students (Fig. 10.1), who join research teams for several weeks and attend lectures in particle physics, accelerator technologies and computing. The technical student programme allows engineering and applied physics students to spend up to 14 months at CERN. The Laboratory also provides the research base for large numbers of doctoral and diploma students from institutes around the world, who work on topics in accelerator physics, applied physics, and experimental and theoretical particle physics. Each year, close to a thousand doctoral degrees are awarded on the basis of work carried out at CERN experiments and accelerators.

^aThe editorial team thanks Giovanni Anelli for his contributions to this chapter.



Fig. 10.1. Each year CERN welcomes some 300 undergraduate students to its long-established Summer Student Programme, where they work with research teams and attend lectures in particle physics, accelerators and computing.

The skills thus acquired are highly attractive for work in other fields. One study found that more than 40% of students went on to work in the private sector [8].

CERN has a long-standing tradition in organizing conferences, workshops and high-level schools in the Member States and beyond. The CERN School of Physics, which originated in the early 1960s, went on to become the European School of High Energy Physics, and inspired the similar CERN–Latin-American Schools and the Asia Europe–Pacific Schools. The CERN School of Computing and the CERN Accelerator School followed in the 1970s and 1980s, respectively. CERN initiated the European Particle Accelerator Conference series, which has merged with other major events to become the International Particle Accelerator Conference. The Laboratory also brings its research and technology to the public and into classrooms, through guided tours, exhibitions and programmes for several hundred high school teachers each year, including courses, frequently in their national language.

For the effective transfer of expertise to different fields, it is essential not only to identify potentially interesting technologies, but also to assess their relevance to society. This can be achieved through multidisciplinary networks and collaborations, where scientists from different fields and industry discuss ideas to establish a common roadmap. This has proved particularly true in healthcare. A prime example is the initiative taken to set up the inaugural meeting for a light-ion-therapy network in Europe, ENLIGHT [9], at CERN in 2002, which

implemented the concept of multidisciplinary collaboration, and led to growing interest, for example, in hadron therapy.

A more recent development is IdeaSquare [10], a facility located in a dedicated building that brings together researchers, engineers, industry and students to stimulate new ideas inspired by CERN's on-going detector and accelerator R&D. IdeaSquare also hosts innovation-related courses and events, such as the Challenge Based Innovation (CBI) course. Benefiting from the technical knowledge of the researchers and engineers working at CERN, this dedicated MSc-level programme is targeted at multidisciplinary student teams.

Knowledge transfer through purchasing and outsourcing contracts

Procurement contracts with industry amount to nearly 60% of CERN's annual budget. These can range from off-the-shelf products (e.g. office furniture) to R&D contracts requiring cutting-edge technologies for the accelerators. According to surveys [11], a majority of companies that have supplied products or services to CERN have indicated that their contract with the Organization led to an increase in their expertise, often resulting in new business opportunities. The benefit to industry in terms of "economic utility", defined as increased turnover plus cost savings, was estimated to be about three times the value of the CERN contracts. Traditionally, this has been the major route to technology transfer.

The CERN Member States expect a "fair return" for their financial contribution to the Organization through industrial contracts. To assist CERN in these efforts, links to industry are maintained via "industrial liaison officers" from each Member State who participate in the knowledge-transfer activities.

Knowledge transfer through joint ventures and collaboration agreements

CERN has a well-established tradition of collaboration with research institutes and companies, with the primary objective of generating technological results for use both by the partners and at the Laboratory, but also with an eye to the potential for commercial exploitation [12]. Through R&D ventures and agreements, CERN has often acted as a catalyst and an active promoter of international standards, notably in electronics and information technology.

Since its foundation, CERN has played an important role in the exchange of ideas between scientists who are studying a topic or planning, constructing, and performing experiments and analysing the results. Over the years, about a thousand experiments have taken place at the Laboratory, with both CERN and the users' institutions benefiting from the mutual experience [13]. In addition, the Organization recognizes experiments in fields allied to particle physics, such as astroparticle physics, that are being performed elsewhere, and are not necessarily accelerator-based. They obtain a modest level of support, including the use of test

beams, provided this does not affect the in-house programme. As of 2016, there are 26 such “recognized experiments”, including, for example, AMS, IceCube, MICE, and LIGO. CERN also benefits from the associated contacts.

The Organization also has a tradition of providing staff and facilities for development work on behalf of other institutes. In an early example, the organization provided tangible help in establishing the European Southern Observatory (ESO). With its experience in building large-scale apparatus and in dealing with industry, CERN was able to bring useful expertise to the project and for several years, the ESO Telescope Project Division was based at CERN.

In other instances, people have come from elsewhere to work side-by-side with a CERN specialist using material provided by their own institute, in particular for the design and construction of components for their accelerators. Examples include: magnet design and measurement for the ELETTRA Sincrotrone Trieste research centre in Italy; klystron modulators for the linac of the European Synchrotron Radiation Facility (based on the modulators for the LEP pre-injector); magnet measurements and supply of some magnets for the Italian Hadron Therapy Centre (CNAO); design and measurement of magnets, vacuum technology, beam diagnostics, and RF (based on the latest solution for the PS Booster at CERN [Highlight 3.4]), for the MedAustron facility in Austria [Highlight 10.2].

Knowledge transfer through new companies

In recent years, transferring CERN technology through the establishment of new companies is gaining interest. The Organization encourages the formation of spin-off companies — start-ups whose activity is based wholly or partly on CERN technologies and which wish to exploit these technologies commercially. CERN does this by giving measured support to its personnel and to external entrepreneurs who wish to establish a spin-off company in a Member State.

To assist entrepreneurs in taking innovative ideas using CERN technology or expertise from concept to market reality, a network of Business Incubation Centres (BICs) [14] has been set up in several countries. The Laboratory supports companies in BICs through technical visits to CERN and preferential rates for licences of CERN Intellectual Property. The incubators advise on establishing a business plan and provide logistical, financial and administrative support.

CERN’s activities in entrepreneurship and start-up creation have also gained momentum, and first successes are appearing on the horizon. For example, as a result of a strategic partnership with NTNU Trondheim, each year students in entrepreneurship spend a week at the Laboratory to evaluate the potential of CERN technologies for starting a company. In 2014, a team of NTNU students started a company that provides professional services and consultancy for Invenio — software originally developed at CERN to manage the increasing volume of digital

information. Invenio has grown into a fully featured digital library platform, and a number of large institutions worldwide are now customers.

Knowledge transfer through licensing

As a principle, CERN has not taken patents on its technological inventions. However, in 1999, this patent policy was revised, not in view of a possible financial return, but rather to protect the Organization's intellectual property and facilitate the transfer of innovations to industry. CERN's patent portfolio now contains a few tens of patents, many of which have been licensed to industry. Most concern the application of CERN's competences and inventions to problems relevant to society. Examples of such transfer through licensing are described in the following sections.

