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60 years 1959–2019

IN FOCUS VACUUM TECHNOLOGY

A retrospective of 60 years' coverage of vacuum technology

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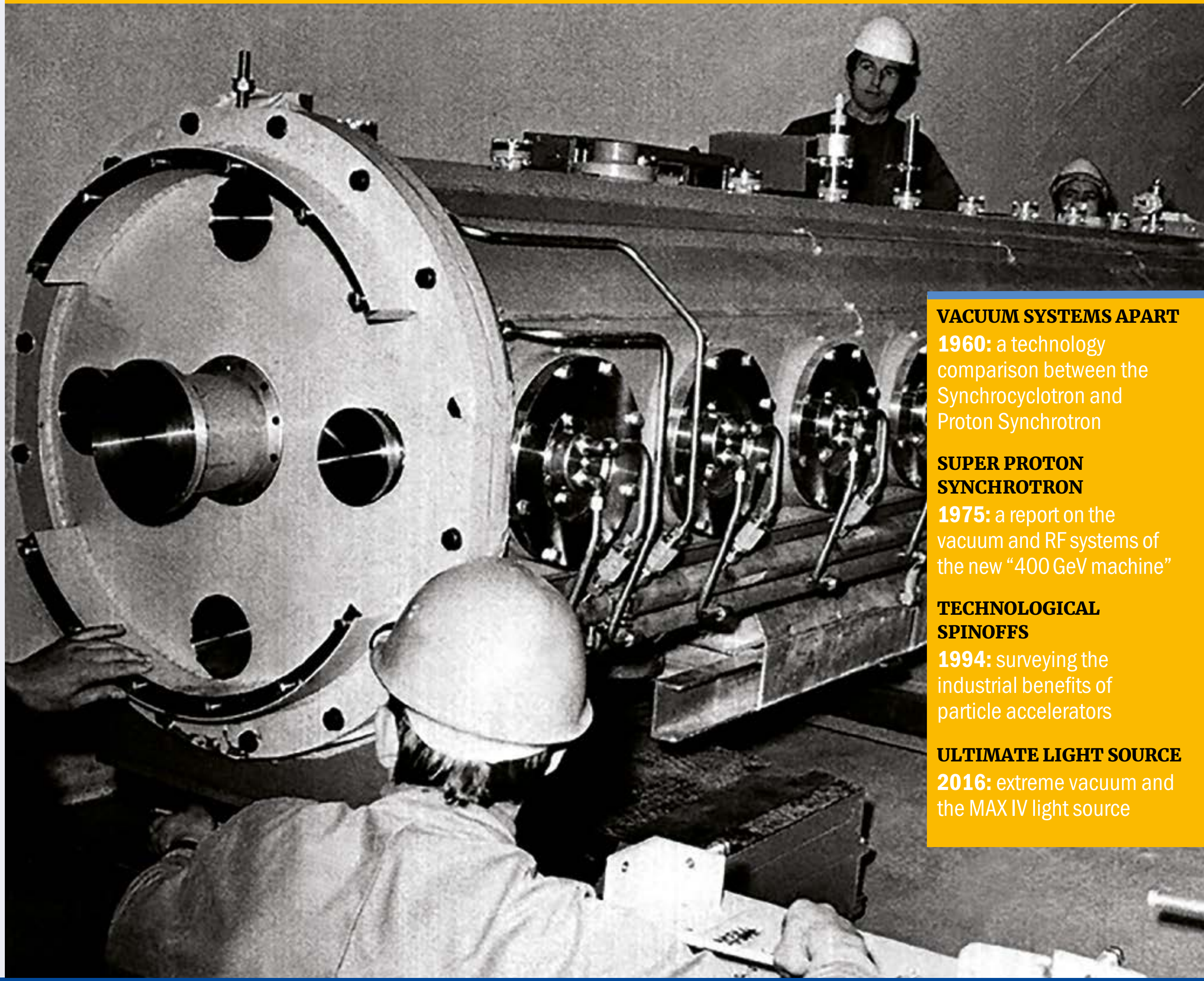

VACUUM SYSTEMS APART
1960: a technology comparison between the Synchrocyclotron and Proton Synchrotron

SUPER PROTON SYNCHROTRON
1975: a report on the vacuum and RF systems of the new "400 GeV machine"

TECHNOLOGICAL SPINOFFS
1994: surveying the industrial benefits of particle accelerators

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2016: extreme vacuum and the MAX IV light source

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CERN COURIER IN FOCUS VACUUM TECHNOLOGY

From the Editor

Welcome to this special *CERN Courier* retrospective, devoted to the topic of vacuum technology. It is part of a series of limited-production issues planned throughout the year to mark the magazine's 60th anniversary, showcasing the riches of the *Courier*'s fully available archive. Vacuum technology represents a global multi-billion-dollar market that covers everything from freeze-dried foods to flat-panel displays, but its application to particle accelerators for high-energy physics reveals its full complexity and multidisciplinary nature. Particle beams require extremely low pressure in the pipes in which they travel to maximise beam lifetimes and minimise backgrounds in the physics detectors, driving much of today's R&D towards simulating, controlling and mitigating the direct and indirect effects of particle beams on material surfaces. CERN brings surface-physics specialists, thin-film coating experts and galvanic-treatment professionals, together with designers and others dedicated to the operation of large vacuum equipment. This makes it one of the world's leading R&D centres for extreme vacuum technology, for projects at CERN and beyond.

Matthew Chalmers

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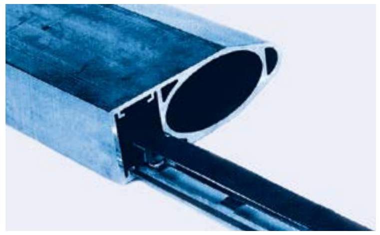

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SPECIAL FOREWORD

A unique vacuum environment

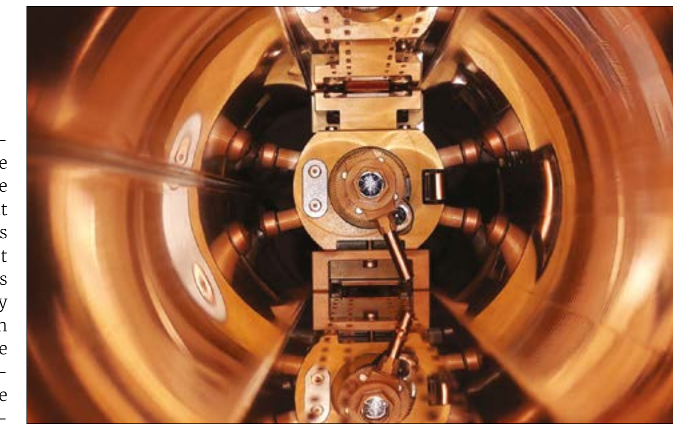
Paolo Chiggiato describes the unparalleled vacuum developments that underpin CERN's science.

Paolo Chiggiato *is leader of the vacuum, surfaces and coatings group at CERN, with interests in materials and treatments for ultra-high vacuum, in particular thin films. A fuller article on CERN's vacuum exploits can be read here:* https://cerncourier.com/cerns-prowess-in-nothingness.

Vacuum technology for particle accelerators has been pioneered by CERN since its early days. The Intersecting Storage Rings (ISR) brought the most important breakthroughs. Half a century ago, this technological marvel – the world's first hadron collider – required proton beams of unprecedented intensity and extremely low vacuum pressures in the interaction areas (below 10^{-11} mbar). Addressing the former challenge led to innovative surface treatments such as glow-discharge cleaning, while the low-vacuum requirement drove the development of materials and their treatments. It also led to novel high-performance cryogenic pumps and vacuum gauges that are still in use today, and CERN's record for the lowest ever achieved pressure at room temperature (2×10^{-14} mbar) still stands.