The KT Fund

Part of the revenue originating from knowledge-transfer (KT) activities at CERN (charges for contract research and services, licensing and consultancy) is allocated to the KT Fund. This provides financial support in the early stages of KT projects, regardless of their field of application, provided they are of potential use to society. Proposals for projects that meet the eligibility criteria are submitted to the KT Group and evaluated by the KT Fund Steering Committee. Together with a technical description of the project, proposers must outline the market potential. Proposals are evaluated based on their quality, likelihood of dissemination, potential impact, and scientific value. Gas-electron multiplier (GEM) detectors [Box 4.6] for flame detection and early earthquake prediction, radio-frequency absorbers for energy recovery, and exotic radioisotopes for medical applications are among the projects that have been partially funded under this scheme.

Transfer of CERN technologies

Transfer originating in CERN core activities

The technological innovations described in this book have been motivated by the needs of CERN core activities. For this reason most of these innovations have found applications in laboratories with a mission similar to that of CERN. In these cases, the transfer occurred naturally via scientific publications and communications. However, in some cases the innovations have been transferred to a wider community as described above.

Whenever industry was not able to provide the required solutions for a particular goal, development work was undertaken in-house and then transferred to industry, through a production contract awarded via competitive tendering. As a result of this process, the selected industries were able to offer this same solution to other customers. In this, the most frequent case, the transfer occurred through

procurement. Examples of this process are the ISR vacuum gauges [Highlight 4.3] and superconducting quadrupoles [Highlight 4.4], and the LEP niobium-coated RF cavities [Highlight 7.4].

In other cases the initial development was done jointly with industry, which then proceeded with the production phase for CERN (and also, possibly, for other clients). Examples include the flexible cryogenic transfer line [Highlight 4.5], and cryogenic system [Highlight 8.3]. In the case of the LHC superconducting magnets [Highlight 8.2] the joint development work also served to whet the appetite of industry for the forthcoming large series of costly devices.

Finally, when tight schedules prevented industrial involvement, the production was carried out at CERN, the innovative solution was protected by patent and the technology transfer done by licensing. In this case the solution was also made generally available. The getter coatings developed for the LHC [Highlight 8.5] provide an example of such transfer. In another approach, the prototypes and an initial 10% of the production were made at CERN, with the remainder supplied partially by purchase from industry via competitive tender, and partially “in-kind”, based on build-to-print specifications [Highlight 8.4].

Transfer motivated by social utility

CERN’s expertise can also be valuable in fields outside the Organization’s core mission. A small fraction of the CERN budget is made available for the development of innovative applications in fields that are outside nuclear and high-energy particle physics, but which have particular relevance for society in general, as described in examples below.

Medical applications^b

The application of CERN expertise in accelerators to the field of cancer therapy, which goes back to the 1980s, has been particularly fruitful. Not only has the laboratory hosted important studies that have contributed to the design of treatment centres that are now operational, it has also been involved in training personnel for the facilities, for example, at MedAustron. With a view to bringing such initiatives more formally into its range of activities, in 2014 the CERN Medical Applications (CMA) Office was set up to stimulate and coordinate activities in medical physics. One major initiative is an open-access facility for biomedical research, OPENMED, to be based on the Low Energy Ion Ring (LEIR), a low-energy accelerator at CERN that supplies heavy ions to the LHC injector chain, for a few weeks each year. Another accelerator-based project is CERN-MEDICIS. Building on a long-standing development of methods of isotope production via the ISOLDE

^bThe editorial team thanks Manjit Dosanjh for her contributions to this chapter.

facility [Highlight 3.8], CERN-MEDICIS will deliver novel radioisotopes for research and applications in therapy and imaging.

Developments in particle detectors have had a big impact on medical imaging, making procedures easier, faster, more accurate and less invasive. Instruments based on the MWPC [Box 4.4], developed at CERN by 1992 Nobel Laureate Georges Charpak, are being used in biology and nuclear medicine. Indeed, Charpak himself immediately saw the possibility of applications in medical imaging. Such activity continues at CERN with the development of the GEM technology [Highlight 4.8] in devices for fast tracking and readout that can be applied to dose-mapping during radiation therapy using X-rays. Medical imaging projects based on other types of particle detector have been initiated at CERN via multidisciplinary collaborations. The Medipix Collaboration [Highlight 10.3] has its roots in hybrid silicon pixel detectors developed for particle tracking in the late 1990s. In one application, a spin-off company in New Zealand is working on using the latest generation of these detectors. The Crystal Clear Collaboration [Highlight 10.4], initiated to develop calorimetry at LEP and the LHC [Highlights 7.9 and 8.8], has adapted these detectors for a variety of medical applications of positron emission tomography (PET).

Computing applications

Data-handling techniques and simulation tools from high energy particle physics now find applications in areas ranging from medicine to financial analysis. In the biomedical field they are applied to help in understanding medical detectors, conducting clinical trials, devising protocols and establishing personalized treatment plans. Grid computing, which allows multiple users to share computing power and storage capacity over the internet, is an ideal tool for a wide range of biomedical fields, from screening of drug candidates, to image analysis, to sharing and processing health records.

FLUKA and Geant4 [Highlight 9.5] are two major simulation packages in particle physics that are widely used in the medical field, amongst others. FLUKA, which is used for calculations of particle transport and interactions with matter, has many applications in high energy physics and engineering, from shielding and detector design to cosmic-ray studies and radiation protection. A number of commercial companies, typically medical hardware and software developers, are FLUKA licensees. The Geant4 toolkit, which allows detailed simulation of particle interactions with matter for a wide range of particle types and energy, also finds applications in medical and space science, as well as in LHC experiments.

Environmental applications

An early transfer of technology to industry was an improved getter technique developed at CERN to fulfil the demanding vacuum conditions for stored beams in colliders [Box 7.3]. This was later applied to vacuum-insulated solar thermal collectors, which are particularly suited to colder, less sunny climates where they are more efficient than traditional solar panels [Highlight 10.5].

In the 1990s, a strategy was proposed to validate new technological concepts (Accelerator-Driven subcritical Systems or ADS) based on the use of particle accelerators to destroy nuclear waste, to produce clean and safe energy, and deliver radioisotopes for nuclear medicine and industry. This led to a trilogy of programmes on basic studies in neutron physics. The First Energy Amplifier Test (FEAT) experiment [15] elucidated the concept of the Energy Amplifier [16], and was followed by the TARC experiment [Highlight 10.6] to study neutron transport in lead and test new ideas for transmutation. The third strand in the trilogy is the CERN neutron time-of-flight facility, n_TOF [Highlight 3.9].

In another, surprising, example of the transfer of CERN know-how — in this case precision engineering expertise — the multi-disciplinary CLOUD Collaboration studies the formation and behaviour of clouds. It uses a beam at the CERN PS to assess the influence of cosmic rays on aerosols and their impact on cloud formation [Highlight 10.7], and is gathering information and developing models that are important for studies related to climate change.

The changing dimension of CERN's mission

This chapter started by asking how the investment in research and education can be best put to use for society. Some of CERN's answers address this through the sharing of technology, knowledge and expertise. However, this raises a related question: is CERN doing this well, too much, or too little?

During the first 40 years, technology transfer occurred naturally through industrial contracts, providing substantial returns for many of the industrial partners. Since then there has been a plethora of initiatives involving technology transfer and knowledge sharing. Is this a distraction from achieving the primary goal of the Organization as defined in the Convention?

To set the scale: the size of CERN's Knowledge Transfer Group is approximately 2% of the CERN staff, with an annual expenditure of the order of 1% of the total material budget. To this one should add the personal effort of knowledge sharing of many of the staff, at the level of some percent overall.

However, the question is not so much whether an organization like CERN, or for that matter a university or an individual scientist, should devote a fraction of the available resources to effective knowledge sharing: today it is considered an

integral part of our social responsibility. This sharing and communicating has to happen at all levels: with peers, with the public, with the decision makers and politicians. More than ever, scientific culture is part of our society and scientists have to be at the forefront of fostering this scientific culture. A scientifically literate public will be the best insurance that politicians follow the lead, appreciate the needs, and allocate appropriate funds to scientific education and research.

Summary

The value of CERN as the host laboratory for worldwide collaborations of scientists and engineers that use its various facilities extends far beyond basic research. CERN and the collaborating universities and institutions are together enhancing their efforts in knowledge transfer and education, triggering innovation and communicating the role of basic research as a motor for new technologies of relevance to society.

10.2 Medical Accelerators: A Tool for Tumour Therapy

Kurt Hübner

The interest in using charged particle beams to treat human cancer stems from the observation [17] that the ionization density, i.e. dose deposition, is very high at the end of the track of a proton or an ion stopped in a tissue (Bragg peak), whereas electrons, X or γ -rays and neutrons deposit the dose decreasingly over the whole range (Fig. 10.2). Thus, protons and light ions stripped of all electrons seem to be very well suited for the well-targeted (conformal) treatment of deeper-seated localized tumours with minimal impact on the surrounding tissue. In particular, carbon ions are of interest due to their enhanced Relative Biological Effectiveness (RBE), a measure of the damage by ionizing radiation per unit of energy deposited in biological tissues. For heavier ions the RBE is less favourable [18].

CERN's contribution to this field started with a study of dedicated medical accelerators in the late 1980s. The study team examined two types of accelerator: a cyclotron with a superconducting magnet and a synchrotron similar to LEAR [Chapter 3.1]. It recommended that the best choice would be a synchrotron providing light ions of 400 MeV/u, ranging from carbon to neon [19]. As for other facilities under construction at that time [20, 21], a synchrotron was preferred for its inherent flexibility in energy and for being based on well-known technology.

In the early 1990s, CERN hosted and contributed to a study of an accelerator-driven spallation source, which included a synchrotron providing fully-stripped carbon or oxygen ions up to 425 MeV/u for hadron therapy [22]. After this project was shelved, CERN and partners from Austria, the Czech Republic and Italy

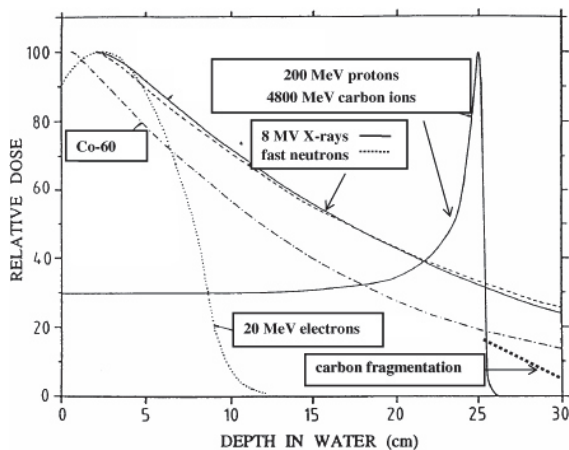


Fig. 10.2. Depth dependence of the deposited dose for photons, electrons and charged particles [18].

decided to concentrate in 1996 on its most promising part and launched the Proton-Ion Medical Machine Study (PIMMS) with the design of a state-of-the-art and cost-effective synchrotron dedicated to hadron therapy as objective. CERN hosted this study group in close contact with GSI, the German research centre conducting similar studies. GSI decided later to pursue its own approach based on experience gained with its SIS synchrotron and associated test facility [23], which was the basis for the successful German facilities HIT [24] and MIT [25], which have been treating patients since 2009 and 2015, respectively.

PIMMS considered an accelerator that would allow the direct clinical comparison of protons and carbon ions for hadron therapy using high-precision scanning [26, 27]. The synchrotron option provided multi-species operation and variable energy as needed for raster scanning. In this process, the beam energy is adjusted to target a slice of the tumour, which is scanned in both horizontal and vertical directions; the beam energy is then readjusted to irradiate the next slice. The maximum energy of the ions determined the size and maximum power of the accelerator while the proton mode determined the design of the injection system and low-energy operation. Applying the lessons learned at LEAR [Highlight 6.4], slow-extraction was chosen for an extended beam spill, allowing on-line dosimetry at the patient. To guarantee a smooth spill, extraction was activated by accelerating the beam into a resonance with a betatron core. This technique has the advantage that it maintains all transverse optical parameters, so that the power converters deliver constant current during extraction, allowing their ripple to be minimized. The betatron core was a 1.5 m long steel toroid around the beam, equipped with a coil changing the magnetic flux that accelerated the beam. Being a high-inductance device, the core smoothed eventual residual ripple.

The PIMMS design was used for the engineering design of the Italian Hadron Therapy Centre (CNAO) [28], which has been treating patients since 2011 (Fig. 10.3). The CNAO technical team is led by scientists who received their training as former junior members in the PIMMS group. CERN also hosted the group performing the magnetic measurements of the dipole magnets, and provided special magnets and expertise with beam diagnostics during design and construction. The design of the accelerator and beam lines of the Austrian Centre for Hadron Therapy (MedAustron) [29], presently being commissioned, is also based on PIMMS, and used parts of the engineering design of CNAO. CERN hosted the design group, composed of senior CERN staff as work-package leaders and staff from MedAustron who were trained on the job and, as for CNAO, went on to assume technical responsibility of the facility. CERN provided substantial assistance for writing specifications and for procurement, as well as space for an injector test facility and for acceptance testing of the magnets and other high-technology components [30]. CERN also contributed to the design, construction and testing of a high-gradient proton linear accelerator operating at 3 GHz. Such a linac in conjunction with a cyclotron could provide a compact facility [31].