The Large Electron Positron (LEP) collider opened a new chapter in CERN's vacuum story. Even though LEP's residual gas density and current intensities were less demanding than those of the ISR, its exceptional length and intense synchrotron-light power triggered the need for unconventional solutions at reasonable cost. Responding to this challenge, the LEP vacuum team developed extruded aluminium vacuum chambers and introduced, for the first time, linear pumping by non-evaporable getter (NEG) strips. In parallel, LEP project leader Emilio Picasso launched another fruitful development that led to the production of the first superconducting radio-frequency cavities based on niobium thin-film coating on copper substrates. It was a great success, and the present accelerating RF cavities of the LHC and HIE-ISOLDE are essentially based on the expertise assimilated for LEP.

The coexistence at CERN of both NEG and thin-film expertise was the seed for another breakthrough in vacuum technology: NEG thin-film coatings, driven by the requirements of the LHC and its project leader Lyn Evans. The NEG material, a micron-thick coating made of a mixture of titanium, zirconium and vanadium, is deposited onto the inner wall of vacuum chambers and, after activation by heating in the accelerator, provides pumping for most of the gas species present in accelerators. The Low Energy Ion Ring was the first CERN accelerator to implement extensive NEG coating in around 2006. For the LHC, one of the technology's key benefits is its low secondary-electron emission, which suppresses the growth of electron clouds in the room-temperature part of the machine.



Small solutions *A miniature robot for* in situ *surface treatments of LHC beam screens, pictured inside the 74 mm-aperture beam screen of a superconducting magnet. The whole robot moves axially along the beam screen via inchworm steps while its "head" turns to direct a laser in the radial direction.*

New concepts

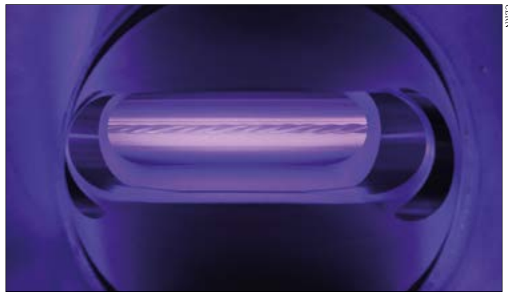
Synchrotron radiation-induced desorption and electron clouds at temperatures of around 4.3 K had to be studied in depth for the LHC, leading CERN's vacuum experts to develop new concepts for vacuum systems at cryogenic temperatures, in particular the beam screen. The more intense beams of the high-luminosity LHC (HL-LHC) upgrade, presently under way, will amplify the effect of electron clouds on both the beam stability and the thermal load to the cryogenic systems. Since NEG coatings are limited for room-temperature beam pipes, an alternative strategy had to be found for the parts of the accelerators that cannot be heated, such as those in the HL-LHC's inner triplet magnets.

Following an idea that originated at CERN in 2006, thin-film coatings made from carbon offer a solution and the material has already been deposited on tens of SPS vacuum chambers within the LHC Injectors Upgrade project. Another idea to fight electron clouds for the HL-LHC involves laser-treating surfaces to make them more rough, so that secondary electrons are intercepted by the surrounding surfaces. In collaboration with UK researchers and GE Inspection Robotics, CERN's vacuum team has recently developed a miniature robot that can direct the laser onto the LHC beam screen (see image above). The possibility of *in situ* surface treatments by lasers opens new perspectives for vacuum technology in the next decades, including studies for future circular colliders. Another benefit of this study is the development of small robots for the *in situ* inspection of long ultra-high vacuum beam pipes, such as those of the LHC's arcs.

The Compact Linear Collider (CLIC)

project, which envisages a high-energy linear electron–positron collider at CERN, demands quadrupole magnets with a very small-diameter beam pipe (about 8 mm) supporting pressures in the ultra-high vacuum range. This can be obtained by NEG-coating the vacuum vessel, but the coating process in such a high aspect-ratio geometry is not easy due to the very small space available for the material source and the plasma needed for its sputtering. This troublesome issue has been solved by a complete change of the production process in which the NEG material is no longer directly coated on the wall of the tiny pipe, but instead is coated on the external wall of a sacrificial mandrel made of high-purity aluminium.

Next-generation synchrotron-light sources share CLIC's need for very compact magnets with magnetic poles as close as possible to the beam, so as to reduce costs and improve beam performance. CERN's vacuum group collaborates closely with vacuum experts of light sources, MAX IV in Sweden and PSI in Switzerland being prominent examples, to develop the required very-small-diameter vacuum pipes. Further technology transfer has come from the sophisticated simulations necessary for the HL-LHC and the Future Circular Collider study, which have also found applications beyond the accelerator field, from the coating of electronic devices to space simulation.


CERN

Advanced deposition *NEG thin-film coating of the ELENA vacuum chambers at CERN's Antiproton Decelerator.*

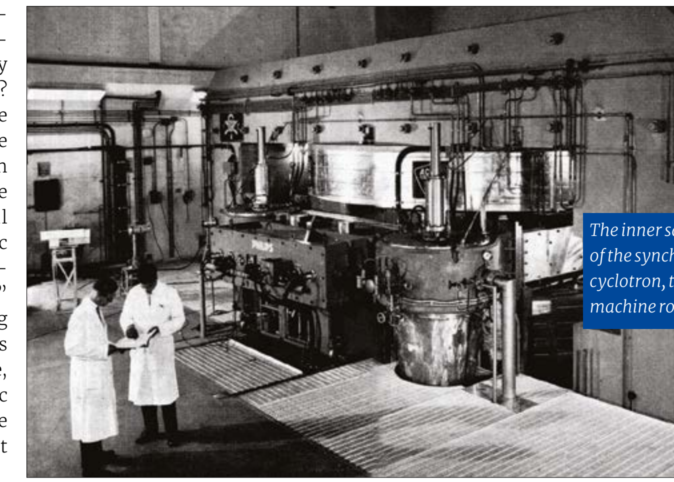
Relations with industry are key to the operation of CERN's accelerators, especially those in the LHC chain. The vacuum industry across CERN's member countries provides us with state-of-art components, valves, pumps, gauges and control equipment that have contributed to the high reliability of the lab's vacuum systems. In return, the LHC gives high visibility to industrial products. Indeed, the variety of projects and activities performed at CERN provide us with a continuous stimulation to improve and extend our competences in vacuum technology. In addition to future colliders are: antimatter physics, which requires very low gas density; radioactive-beam physics, which imposes severe controls on contamination and gas exhausting; and gravity-wave physics for which the tradeoff between cost and performance of vacuum systems is essential for the approval of next-generation observatories.

An orthogonal driver of innovation in vacuum technology is the reduction of costs and operational downtime of CERN's accelerators. Achieving ultra-high vacuum in a matter of a few hours at a reduced cost would also have an impact well beyond the high-energy physics community. This and other challenges involved in fundamental exploration are guaranteed to drive further advances in vacuum technology. ●

A COMPARISON

In the summer of 1960, the Courier compared and contrasted the 600 MeV Synchrocyclotron (CERN's first accelerator) and the 28 GeV Proton Synchrotron, which had accelerated its first protons the previous year. The vacuum system was one of several clear differences between these two early machines.

The two particle accelerators built at CERN for studying the structure of matter are called the synchro-cyclotron and the synchrotron. What similarity and what difference is there between these two machines? All accelerators have certain points in common: a source of particles to accelerate; a vacuum tank in which the particles can move without being slowed down too much by air molecules; and a target, internal or external. Like all accelerators, the CERN machines both use electrical phenomena for "pushing" the particles, and a magnetic field to keep them on an almost circular orbit. The synchro-cyclotron and the synchrotron are "circular accelerators" also called "orbital accelerators". The particles move along curved trajectories. In both CERN machines these particles are protons or nuclei of the hydrogen atom. By and large, the resemblance can be said to end here. There are basic differences in the design of the two machines and in the kinetic energy – or acceleration – which they can impart to the nuclear projectiles.



The inner sanctum of the synchro-cyclotron, the machine room.