CERN's existing antiproton source (AD) [Chapter 6] has served to study the biological effect of antiprotons and so provide a basis for comparison with carbon ions and protons [32]. Now a broader approach is being considered, with an open-access facility for biomedical research based on the existing Low-Energy-Ion Ring (LEIR). This new facility could provide a variety of ions with energies up to 440 MeV/u for testing their effectiveness, dosimetry and cellular responsiveness in humanoid models (“phantoms”) and cell cultures [33].



Fig. 10.3. The CNAO synchrotron providing protons up to 250 MeV and carbon ions up to 400 MeV/u with its injector inside the ring (courtesy CNAO).

10.3 Medipix: The Image is the Message

Michael Campbell

The Medipix story began at CERN in the early 1990s with the R&D on hybrid and monolithic silicon micro-pattern detectors, in particular for the LHC. The group developed the first microchips with the typical readout architecture for high-energy physics on each pixel: preamplifier/shaper/discriminator/delay-line and electronic logic that would “freeze” data in time with a strobe signal, so that only strobed hits were read out. The chips were bonded to the detector pixels through “bumps”, and to check for missing bonds the chip/sensor assemblies were exposed to radioactive sources, and the data added up to make an X-ray image of the source. The images were not very good as the pixels were rectangular. It also took a long time to make an image, because the chip recorded only the strobed events. It became obvious that one should develop a chip with square pixels and a counter for each pixel, which could be activated with an externally applied shutter (as in a digital camera).

This led to the idea that counting every photon would make more efficient use of the X-ray dose given to patients in medical applications. Several teams began to explore the possibilities, among them an informal collaboration of four research groups (CERN, Freiburg, Glasgow and Pisa). Unlike the others, this team went all the way to making a big chip, which became known as Medipix1 [34]. The Medipix1 chip had 64×64 square pixels at a pitch of $170 \mu\text{m}$. It proved that counting single photons was indeed possible, and particularly powerful in providing clean X-ray images in a low-rate environment. The pixel size, the limited number of pixels per chip, and the fact that the chip could not be abutted to others — i.e. placed side-by-side with no “dead” edges between — meant that Medipix1 was not widely used, but it did set the stage for further developments.

The big breakthrough came with Medipix2 (Fig. 10.4), developed within a collaboration that was this time grouped formally, in 1999, initially with thirteen members. The $250 \mu\text{m}$ CMOS process employed for the silicon pixel detector in the LHC ALICE experiment (but without the radiation-tolerant design techniques) was used to make a chip with 256×256 pixels on a pixel pitch of $55 \mu\text{m}$. Each pixel had a window discriminator and a 14-bit counter on board, and the chip used the same camera-like logic as the first generation. Aimed at medical X-ray imaging, the chip could be butted up on three sides and was therefore better suited than the Medipix1 to covering large areas. The number of uses to which the Medipix2 chip could be put simply exploded over the years and the collaboration peaked at about 17 members [35].

Around 2005, colleagues from the EU-funded EUDet project approached the Medipix2 design team and asked for the pixel readout to be changed so that they could read out a gas detector and obtain track information in three dimensions. This involved sending a clock signal around the chip such that each pixel could be made to count clock ticks from the moment it was hit until the end of the shutter signal. This timing information provided the z-direction for the tracks in the gas volume, the x- and y-coordinates coming from the pixel location. It was obvious to the chip designers that one could also propose adding a third mode to each pixel (after particle counting and arrival time), namely time-over-threshold (ToT), giving the amplitude of the charge deposited in a pixel. This led to the Timepix chip, which has proven to be even more versatile and popular than Medipix.

A significant contribution to the dissemination of this technology has been the miniaturized USB readout and software developed by collaboration members at CTU, Prague. New applications continue to appear: the chip is the main workhorse for the CERN@school project, which began with a visit by a group of UK high school students and their inspirational teacher to the Medipix design team in 2007.

One early idea was to take the first steps towards spectroscopic X-ray imaging, which would permit colour X-ray imaging. However, during the work on Medipix2/Timepix, it became clear that the main obstacle to the extraction of

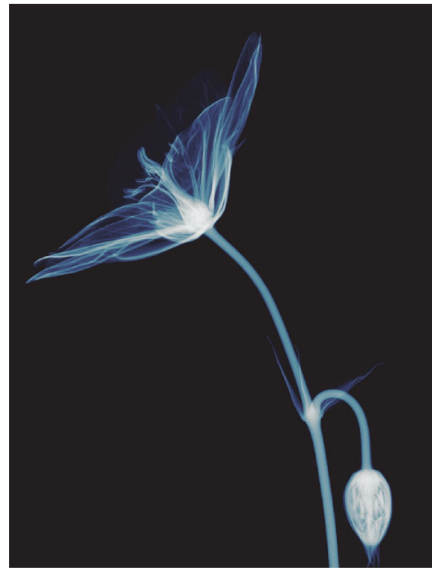
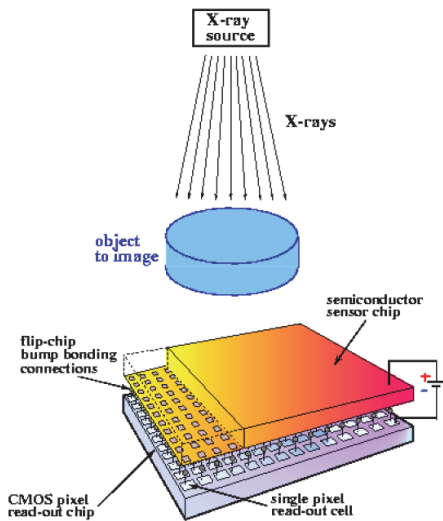


Fig. 10.4. Schematic showing the operation of the Medipix2 chip, left, with an example of the image resolution achievable, right. (Courtesy Medipix2 Collaboration.)

spectroscopic X-ray information comes from charge sharing between neighbouring pixels, caused by charge diffusion during collection (or even the fluorescence present in the heavy materials needed in the diagnostic energy range). One could compensate for the influence of charge sharing by using the Timepix chip in ToT mode and doing cluster analysis offline. However, if there are too many hits per frame, the clusters mingle. To achieve spectroscopic imaging at high count rates, something has to be done at the pixel level in real time. The Medipix3 architecture does just this: it sums charge over neighbouring pixels on an event-by-event basis, but allocates the result to only one pixel — the one with the largest charge from the cluster.