The synchro-cyclotron

Derived from the cyclotron, which it resembles from outside, the synchro-cyclotron – or SC – gives the accelerated particles a curved trajectory. It forces them repeatedly to cross an accelerating electrode, called a "Dee" because of its shape. The particles are injected 54 times per second from a source in the middle of the vacuum tank. Each accelerating push increases the speed of the proton which, owing to centrifugal force, has a trajectory in the shape of a growing spiral.

The accelerating process lasts a few milliseconds, during which the particles make 150 000 turns in the vacuum tank, covering about 2500 km, and reach 80% of the velocity of light! When the pulsed proton beam reaches the energy at which it is used – a maximum of 600 MeV – i.e. at the circumference of the vacuum tank, there are two ways of using it. The proton beam can be extracted as it is and directed towards the experimental apparatus, or the beam may strike a target inside the vacuum tank; in this way, a source of secondary particles – neutrons or pi mesons – is created and they in turn are directed towards the experimental apparatus.

The photograph above shows the inner sanctum of the SC, the machine room, which no one may enter when the machine is operating.

There one can see the huge structure of the 2500-ton electro-magnet. Its horizontal yoke consists of 18 magnetic steel plates, 11 m long, 1.5 m high and 36 cm thick. The electro-magnet is excited by two enormous coils. One is clearly visible on the photograph: its aluminium cover can be seen shining at the top of the photograph. The other is placed symmetrically to it but is in the shadow and does not show up so clearly. Each of the coils weighs 55 tons, measures 7.2 m in diameter and consists of 9 pancakes of aluminium conductors measuring 19 cm² in cross section. There is a 3 cm² hole in the centre of the conductor for the circulation of 30 000 litres/hour of demineralized cooling water. This is necessary as the exciting current is 1750 amperes d.c. at 400 volts. It was a considerable undertaking to bring these two coils from the factory where they were made in Belgium, by barge up the Rhine and on a special trailer through Switzerland.

The magnetic field set up by the electro-magnet is constant: 18 500 gauss. For the sake of comparison the magnetic field of the earth is 1 gauss, the strongest field which the best anti-magnetic watches can stand is 1000 gauss. The 18 500 gauss field is applied across the vacuum tank between the 5 m diameter poles of the electromagnet – which were forged at Rotterdam and machined at Le Creusot. It "focuses" the accelerated particles on their spiral orbit in the vacuum tank.

The vacuum tank, in which the protons turn, has a cubic

This article was adapted from text in *CERN Courier* vol. 1, September 1960, pp6–8

Comparison between the CERN accelerators

	SC (Synchro-cyclotron)	PS (Synchrotron)
Basic data		
● particles accelerated	protons	protons
● maximum kinetic energy	600 MeV	28 000 MeV
● ion source situated	in the middle of the vacuum tank	on the input side of a linear accelerator
● cost	24 million Swiss Frs	120 million Swiss Frs
Magnets and excitation		
● magnetic field (gauss)	constant : 18 500	variable between 147 and 14 000
● weight of magnet	1 x 2500 t	100 x 28.7 t
● weight of exciting coils	2 x 55 t	100 x 1.2 t
● maximum power supplied the magnet	700 kW	32 000 kW
● magnet gap	45 cm	10 cm
Accelerating radio-frequency		
● system	a Dee	16 cavities
● frequency in Mc/s	decreasing from 29.3 to 16.4	increasing from 2.9 to 9.55
● energy increase per turn	4 keV	54 keV
● number of turns	150 000	450 000
● velocity of particles at maximum energy (as a percentage of the velocity of light)	80 %	99.94 %
● pulse repetition rate	54 per second	1 per 3 seconds (at 25 GeV) or 1 per 5 seconds (at 28 GeV)
● duration of accelerating cycle	9 milliseconds	1 second
Vacuum system		
● vacuum tank	cubic 23 m³	toroidal cross section 14 x 7 cm, length 628 m
● wall thickness	up to 60 mm	2 mm
● material	stainless steel	stainless steel
● pumps	2	66 + 5
● acceptable vacuum	10^{-5} mm Hg	10^{-5} mm Hg

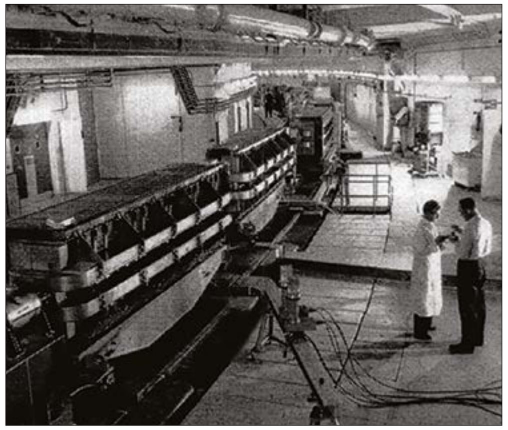
capacity of 23 m³ and its stainless steel walls are 60 mm thick. The vacuum in this tank is better than 10^{-5} mm of mercury, in other words the pressure is 76 million times less than that of the earth's atmosphere. This vacuum is created and maintained by two large vacuum pumps, one of which is clearly visible in the foreground of the photograph.

The radio-frequency system generates the alternating electric field which accelerates the particles. The frequency decreases from 29.3 to 16.4 Mc/s (millions of cycles per second) as the velocity and mass of the particles increase. The most spectacular part of the system is perhaps the modulator in the shape of a tuning fork, 0.5 m long and 2 m wide, housed in the bulge in the vacuum tank which can be seen to the left of the pump.

The concrete building in which the SC operates is intended to stop radiation. The walls which box in the SC are up to 5.8 m thick and are fitted with two 200-ton doors, which slide slowly into position to block the entrances. The total weight of concrete – standard or with baryte added – is 22 000 tons.

The cost of the synchro-cyclotron? About twenty-four million Swiss francs, including the buildings. The staff in charge of maintenance, operation and technical development, totals 26, excluding the experimental physicists.

What place does the SC occupy in the world of accelerators? Out of the 18 synchro-cyclotrons now operating, the CERN SC comes third in respect of energy (600 MeV), after the 730 MeV SC at Berkeley in California and the 680 MeV machine at Dubna, in Russia.



The tunnel – the 200 m diameter ring – in which the synchrotron is installed.

The synchrotron

The synchrotron looks quite different from the SC. It is as extensive as the SC is massive and squat.

The PS also curves the trajectory of the particles it accelerates, but the fixed radius of curvature is about 100 m. The protons go through 16 accelerating units, placed at intervals round the 628 m circumference. They are generally injected into the big accelerator's vacuum tank, once every three seconds, after having gone through a pre-accelerator and a linear accelerator. When they enter the 200 m diameter ring, the particles already have an initial kinetic energy of 50 million electronvolts (MeV). Every time the protons pass through one of the 16 accelerating cavities, their velocity is increased, while a growing magnetic field keeps their trajectory on an orbit of constant radius.

In the PS the acceleration process lasts one second. During this time the particles make some 450 000 turns in the vacuum tank, covering about 300 000 km and reaching 99.94% of the velocity of light.

Once maximum energy – 25 or 28 thousand million electronvolts (GeV) – has been reached, the bunches of particles strike a target in the vacuum tank itself. This produces secondary beams of particles and antiparticles. In 1961, it will be possible to extract the primary proton beam and make use of it; at present, only a small proportion of the protons scattered by the nuclei of the target cross the wall of the vacuum tank and can be used as a high energy proton beam for experiments.

The photograph at the top of the page was taken in the tunnel – the 200 m diameter ring in which the synchrotron is installed. Of course, nobody is allowed in the ring when the machine is operating, because of the radiation danger.

The electro-magnet consists of 100 separate units placed right round the circumference. Each unit weighs 28.7 tons net and consists of ten C-shaped blocks made up of laminations 1.5 mm thick. Each of the 100 units is excited by two coils placed longitudinally on the pole pieces of the units. Each coil consists of two pancakes, each with 5 windings of aluminium conductor 21 cm² in cross-section; this conductor is hollow to let cooling water through since the current can reach 6400 amperes at 5400 volts.

The magnetic field produced varies from 147 gauss when the particles are injected into the synchrotron to 12 000 or 14 000 gauss when they have been fully accelerated. The magnetic field is applied across the vacuum tank, a long elliptical tube with a cross-section of 14 × 7 cm, curving round the 628 m circumference of the machine between the poles of the 100 magnet units. The walls of the tank are made of stainless steel, in order to be unaffected by the magnetic field and are only 2 mm thick. A vacuum better than 10^{-5} mm of mercury is maintained in the tank by 66 pumps on the outer edge of the ring and 5 others in the injection system.

In each accelerating cavity, the radio-frequency system creates the alternating electric field which accelerates the protons. As we have seen in the SC, the applied radio-frequency has to decrease in order to keep in step with particles which take more and more time to go round as the orbit expands; in the PS, on the other hand, the orbit is constant and the ever-increasing velocity of the particles calls for an increase in frequency from 2.9 to 9.55 M c/s.

The ring-shaped concrete building which contains the PS is buried underground as an additional protection against gamma and fast neutron radiation: the 40 cm of concrete walls are covered with more than 3 m of earth and stones.

There are no gigantic doors here as in the SC: a zigzag passage is used to stop radiation, while giving access to the machine when it is not operating. When it is in operation, a whole network of electric connections would stop the accelerator if anyone, regardless of the danger, tried to gain access to it by forcing one of the locked doors. The level of radio-activity is probably more intense between the two experimental halls – north and south – because of the presence of the targets. There the ceiling of the funnel is made of 2 m of special baryte concrete with a density of 3.5 t/m³. There is a series of movable blocks in the walls so that openings can be made as required for admitting the beams into the experimental halls.

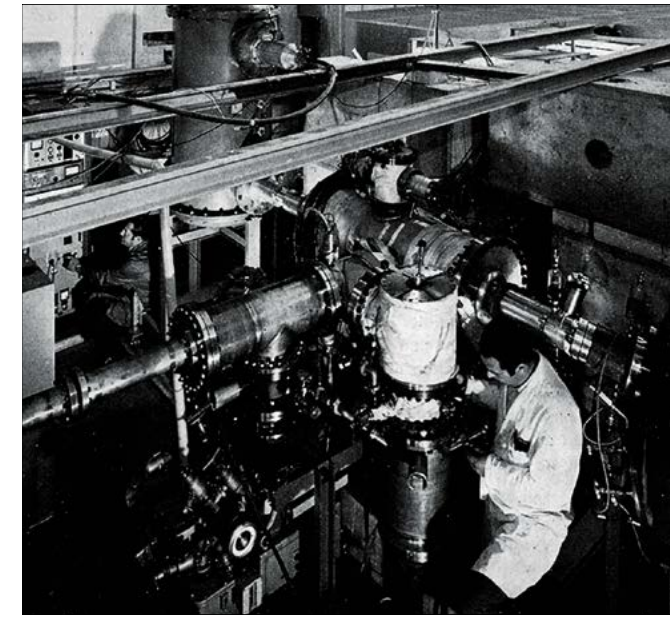
The synchrotron cost 120 million Swiss francs: ten cigarettes for each of the 220 million inhabitants of CERN's twelve Member States.

The "Machine Group" in charge of exploiting and developing the PS is a team of 139. The actual running of the machine needs ten operators.

As for the position of the PS with respect to other accelerators, the CERN synchrotron comes second in the world with 28 GeV, after the 31 GeV synchrotron commissioned at Brookhaven on 30 July. ●

HIGH VOLTAGE IN VACUUM

This article from July 1969, written by the leader of the Electromagnetism Studies and Applications group, F. Rohrbach, covered the research carried out at CERN and elsewhere on the subject and future of very high voltage in vacuum.



Vacuum cavity constructed at CERN as part of a programme to study high voltage in vacuum. This cavity has, among other things, shown the importance of cleanliness in high voltage phenomena, and made it possible to measure the breakdown delay time during pulsing, and to attempt to detect the micro-particles which could cause the sparking.

Whether it be in accelerators (accelerating columns, electrostatic inflectors, r.f. cavities or fast ejection units), secondary beams (separators and deflectors) or detectors (all types of spark chamber), the technological problems to be solved often centre around the insulation or switching of high voltages. In the case of insulation, attempts are made to minimize leakage currents, to eliminate flashover, to increase electric field gradients, or to lengthen the useful life and operational reliability. In the case of electrical breakdown, the salient factors are certain features of the arc such as jitter, rise time, lifetime, etc. for spark gaps; and brilliance, plasma size, memory, etc. for spark chambers and especially streamer chambers.

Over the past ten years, a great deal of work has been done, particularly in the USA and the USSR, on the insulation of high voltage in vacuum and on the physics of arcs, because of the rapid development of novel applications for high voltages – including X-ray flash tubes (operating at several MeV), circuit breakers, very high voltage electron microscopy (MV range), and equipment used in plasma physics and in high energy physics. Vacua, and even ultra high vacua, are involved in most of these new applications.

In 1964, the Massachusetts Institute of Technology, together with the University of Illinois and industry (the Ion Physics Corporation and the High Voltage Engineering Company), organized the first International Symposium on High Voltage Insulation in Vacuo. Currently these symposia take place every two years and are attended by delegates from all over the world. An international committee, on which CERN is represented, has been set up.

Since 1961, CERN has devoted special attention to this subject by stimulating applied research in connection with the development of electrostatic separators (see for example CERN COURIER vol. 9, page 132) and accelerating columns.

This article was adapted from text in *CERN Courier* vol. 9, July 1969, pp208–210

Technical developments with d.c. voltages

In spite of some spectacular fundamental discoveries concerning the physics involved, and some notable technological advances, the theory of breakdown in vacuum at very high voltage has still to be formulated. The most important technological advances, in which CERN has often played a pioneering role, include:

- Considerable improvements in voltage holding by abandoning stainless steel for the cathode in favour of heated glass (Berkeley), aluminium oxide (CERN) or titanium (CERN).
- Discovery of the marked effect of pressure and of the nature of the residual gas between 10^{-5} and 10^{-3} torr on behaviour under voltage and on operating life (many Laboratories including CERN).
- Discovery of the importance of the cleanliness of the surfaces subjected to powerful electric fields leading to the use of ultra high vacuum techniques (CERN).

The progress in the last ten years with homogeneous fields using large electrodes of the order of a square metre has made it possible to pass from 55–60 kV/cm over 5 cm and 40–50 kV/cm over 10 cm in 1960, to 150–160 kV/cm over 5 cm and 100–110 kV/cm over 10 cm in 1969. Nevertheless this is still far from the theoretical limit set by the field emission – 100 000 kV/cm!

The state of the theory

The large difference between the values obtained and the theoretical limit can now be explained. Though no new results have been published for some years on technical aspects, there have been some fundamental discoveries throwing new light on the mechanisms at the origin of an electric arc in vacuum. It has been found that there is high local amplification of the electric field at microscopic points which appear on metal surfaces under the action of intense fields. The heights of these points vary between a few tenths and several hundreds of microns. They can occur at either the anode or the cathode, but exactly how they are produced is still completely unknown.

There have been some fundamental discoveries throwing new light on the mechanisms at the origin of an electric arc in vacuum

It is now believed that there are several mechanisms which give rise to breakdown, the predominant one depending on parameters such as distance, voltage, residual pressure and the surface state of the electrodes. There are essentially two major regimes:

1. Short gaps between electrodes (less than a few millimetres) in a uniform field, or strong electric fields which are non-uniform (point-plane geometry);

2. Large gaps (more than a few millimetres) and very high voltages (more than a few hundred kV).

1. In the first regime, breakdown follows local heating either at the cathode due to field emission at the points which mysteriously develop, or at the anode by electron bombardment. The heating causes serious vaporization when current densities reach critical values between 10^7 and 10^8 A/cm^2. The metal vapour thus produced is then rapidly ionized by cold emission electrons, leading to the final breakdown within a period varying from a few nanoseconds to a few hundred nanoseconds.