The Medipix3 Collaboration, formed in 2005, has developed two chips: Medipix3, which implements the charge summing and allocation scheme, and Timepix3, which (like Timepix) is intended for use with lower hit rates. Timepix3 uses an entirely different readout approach from the frame-based readouts of Medipix, Medipix2, Timepix and Medipix3. In Timepix3, each time a pixel is hit it generates a data package to send off-chip the hit coordinates, the ToT value (the amplitude of the charge deposited) and the arrival time, with a precision of 1.6 ns. The precise time-stamp recording allows a semiconductor detector to be read out in the same way as a gas-based time projection chamber [Box 4.5].

Recently, through-silicon-via (TSV) technology has become available and can be used in pixel detector readout to take signals away from a face of the chip rather than from an edge. As a consequence, the Medipix4 Collaboration will develop chips that for the first time are buttable on all four sides. This should permit almost seamless tiling over large detection areas. The Medipix4 chip will be aimed at reaching full count rates for human CT scans while Timepix4 will have improved throughput with respect to Timepix3, better time-tag precision and smaller pixels.

10.4 Crystal Clear: From Higgs to PET

Paul Lecoq

The Crystal Clear Collaboration [36] was formed in 1990 with as primary goal to identify and develop a crystalline scintillating material suitable for a high-resolution electromagnetic calorimeter that could detect production of the Higgs boson at the LHC, through its decay into two energetic gamma rays [Highlight 8.8]. The crystal would have to be very dense, with a fast scintillation response and no afterglow, to withstand the 40 MHz beam-crossing rate of the LHC, and resistant enough to the effects of radiation to guarantee the stability of its optical properties within a few percent for at least 10 years of operation. In addition, the collaboration had to address the need to produce about 100 tons of crystals with a

consistently high quality within a few years and at an affordable cost. Initial studies concentrated on cerium fluoride (CeF_3), lead tungstate (PbWO_4), and heavy metal fluoride glasses.

This formidable list of challenges required a large multidisciplinary effort. The Crystal Clear Collaboration co-opted a number of world experts in different areas of material sciences (crystallography, solid state physics, luminescence, defects in solids) to develop together suitable new inorganic scintillators. Based on Crystal Clear's studies and recommendations, in 1994 both the CMS and ALICE collaborations selected the lead tungstate scintillator for their electromagnetic calorimeters. This choice proved to be judicious and significantly contributed to the discovery of the Higgs boson at the LHC.

At the same time, Crystal Clear succeeded in establishing and motivating a community of scientists to contribute to applied research on the physics of scintillation processes in solids. This attracted scientists and engineers from other areas making use of scintillating materials, resulting in a total community of about 250 scientists worldwide. This community meets every second year at the international SCINT conference, which the Crystal Clear Collaboration has been organizing since 1992.

The ClearPET project [37]

In order to leverage the synergy available within Crystal Clear for further applications, the collaboration decided to focus on medical imaging instrumentation; in particular, to use its high energy physics expertise in integrating multi-thousand-channel detectors to develop a compact high-performance scanner for Positron Emission Tomography (PET), using new kinds of crystals and photon detectors, and low-noise and fast signal processing. The collaboration first proposed to build a PET scanner for small animals, the ClearPET, together with several biologists and medical groups. For this purpose Crystal Clear developed a very dense and fast scintillating crystal (cerium-doped lutetium aluminum perovskite: $\text{LuAP}:\text{Ce}$) used in combination with another crystal (cerium-doped lutetium orthosilicate) to reduce the parallax error that limits the spatial resolution in PET scanners with small detector-rings. In early 2000, a resolution better than 1.5 mm over the whole field of view was obtained — a significant breakthrough at the time — and the process was patented and licensed to a German company.

ClearPEM and ClearPEM-Sonic [38]

After the ClearPET success, Crystal Clear decided to develop the ClearPEM, a dedicated breast-imaging PET scanner. It was soon realized that the ClearPEM,

which provides metabolic information on breast tumours, could benefit from the combination with another modality for anatomic imaging. The ClearPEM-Sonic is an innovative imaging system that combines a mammography PET and a 3-D ultrasound and elastography system, and thus allows the combination of metabolic, morphologic and structural information for a more refined diagnosis. Phase 1 of the clinical trial, which started in March 2012 on 10 patients at the Hôpital Nord in Marseille (Fig. 10.5), gave excellent results, and was followed by a second, more ambitious clinical trial on 100 patients at the San Gerardo hospital in Milano, which was still running at the time of writing (2016).

ENDOTOPET-US [39]

The year 2011 saw the launch of ENDOTOPET-US, a European project for the design of a high-performance medical imaging device to be used in research on pancreatic cancer. The project, funded by the European Union FP7 programme, is a collaborative effort between CERN and 13 partners, including hospitals and companies. The primary objective is the design of a state-of-the-art endoscopic probe associated with an external detector, and the development of biomarkers, with priority for the pancreas and prostate. The ENDOTOPET-US endoscope is a dual-mode imaging system comprising a miniaturized PET detector-head with excellent 200 ps time-of-flight (TOF) capability, which is attached to an ultrasound probe with a biopsy needle. The ultrasound signals will provide an anatomical image of the tumour, while the PET head will supply highly detailed information



Fig. 10.5. The ClearPEM Sonic, installed at the University Hospital of Marseille for clinical trials in December 2011. (Courtesy Crystal Clear Collaboration.)

about the tumour activity and, indirectly, the associated proteins. The results of the imaging will be correlated with the biological analysis of the tumour. Two versions of the ENDOTOPPET-US have been built, one for the prostate and one for the pancreas. These will be tested at hospitals in Munich and Marseille, respectively.

Photonic crystals [40]

It is not only in physics and astronomy that inorganic scintillators find use in detection systems, but also in applications related to homeland security, medical, imaging, non-destructive industrial testing and more. In all of these detectors, light produced in the scintillator has to be transported towards a photodetector, but the standard optical coupling suffers from inefficient light extraction from the crystal due to the total internal reflections caused by the high refractive index of the scintillator. By using photonic crystals — i.e., by nano-structuring the different surfaces of the scintillator to produce constructive interferences of the evanescent wave near the surface — the transport of the light output can be tailored to optimize the timing performance and light yield of the detector. Some members of the Crystal Clear Collaboration have demonstrated that a factor of two in the light-extraction efficiency can be obtained with crystals commonly used in medical imaging. A European-funded project, TURBOPET, has been launched in collaboration with industry to demonstrate the clinical benefit of such a treatment, using the crystal on the MAMMI breast-imaging PET scanner that has been developed by a Spanish company.

10.5 Solar Collectors: When Nothing is Better

Cristoforo Benvenuti

In a standard solar thermal collector, the air molecules bouncing back and forth between the light absorber (hot) and the front glass window (cold) result in large thermal losses which limit the collector efficiency. To have a vacuum (i.e. nothing) inside the collector would remove this inconvenience.

Despite this well-known fact, evacuated flat-plate solar thermal collectors have never been produced because of the (almost) insurmountable difficulty of making a vacuum-tight joint between the glass window and the metal frame of the collector. A CERN patent [41] shows that this problem may be solved by plasma spray coating the perimeter of the glass with a metallic layer to which a metal joint may be fixed by soft soldering. This CERN patent was licensed in 2005 to a company, SRB Energy, created to produce and commercialize an evacuated thermal solar collector (Fig. 10.6).

The glass-to-metal joint is the main, but not the only, difficulty to be overcome to produce the collector. In addition:

- After the initial evacuation, the vacuum must be maintained despite the continuous outgassing of the collector components;
- The infrared emission from the hot light absorbers must be minimized;
- The pressure of 10 t/m² applied to the collector by the external atmosphere, tending to implode the collector glass, must be neutralized.

The vacuum inside the collector is maintained by a non-evaporable getter (NEG) pump [Box 7.3] [43] of which the surface is continuously cleaned by solar heating. The NEG thin-film technology developed for the LHC accelerator [Highlight 8.5] [44] has been used to coat a thin aluminium foil with a getter layer by means of a “roll-to-roll” coating machine developed *ad hoc* by SRB. This machine can coat automatically a few hundred metres of foil per week. To decrease the losses due to emission of radiation, the collectors are coated with a film that absorbs 90% of the solar light but presents a low emissivity in the infrared range (less than 0.07). The external pressure is withstood by spacers placed between the two glass plates.

Two cylindrical mirrors are coupled to the collector, as shown in Fig. 10.7. These mirrors convey the light they receive to beneath the panel, so as to double the incident power on the panel without doubling the cost. It is important to note that although the diffused light cannot be focused, these mirrors transmit it to the collector equally well as the direct light. This feature is particularly important in central Europe, where diffused light may exceed 50% of the total.

The collector with the mirrors may reach a temperature of 400°C in the best sunlight conditions. The available thermal efficiency is shown in Fig. 10.8. The pressure inside the collector varies between 10⁻⁴ Pa at 400°C and below 10⁻⁷ Pa

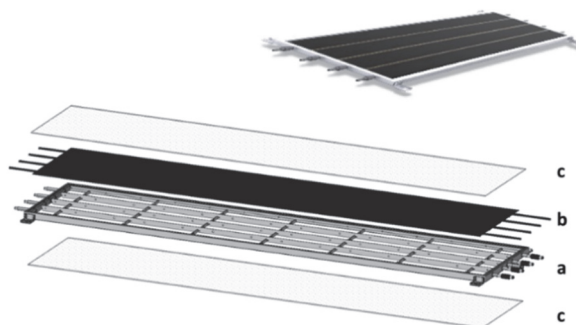


Fig. 10.6. Schematic of the SRB solar panel: (a) frame with spacers, (b) absorbers with cooling pipes, (c) glass windows [42]. (Courtesy SRB Energy.)

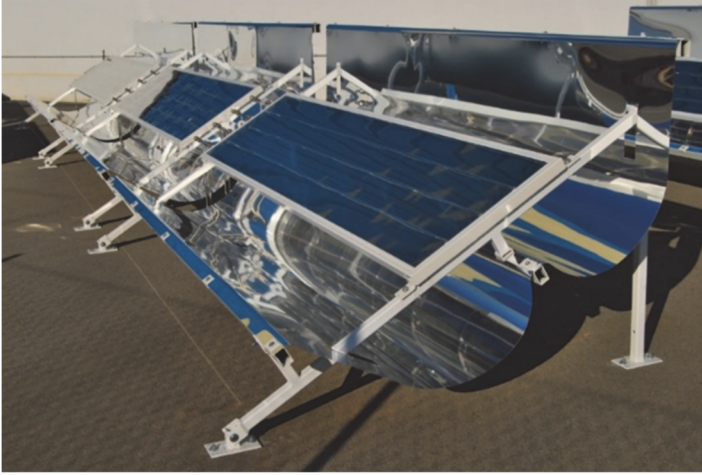


Fig. 10.7. The SRB collector with cylindrical mirrors. The collector is 3 m long and 70 cm wide. The mirrors enable the collection area and the power production to be doubled. (Courtesy SRB Energy.)

during the cold winter nights. These pressures, much lower than needed to profit fully from vacuum insulation (10^{-2} Pa), are a by-product of the large amount of NEG required to maintain the vacuum over 30 years.

The collector design was finalized in 2007 and a pilot production plant came into operation at the end of 2008. The SRB collector is multipurpose: it can be used for heating, water desalination, cooling and for the production of electricity. Among the many installations made so far, a good example is that of Geneva airport (about 1200 m²), where it is used for both heating and air conditioning.

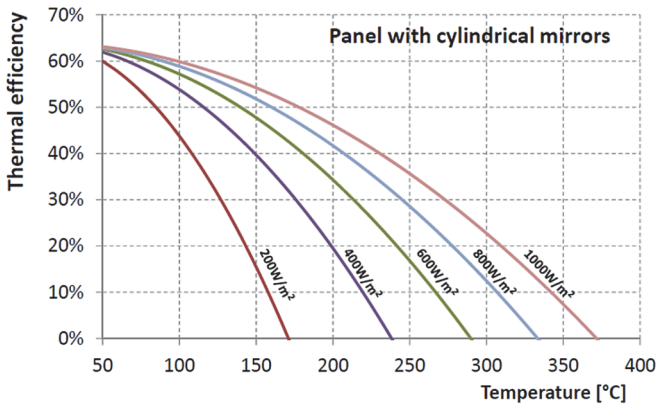


Fig. 10.8. Dependence of the SRB collector efficiency on the incident solar power and on the temperature of operation. The decrease of efficiency at higher temperatures is due to the increase of the thermal losses by IR radiation emission. (Courtesy SRB Energy.)

10.6 The TARC Experiment at CERN: Modern Alchemy

Jean-Pierre Revol

TARC, which stands for Transmutation by Adiabatic Resonance Crossing, was the idea of Carlo Rubbia to make use of the unique properties of lead to enhance, by orders of magnitude, the transmutation rate of long-lived fission fragments, such as ^{99}Tc and ^{129}I (two elements that represent 95% of the radio-toxicity of long-lived fission fragments in nuclear waste). Conversely, the same method may be applied to produce radioisotopes from stable elements, using accelerator-driven systems (ADS) instead of nuclear reactors. The goal of the TARC experiment (PS211), proposed at the CERN PS in 1995 [45], and carried out in 1996 and 1997, was to demonstrate the feasibility of these two attractive possibilities.