As the breakdown threshold is closely related to a critical current, and thus to a field, the characteristic breakdown voltage V_s as a function of the gap d between the electrodes should be linear. Also, the law of the variation of current with field should follow the predictions of field emission theory. These results have been confirmed over the past few years up to distances of a few millimetres between electrodes in a uniform, d.c, pulsed or high frequency field. The improvements in behaviour under pulsed voltage that can possibly be gained in this case are very small, when the time for which the voltage is applied is longer than a few tens of nanoseconds.

2. At CERN, with only a few exceptions, most of the applications of high voltage in vacuum are in the second regime which it had been difficult to study in University research laboratories because of the cost involved. Theoretical studies, in conjunction with experiments, were undertaken at CERN and have led to several new experimental observations and the elaboration of a model of the discharge phenomena.

When voltages are increased beyond a few hundred kV, the behaviour of the breakdown voltage threshold as a function of the different parameters changes completely. The characteristic V_s as a function of d is no longer linear but proportional to the square root of d. The residual pressure is of considerable importance (which is not so with short distances) and the threshold V_s is no longer determined by a critical current – the current before breakdown varies by several orders of magnitude when the distance varies only by a factor of two or three. Finally, and this is a fundamental point, the average time-lag to breakdown lengthens considerably – in the range of microseconds to several milliseconds.

These characteristics can be explained by the 'micro-particle' hypothesis. The mechanism leading to breakdown could then be described as the following: a collection of atoms is torn away from the anode as a result of the application of the field and electron bombardment. This micro-particle, electrically charged, is accelerated by the field between the electrodes and strikes the cathode with a velocity v and an energy W. If v and W are higher than critical values v_c and W_c, the energy dissipated at the moment of striking is high enough, and remains within the interaction volume for long enough, to give rise to intense vaporization. Breakdown can then take place inside the bubble of gas thus formed. It can be shown by the double condition W greater than W_c and v greater than v_c that the characteristic V_s as a function of d is then indeed of the square root form and that the minimum time lag T min is such that In T min is linear with V^2.

Application of the theory to pulsed voltages

For high voltages (MV) and large distances (cm) in ultra high vacua (10~^{9} to 1CT^8 torr), present investigations at CERN show that, in fact, the mechanism involved in initiating a breakdown takes a considerable time (jis to ms) to develop and that these times are statistically distributed in such a way that T min is proportional to V^2. Because of these results, obtained with stainless steel and titanium electrodes, it would be possible to increase the strength of electric fields in vacuum very appreciably for all applications where the field is needed for only a short time (a maximum of several microseconds), which is often the case around large particle accelerators. The advantages obtained would allow the present values of d.c. fields to be doubled for times of the order of a few microseconds and distances between electrodes greater than a centimetre.

Future possibilities

Such an increase in the intensity of electric fields would allow further steps forward in the use of high energy particle separators and fast deflectors. Other conceivable applications include strong field accelerating lines in electron ring accelerators, coaxial beam guides, electromagnetic lenses, etc.

In all these applications, the new technical problem which arises is that of generating voltage pulses of several

MV with very steep leading edges (less than 10 ns). The duration of the pulse depends on the application in view (from 10 ns to a few lis). A Marx generator in conjunction with a Blumlein line can be used for very short pulses as is already done for the Stanford 600 kV streamer chamber (see CERN COURIER vol. 7, page 219). The most delicate problems are those involved in striking the main spark-gap in the Blumlein line with a very low jitter (ns), since this spark-gap must operate at 2 MV with an impedance of 30 ohms. There are thoughts of using a ruby laser, a multiple-electrode spark-gap or perhaps a liquid dielectric spark-gap. A rise time of 50 to 100 ns would be adequate for pulses lasting several mircroseconds, in which case the Blumlein line would not be needed.

In an application of the deflector or separator type, the beam element can be included in the load on the Blumlein line. Profit could then be drawn from having the magnetic field in phase with the electric field, and a TEM (transverse electromagnetic) wave is then set up. There are two advantages:

1. If the particles are sent into the equipment in the same direction as that of the propagation of the wave, the unit is an electromagnetic separator – a velocity selector with automatic magnetic compensation (with chromatic aberrations reduced to a minimum).

2. If the particles are sent in the opposite direction to the TEM wave, then the electric and magnetic deflections are added together and an electromagnetic deflector is formed. In view of the present technical results, deflectors can be made with 450 to 500 kV/cm (1 MV over 2 cm), or the equivalent of 3 kG. Thus the same piece of equipment can serve either as a deflector or as a separator.

The main potential of high electric field electromagnetic separators lies in the field of the separation of low-energy (a few hundred MeV) kaon beams for bubble chambers. It is possible in these cases to reduce the length of the separator considerably while retaining the same angle of separation, and thus to have particle beams with a short decay length (0.75 m for 100 MeV charged kaons).

The refined technology which has been developed to obtain very high voltage pulses and to overcome the complex problems in striking a spark-gap operating at several MV, allow one to think of building streamer chambers with very high gaps (of the order of a metre) using such high voltages. It is probably in this direction that interest in pulsed high voltages will be concentrated, because the advantages offered by such chambers are so attractive that physicists will almost certainly want them built. Finally, it is interesting to note that many other laboratories and commercial firms are particularly interested in the work currently being done at CERN in the field of high voltages. These laboratories and firms include those working in such varied fields as emitters, the transmission of electric power, circuit breakers, rectifiers, colour television, etc... ●

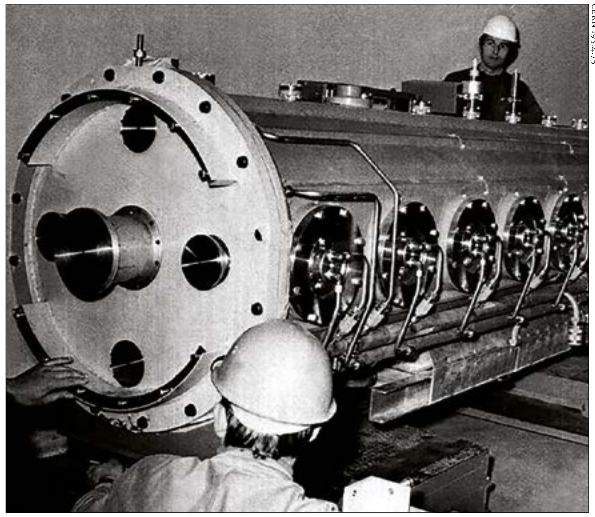
Many other laboratories and commercial firms are particularly interested in the work currently being done at CERN in the field of high voltages

400 GEV MACHINE VACUUM AND R.F. PROGRESS

With construction of the Super Proton Synchrotron – known simply as the "400 GeV machine" – in full swing, the May 1975 issue of the Courier published a progress report on its vacuum and radio-frequency systems.

CERN 150.3.75

The vacuum chamber straddling a straight section of the 400 GeV synchrotron. A length of 970 m of the vacuum system has now been pumped down and is at 1×10^{-8} torr. An ion pump can be seen hanging below the chamber at the centre of the straight section.



CERN 193.4.75

On 17 April two of the five sections of an r.f. accelerating cavity descended to the tunnel of the 400 GeV proton synchrotron. These sections are being used to check couplers, the vacuum system and the co-axial line which links the cavity in the tunnel to its power supply in the equipment building on the surface.

Things are obviously hotting up in the construction of the 400 GeV proton synchrotron, the SPS. With completion of the ring not much more than a year away, there is new information every month concerning the progress of installation. This time the vacuum system and the radio-frequency acceleration system have passed two important milestones.