The physics of TARC is rather simple and based on a unique combination of properties of neutrons produced inside a volume of lead. Lead is an excellent material for the production of spallation neutrons through the impact of a proton beam; it is an element with one of the lowest cross-sections for neutron capture; it has a short elastic-collision length, $l_0 \approx 3$ cm; and it has a large nuclear mass compared to the neutron mass, which leads to an average fractional neutron energy loss in an elastic collision, quantified by the lethargy coefficient η_0 , that is very small, $\sim 9.7 \times 10^{-3}$. In this low-lethargy medium, time and velocity are strongly correlated, such that there is a simple relation between velocity, v , and time ($t \approx 2l_0/\eta_0 v$). In this way, the time at which a neutron is observed in the experiment is correlated with its velocity and, hence its kinetic energy, providing a simple way to determine energy from time measurements [46].

Because of the very low neutron-capture probability, in a sufficiently large volume of lead a 1 MeV spallation neutron will survive for a long time, typically 3 ms, undergoing 1800 scatterings along a 60 m path, before it is eventually captured as thermal energy. Neutrons of MeV energies thus slow down in lead through many very small energy losses. If some ^{99}Tc is incorporated in the lead, such neutrons are certain to go through the energy of a resonance in the neutron-capture cross-section of ^{99}Tc and so enhance by orders of magnitude the transmutation probability of ^{99}Tc , which is radioactive, into ^{100}Ru , a stable element. This process is referred to as adiabatic resonance crossing. The long lifetime of neutrons in lead and the small elastic-collision length have the additional effect of increasing the neutron flux locally, as a neutron is likely to cross the same elementary surface several times during its random walk.

In the TARC experiment, these expected properties of neutrons in lead were beautifully verified with high precision in 334 tonnes of pure lead installed in a CERN PS proton beam line. It was particularly important to check that a sufficiently large fraction of neutrons would survive the capture resonances of lead

and reach the capture resonances of interest, for the destruction of long-lived fission fragments (Fig. 10.9). Using ${}^6\text{Li}/{}^{233}\text{U}$ target silicon detectors, ${}^3\text{He}$ ionization detectors, and many activation methods, the TARC collaboration measured with unprecedented precision neutron fluxes over neutron energies covering eight orders of magnitude [47].

Tests of transmutation of ${}^{99}\text{Tc}$ and ${}^{127}\text{I}$ carried out at various locations inside the lead volume of the TARC experiment, validated both the TARC method and the simulation developed specially for the Energy Amplifier studies [16]. The simulation can therefore be trusted to predict the performance of an industrial system either to destroy long-lived fission fragments or to produce radioisotopes for nuclear medicine and other industrial applications. It was shown that in an Energy Amplifier in which ${}^{99}\text{Tc}$ or ${}^{127}\text{I}$ have been diluted in the lead volume, it is possible to destroy these elements at about twice the rate at which they are produced in nuclear reactors [47].

The TARC collaboration also measured the production rate of ${}^{99\text{m}}\text{Tc}$, an isomer of ${}^{99}\text{Tc}$, the most widely used radioisotope in medicine, from the activation of natural molybdenum, and confirmed the feasibility of an industrial activator for

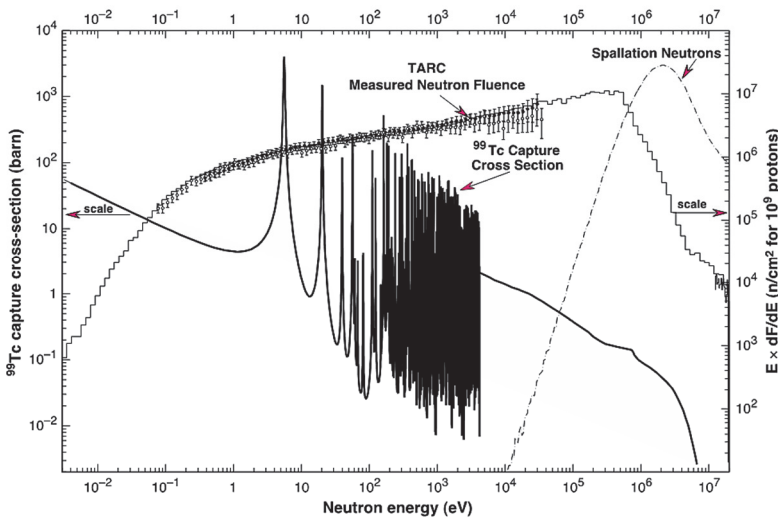


Fig. 10.9. The flux of relatively high energy spallation neutrons (dashed line) is transformed into a neutron flux covering many orders of energy. The resonances in the capture cross-section of ${}^{99}\text{Tc}$ cannot be missed, as the average energy loss of a neutron through elastic scattering is typically smaller than the width of resonances. Data points are taken from TARC neutron flux measurements for 3.5 GeV/c protons [47]. The histogram (full thin line) is the neutron flux obtained with the TARC simulation [47]. The ${}^{99}\text{Tc}$ neutron capture cross-section (full thick line) [48] exhibits two most prominent resonances at 5.6 eV and 22.3 eV.

the production of such an element, or of other radioelements used in medical imaging, diagnostics, and therapy. As a result, CERN took a patent [49] on the TARC idea, and various industrial pharmaceutical companies showed interest in its exploitation. The patent, valid until 2017, is very much of interest, as the demand for ^{99m}Tc has exploded and new therapies based on lutetium, rhenium, holmium, etc. are in rapid development.

The TARC experiment was a landmark experiment, which studied the phenomenology of neutrons in lead. It showed that ADS may be used to destroy nuclear waste and provide an alternative to nuclear reactors in the production of radioisotopes. It validated an innovative simulation that is now used for the design of ADS. The TARC concept also led to the design and construction of the CERN neutron Time-Of-Flight facility, n_TOF [Highlight 3.9], with its high rate, high precision neutron flux and low background. It offers unique conditions for the measurement of neutron cross-sections, a necessary input to any reliable simulation and development of new nuclear systems.

10.7 A CLOUD Chamber with a Silvery Lining

Jasper Kirkby

During his first visit to the Ben Nevis Observatory in 1894, the future Nobel laureate C.T.R. Wilson became fascinated by clouds and the beauty of coronas and “glories” (coloured rings surrounding shadows cast on clouds). He returned to the Cavendish Laboratory in Cambridge determined to re-create clouds in the laboratory and study their physical phenomena. This led him to develop the expansion cloud chamber — a detector on which much of the experimental foundation of particle physics was built in the first half of the 20th century.

More than a hundred years later, a new cloud chamber is in operation at CERN. The CLOUD experiment is optimized to study the influence of cosmic rays on aerosols and clouds [50]. CLOUD reproduces atmospheric conditions in a large chamber (Fig. 10.10) to study aerosol particle formation and growth in controlled laboratory conditions. Clouds are generated by adiabatic pressure reductions of humid air parcels, as in Wilson’s cloud chamber, but at the much smaller water vapour supersaturations found in natural clouds (a few times 0.1%, compared with around 500% for a Wilson cloud chamber). Depending on the air temperature and the nature of the seed particles, either liquid or ice clouds form.