Assembly and testing on the vacuum chamber and the pumping stations in the SPS tunnel began last November and the work has continued at about the rate at which the magnets have been installed – 32 m per day, equivalent to one half-period. By now a tenth of the full system, including beam transfer lines, has been evacuated and held under vacuum for a month.

At the beginning of February, a 550 m length of the vacuum chamber in sextant 3 was pumped down. The pressure was taken to the region of 10^{-5} torr by three roughing pump stations fitted with vane and turbo-molecular pumps. At this stage, the control computer in auxiliary building No. 3 brought in forty-one ion pumps with a capacity of 25 l/s, distributed along the length of the vacuum pipe.

The time involved in reducing the pressure from atmospheric to the nominal operating pressure of the SPS – 3×10^{-7} torr – in this first pump down, was sixteen hours. A pressure of 1×10^{-7} torr was reached in forty-five hours.

It was then necessary to open up the chamber. The second pump down gave the nominal pressure after only five hours. In March, a further 420 m section was pumped with the same success. After a month under vacuum, this 970 m length is at 1×10^{-8} torr.

Two sections of one of the r.f. accelerating cavities have now been installed in the SPS tunnel and have successfully

This article was adapted from text in *CERN Courier* vol. 15, May 1975, pp156–158

Excavation work for the North Experimental Area of the SPS began in April. In the photograph a bulldozer and two scrapers are in action, against the background of the Jura mountains, removing the top soil from an area of 8 hectares.

undergone vacuum tests. Each cavity is some 20 m long with five tank sections and the machine will have two cavities located in straight section No. 3.

The five sections for the first cavity are now at CERN. Some work has to be carried out on them before they are taken down to the tunnel – the trickiest job being the fitting of the drift tubes. There are eleven in each section and they have to be aligned with great precision. Allowance must be made for any irregularity in the shape of the tank and the length of the drift tube bars has to be adjusted before they are welded and brazed to the mounting blocks which make contact with the tank walls.

The coaxial lines and couplers which feed the power to the cavities in the tunnel are already in place. The lines, some 80 m long, go up to the power amplifiers in auxiliary building No. 3. Cooling pipes are also installed as are the terminating loads which absorb the r.f. power once it has passed through the cavities.

All that remains to be done in the tunnel is to install and connect up the tank sections. They must be aligned very accurately so that the intermediate seals remain completely vacuum-tight and allow the cavity's 500 kW of r.f. power at 200 MHz to be properly conducted all the way around the tank. The sections rest on special supports which are designed to absorb any distortion caused by temperature rise in the cavities during operation.

The last three sections of the first cavity will be taken down to the tunnel at the rate of one every three weeks and the cavity will be completed towards the middle of June. The second cavity will be installed in Autumn. ●

UHV Design advances bellows-free drive for critical beamline applications at CERN

Spring-loaded magnetically-coupled device provides a fail-safe solution that could reduce unscheduled downtime due to loss of ultra-high vacuum.

Compact, bellows-free actuator.

Innovative design

A customer enquiry for a linear power probe – a magnetically-coupled actuator that can operate remotely in vacuum – has led to a new fail-safe design that could improve the operability of beamlines around the world.

"CERN explained that they were looking for a product that would avoid using bellows", says Jonty Eyres, engineering director at UHV Design. The UK-based firm specializes in the design, manufacture and supply of motion and heating products specified for use in high- and ultra-high vacuum conditions.

"Bellows-sealed devices have been the go-to space for moving things in and out in a clean manner and with minimal outgassing", Eyres explains. Depending on the type of bellows used, and their application, their service life can reportedly range from 10 000 up to as many as 2 million actuations. But they won't last forever. And when they fail it can lead to an unexpected loss of vacuum and costly delays.

The challenge for Eyres and his colleagues was to come up with a solution that reproduced the clean operation of a bellows-sealed device, but in a fail-safe manner.

Over the past 20 years, the firm has developed considerable expertise in magnetically-coupled devices. Their bellows-free approach features an arrangement of magnets located inside and outside a rigid tubular vacuum envelope. Moving the magnetic housing on the outside advances and retracts an actuation shaft held centrally inside the device.

The team used specialized software to optimize both the magnetic coupling between the inside and the outside, and the screening of the device.

Online meetings allowed the client – in this case CERN – to voice the product criteria that were important to them. "We used the sessions to discover their feedback, the pros and cons and where we think the scope is in terms of performance", Eyres explains.

"Once we are confident in a prototype, the next stage is to put it on a vacuum rig and start running rigorous tests on performance and precision", says Eyres.

This includes carrying out residual gas analysis using a mass quadrupole device to examine how the mechanism affects the vacuum pressure. A major benefit of the firm's design is that there are no bellows to fail. But instead the team has to contend with moving parts in vacuum.

The engineers tackled this by keeping the contact areas to a minimum and using rolling parts, not sliding parts, to limit any pressure rise during operation. Preserving ultra-high vacuum conditions is critical.

Designed for cleanliness

But having rolling contacts isn't the end of the story. In addition, the materials combination must be inert to prevent the mechanism from bonding or sticking over time. And the requirement for absolute cleanliness means that all of the bearings have to be designed to operate without lubrication.

The company's solution was to use silicon nitride (a hard ceramic) ball races that pressed against two extremely tough shafts made out of tungsten carbide. This arrangement keeps the internal push-rod centrally supported, paving the way for precise movement into and out of the beamline. Furthermore, external constant force springs retract the in vacuum mechanism should any failure occur in the pneumatics driving the unit. In this fail-safe position, the linear actuator has no effect on the beam.

A system of flexures ensures that no undue stresses are placed on any of the critical parts during bake out as they expand at different rates according to their composition.

The firm's bellows-free solution brings together creative design, smart materials selection and precision operation. Now that the linear drive is in its final prototype phase the team is working towards fulfilling multiple orders from CERN for what will be a bolt-on solution pre-wired with all of the necessary cables and switches.

"Every beamline in the world needs beam diagnostics," Eyres comments. "And off the back of this project we're ready to work with more clients who are also looking to move away from bellows in critical areas."

For more information, visit **www.uhvdesign.com/products/push-pull-devices**

UHVD

Web www.uhvdesign.com
Email sales@uhvdesign.com

MAX IV PAVES THE WAY FOR ULTIMATE X-RAY MICROSCOPE

Writing in the September 2016 issue, Mikael Eriksson of Maxlab and Dieter Einfeld of the ESRF described the extreme vacuum technology and other challenges in building Sweden's MAX IV light source.

Since the discovery of X-rays by Wilhelm Röntgen more than a century ago, researchers have striven to produce smaller and more intense X-ray beams. With a wavelength similar to interatomic spacings, X-rays have proved to be an invaluable tool for probing the microstructure of materials. But a higher spectral power density (or brilliance) enables a deeper study of the structural, physical and chemical properties of materials, in addition to studies of their dynamics and atomic composition.

For the first few decades following Röntgen's discovery, the brilliance of X-rays remained fairly constant due to technical limitations of X-ray tubes. Significant improvements came with rotating-anode sources, in which the heat generated by electrons striking an anode could be distributed over a larger area. But it was the advent of particle accelerators in the mid-1900s that gave birth to modern X-ray science. A relativistic electron beam traversing a circular storage ring emits X-rays in a tangential direction. First observed in 1947 by researchers at General Electric in the US, such synchrotron radiation has taken X-ray science into new territory by providing smaller and more intense beams.

Perry Nordeng

The newly completed MAX IV facility near Lund, Sweden.

Generation game

First-generation synchrotron X-ray sources were accelerators built for high-energy physics experiments, which were used "parasitically" by the nascent synchrotron X-ray community. As this community started to grow, stimulated by the increased flux and brilliance at storage rings, the need for dedicated X-ray sources with different electron-beam characteristics resulted in several second-generation X-ray sources. As with previous machines, however, the source of the X-rays was the bending magnets of the storage ring.

The advent of special "insertion devices" led to present-day third-generation storage rings – the first being the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, and the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory in Berkeley, California, which began operation in the early 1990s. Instead of using only the bending magnets as X-ray emitters, third-generation storage rings have straight sections that allow periodic magnet structures called undulators and wigglers to be introduced. These devices consist of rows of short magnets with alternating field directions so that the net beam deflection cancels out. Undulators can house 100 or so permanent short magnets, each emitting X-rays in the same direction, which boosts the intensity of the emitted X-rays by two orders of magnitude. Furthermore, interference effects between the emitting magnets can concentrate X-rays of a given energy by another two orders of magnitude.

This article was adapted from text in *CERN Courier* vol. 56, September 2016, pp38–44

Third-generation light sources have been a major success story, thanks in part to the development of excellent modelling tools that allow accelerator physicists to produce precise lattice designs. Today, there are around 50 third-generation light sources worldwide, with a total number of users in the region of 50,000. Each offers a number of X-ray beamlines (up to 40 at the largest facilities) that fan out from the storage ring: X-rays pass through a series of focusing and other elements before being focused on a sample positioned at the end station, with the longest beamlines (measuring 150 m or more) at the largest light sources able to generate X-ray spot sizes a few tens of nanometres in diameter. Facilities typically operate around the clock, during which teams of users spend anywhere between a few hours to a few days undertaking experimental shifts, before returning to their home institutes with the data.

Although the corresponding storage-ring technology for third-generation light sources has been regarded as mature, a revolutionary new lattice design has led to another step up in brightness. The MAX IV facility at Maxlab in Lund, Sweden, which was inaugurated in June, is the first such facility to demonstrate the new lattice. Six years in construction, the facility has demanded numerous cutting-edge technologies – including vacuum systems developed in conjunction with CERN – to become the most brilliant source of X-rays in the world.

The multi-bend achromat

Initial ideas for the MAX IV project started at the end of the 20th century. Although the flagship of the Maxlab laboratory, the low-budget MAX II storage ring, was one of the first third-generation synchrotron radiation sources, it was soon outcompeted by several larger and more powerful sources entering operation. Something had to be done to maintain Maxlab's accelerator programme.

The dominant magnetic lattice at third-generation light sources consists of double-bend achromats (DBAs), which have been around since the 1970s. A typical storage ring contains 10–30 achromats, each consisting of two dipole magnets and a number of magnet lenses: quadrupoles for focusing and sextupoles for chromaticity correction (at MAX IV we also added octupoles to compensate for amplitude-dependent tune shifts). The achromats are flanked by straight sections housing the insertion devices, and the dimensions of the electron beam in these sections is minimised by adjusting the dispersion of the beam (which describes the dependence of an electron's transverse position on its energy) to zero. Other storage-ring improvements, for example faster correction of the beam orbit, have also helped to boost the brightness of modern synchrotrons. The key quantity underpinning these advances is the electron-beam emittance, which is defined as the product of the electron-beam size and its divergence.

Despite such improvements, however, today's third-generation storage rings have a typical electron-beam emittance of between 2–5 nm rad, which is several hundred times larger than the diffraction limit of the X-ray beam itself. This is the point at which the size and spread of the electron beam approaches the diffraction properties of

X-rays, similar to the Abbe diffraction limit for visible light. Models of machine lattices with even smaller electron-beam emittances predict instabilities and/or short beam lifetimes that make the goal of reaching the diffraction limit at hard X-ray energies very distant.

Although it had been known for a long time that a larger number of bends decreases the emittance (and therefore increases the brilliance) of storage rings, in the early 1990s, one of the present authors (DE) and others recognised that this could be achieved by incorporating a higher number of bends into the achromats. Such a multi-bend achromat (MBA) guides electrons around corners more smoothly, therefore decreasing the degradation in horizontal emittance. A few synchrotrons already employ triple-bend achromats, and the design has also been used in several particle-physics machines, including PETRA at DESY, PEP at SLAC and LEP at CERN, proving that a storage ring with an energy of a few GeV produces a very low emittance. To avoid prohibitively large machines, however, the MBA demands much smaller magnets than are currently employed at third-generation synchrotrons.

In 1995, our calculations showed that a seven-bend achromat could yield an emittance of 0.4 nm rad for a 400 m-circumference machine – 10 times lower than the ESRF's value at the time. The accelerator community also considered a six-bend achromat for the Swiss Light Source and a five-bend achromat for a Canadian light source, but the small number of achromats in these lattices meant that it was difficult to make significant progress towards a diffraction-limited source. One of us (ME) took the seven-bend achromat idea and turned it into a real engineering proposal for the design of MAX IV. But the design then went through a number of evolutions. In 2002, the first layout of a potential new source was presented: a 277 m-circumference, seven-bend lattice that would reach an emittance of 1 nm rad for a 3 GeV electron beam. By 2008, we had settled on an improved design: a 520 m-circumference, seven-bend lattice with an emittance of 0.31 nm rad, which will be reduced by a factor of two once the storage ring is fully equipped with undulators. This is more or less the design of the final MAX IV storage ring.

In total, the team at Maxlab spent almost a decade finding ways to keep the lattice circumference at a value that was financially realistic, and even constructed a 36 m-circumference storage ring called MAX III to develop the necessary compact magnet technology. There were tens of problems that we had to overcome. Also, because the electron density was so high, we had to elongate the electron bunches by a factor of four by using a second radio-frequency (RF) cavity system.

Block concept

MAX IV stands out in that it contains two storage rings operated at an energy of 1.5 and 3 GeV. Due to the different energies of each, and because the rings share an injector and other infrastructure, high-quality undulator radiation can be produced over a wide spectral range with a marginal additional cost. The storage rings are fed electrons by a 3 GeV S-band linac made up of 18 accelerator units, each comprising one SLAC Energy Doubler RF station. To optimise the economy over a potential three-decade-long operation lifetime, and also to favour redundancy, a low accelerating gradient is used.

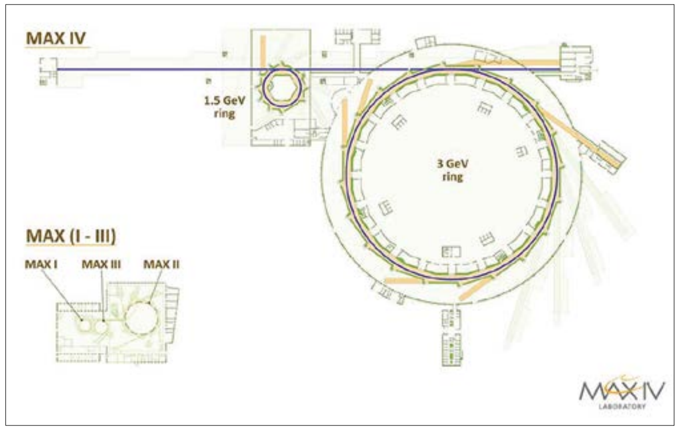

Johan Bävman

An undulator at MAX IV, which generates intense synchrotron X-rays as electrons pass through a periodic magnetic structure.

The 1.5 GeV ring at MAX IV consists of 12 DBAs, each comprising one solid-steel block that houses all the DBA magnets (bends and lenses). The idea of the magnet-block concept, which is also used in the 3 GeV ring, has several advantages. First, it enables the magnets to be machined with high precision and be aligned with a tolerance of less than 10 μm without having to invest in aligning laboratories. Second, blocks with a handful of individual magnets come wired and plumbed direct from the delivering company, and no special girders are needed because the magnet blocks are rigidly self-supporting. Last, the magnet-block concept is a low-cost solution.