The primary scientific goal of CLOUD is to answer the question of whether or not cosmic rays exert a climatically significant effect on aerosols and clouds, as suggested by satellite observations first reported in 1997 [51]. This intriguing

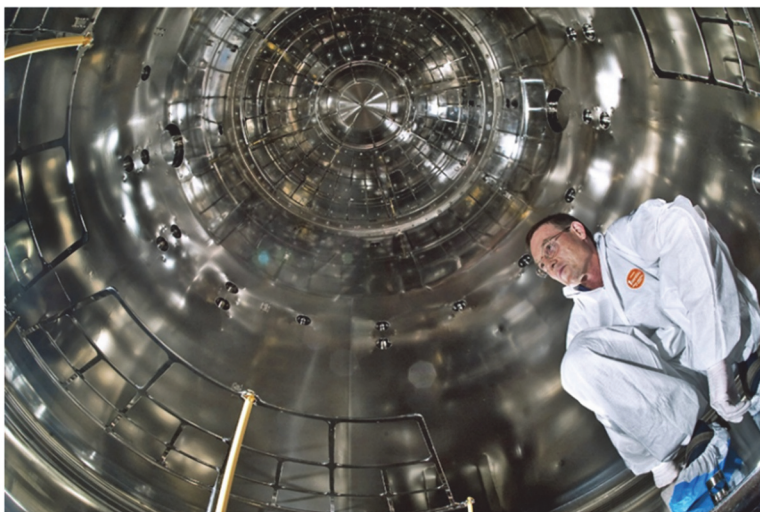


Fig. 10.10. Fisheye view vertically upwards inside the 3 m CERN CLOUD chamber. The inner surface of the stainless steel chamber is electro-polished to reduce retention of contaminants. An array of 265 fused silica fibre-optic feedthroughs is installed on the roof of the chamber to provide a uniform column of UV light for simulating atmospheric photolytic chemistry. A pair of magnetically-coupled stainless steel fans (not shown) mounted on the upper and lower manhole covers ensure mixing of the air, trace gases, ions and aerosol particles inside the chamber. Fast response (< 1 s) thermometer strings (not shown) measure the air temperature, which can be adjusted between -70°C and $+100^{\circ}\text{C}$ by a precise thermally-controlled environment. Two transparent high voltage electrodes, supported on partially-conducting ceramic rods, provide an electric field of up to 20 kV/m to clear ions from the chamber for ion-free experiments. Sampling probes (not shown) are inserted through a ring of DN100 ports seen in the mid plane of the chamber. These are connected externally to state-of-art instruments such as mass spectrometers that continuously analyse the contents of the chamber during experimental measurements. The configuration of analysing instruments is modified for each experimental run according to the scientific goals.

possibility could shed new light on the long-sought mechanism for solar-climate variability in the pristine pre-industrial climate [52, 53]. Atmospheric aerosols and their effect on clouds are recognized by the Intergovernmental Panel on Climate Change [54] as the largest source of uncertainty in anthropogenic radiative forcing. A second scientific goal of CLOUD is therefore to quantify the fundamental physico-chemical processes controlling aerosol particle formation and growth in the atmosphere, and thereby help to reduce the current uncertainty in Earth's climate sensitivity and sharpen global temperature projections for the 21st century.

CLOUD is the first — and so far only — experiment to reach the demanding technological performance required to study these processes under atmospheric conditions in the laboratory. Extraordinary care has been paid in the design and construction of the CLOUD chamber and its associated systems — gas, thermal,

UV and electric field — to suppress contaminants at the technological limit. CLOUD experiments have shown that atmospheric nucleation and growth is driven by atmospheric vapours that are present in minute amounts of only a few parts-per-trillion by volume (pptv). The key vapours comprise sulphuric acid, ammonia, amines and highly oxidized biogenic molecules originating from trees [55-59]. Ions from galactic cosmic rays and natural radioactivity play an important role in the formation of aerosol particles under certain conditions (Fig. 10.11), although evaluating their climatic significance requires further measurements.

Why CERN? First, the CERN PS provides an artificial, adjustable source of “cosmic rays” that reproduces, in a chamber, ion concentrations found between ground level and the lower stratosphere. Second, the unrivalled technical performance of the chamber and its associated systems is the result of a great deal of CERN expertise. Finally, there is an important cultural “trading zone” between scientific disciplines. CLOUD is a “general purpose” detector that measures every aspect of the physical process under study. Although familiar to high energy physics, pooling the resources of a large collaboration in this way and building a single, integrated high-performance detector is new to atmospheric science.

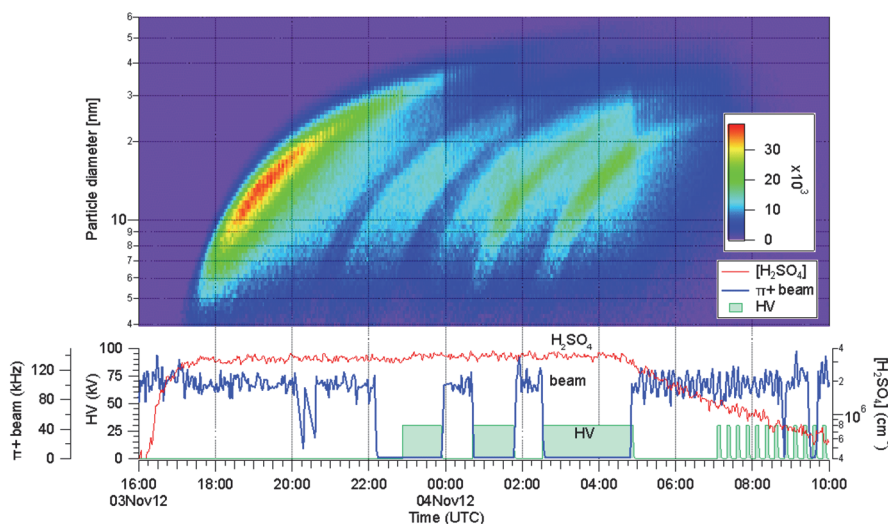


Fig. 10.11. Formation of new aerosol particles from trace atmospheric vapours in CLOUD (upper panel). The aerosol particles grow in size (vertical axis) by condensation over a period of several hours (horizontal axis), reaching sizes sufficient to seed cloud droplets. The characteristic “banana” shapes show fresh bursts of particles that form during periods of high ionization in the chamber due to the π^+ beam from the CERN PS and the absence of an electric clearing field. In this case the trace gases included 0.15 pptv sulphuric acid and oxidized biogenic vapours. The lower panel shows the π^+ beam intensity (blue line), the clearing field (green blocks) and the amount of sulphuric acid (red line).

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