We also needed to build a different vacuum system, because the small vacuum tube dimensions (2 cm in diameter) yield a very poor vacuum conductance. Rather than try to implement closely spaced pumps in such a compact geometry, our solution was to build 100% NEG-coated vacuum systems in the achromats. NEG (non-evaporable getter) technology, which was pioneered at CERN and other laboratories, uses metallic surface sorption to achieve extreme vacuum conditions. The construction of the MAX IV vacuum system raised some interesting challenges, but fortunately CERN had already developed the NEG coating technology to perfection. We therefore entered a collaboration that saw CERN coat the most intricate parts of the system, and licences were granted to companies who manufactured the bulk of the vacuum system. Later, vacuum specialists from the Budker Institute in Novosibirsk, Russia, mounted the linac and 3 GeV-ring vacuum systems.

Due to the small beam size and high beam current, intra beam scattering and "Touschek" lifetime effects must also be addressed. Both are due to a high electron density at small-emittance/high-current rings in which electrons are brought into collisions with themselves. Large energy changes among the electrons bring some of them outside



The MAX IV 3 GeV ring, which has a diameter of 168 m, compared to previous machines at Sweden's Max lab facility.

of the energy acceptance of the ring, while smaller energy deviations cause the beam size to increase too much. For these reasons, a low-frequency (100 MHz) RF system with bunch-elongating harmonic cavities was introduced to decrease the electron density and stabilise the beam. This RF system also allows powerful commercial solid-state FM-transmitters to be used as RF sources.

When we first presented the plans for the radical MAX IV storage ring in around 2005, people working at other light sources thought we were crazy. The new lattice promised a factor of 10–100 increase in brightness over existing facilities at the time, offering users unprecedented spatial resolutions and taking storage rings within reach of the diffraction limit. Construction of MAX IV began in 2010 and commissioning began in August 2014, with regular user operation scheduled for early 2017.

On 25 August 2015, an amazed accelerator staff sat looking at the beam-position monitor read-outs at MAX IV's 3 GeV ring. With just the calculated magnetic settings plugged in, and the precisely CNC-machined magnet blocks, each containing a handful of integrated magnets, the beam went around turn after turn with proper behaviour. For the 3 GeV ring, a number of problems remained to be solved. These included dynamic issues – such as betatron tunes, dispersion, chromaticity and emittance – in addition to more trivial technical problems such as sparking RF cavities and faulty power supplies.

As of MAX IV's inauguration on 21 June, the injector linac and the 3 GeV ring are operational, with the linac also delivering X-rays to the Short Pulse Facility. A circulating current of 180 mA can be stored in the 3 GeV ring with a lifetime of around 10 h, and we have verified the design emittance with a value in the region of 300 pm rad. Beamline commissioning is also well under way, with some 14 beamlines under construction and a goal to increase that number to more than 20.

It was the advent of particle accelerators in the mid-1900s that gave birth to modern X-ray science

Sweden has a well-established synchrotron-radiation user community, although around half of MAX IV users will come from other countries. A variety of disciplines and techniques are represented nationally, which must be mirrored by MAX IV's beamline portfolio. Detailed discussions between universities, industry and the MAX IV laboratory therefore take place prior to any major beamline decisions. The high brilliance of the MAX IV 3 GeV ring and the temporal characteristics of the Short Pulse Facility are a prerequisite for the most advanced beamlines, with imaging being one promising application.

Towards the diffraction limit

MAX IV could not have reached its goals without a dedicated staff and help from other institutes. As CERN has helped us with the intricate NEG-coated vacuum system, and the Budker Institute with the installation of the linac and ring vacuum systems, the brand new Solaris light source in Krakow, Poland (which is an exact copy of the MAX IV 1.5 GeV ring) has helped with operations, and many other labs have offered advice. The MAX IV facility has also been marked out for its environmental credentials: its energy consumption is reduced by the use of high-efficiency RF amplifiers and small magnets that have a low power consumption. Even the water-cooling system of MAX IV transfers heat energy to the nearby city of Lund to warm houses.

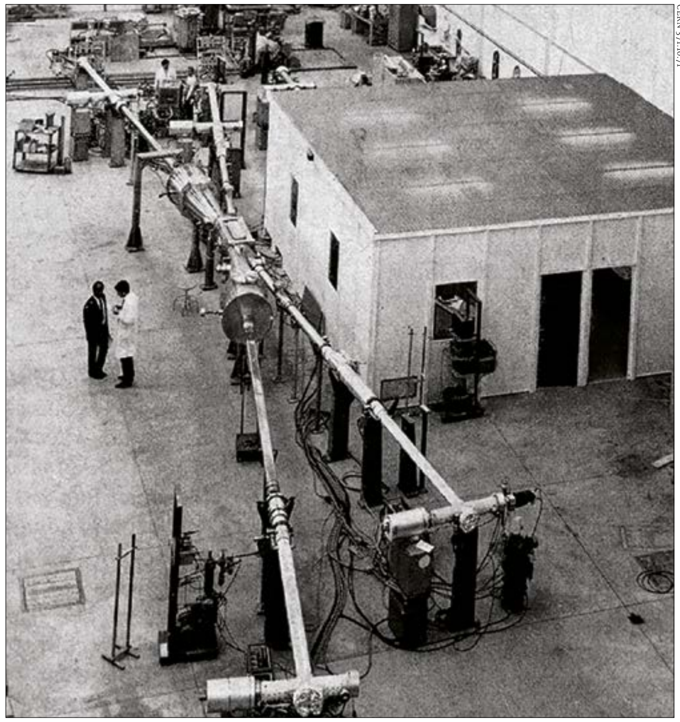
The MAX IV ring is the first of the MBA kind, but several MBA rings are now in construction at other facilities, including the ESRF, Sirius in Brazil and the Advanced Photon Source (APS) at Argonne National Laboratory in the US. The ESRF is developing a hybrid MBA lattice that would enter operation in 2019 and achieve a horizontal emittance of 0.15 nm rad. The APS has decided to pursue a similar design that could enter operation by the end of the decade and, being larger than the ESRF, the APS can strive for an even lower emittance of around 0.07 nm rad. Meanwhile, the ALS in California is moving towards a conceptual design report, and Spring-8 in Japan is pursuing a hybrid MBA that will enter operation on a similar timescale.

Indeed, a total of some 10 rings are currently in construction or planned. We can therefore look forward to a new generation of synchrotron storage rings with very high transverse-coherent X-rays. We will then have witnessed an increase of 13–14 orders of magnitude in the brightness of synchrotron X-ray sources in a period of seven decades, and put the diffraction limit at high X-ray energies firmly within reach.

One proposal would see such a diffraction-limited X-ray source installed in the 6.3 km-circumference tunnel that once housed the Tevatron collider at Fermilab, Chicago. Perhaps a more plausible scenario is PETRA IV at DESY in Hamburg, Germany. Currently the PETRA III ring is one of the brightest in the world, but this upgrade (if it is funded) could result in a 0.007 nm rad (7 pm rad) emittance or even lower. Storage rings will then have reached the diffraction limit at an X-ray wavelength of 1 Å. This is the Holy Grail of X-ray science, providing the highest resolution and signal-to-noise ratio possible, in addition to the lowest-radiation damage and the fastest data collection. Such an X-ray microscope will allow the study of ultrafast chemical reactions and other processes, taking us to the next chapter in synchrotron X-ray science. ●

MUCH ADO ABOUT NOTHING

In November 1972, CERN's Roger Calder described in detail the unprecedented vacuum system of the world's first hadron collider, the Intersecting Storage Rings.



The special vacuum chamber prepared for intersection region 1–6 undergoing tests in the West Experimental Hall. Note the conical form of the two downstream sections of the chamber. Thin walls at the ends of the cones enable particles produced in the interactions to escape to the detectors almost without hindrance.

The vacuum system of the CERN Intersecting Storage Rings differs from those of typical particle accelerators in one vital respect: the pressure has to be four to five orders of magnitude lower. This requirement can be readily understood in terms of the time ratio the particles spend circulating (of the order of one second in an accelerator and, typically, one day in the ISR). It would be an exaggeration to say that the problem of attaining this vacuum was more difficult in the same ratio but it was considerably more difficult and involved many basically different techniques. Some of these were known on a small scale from the laboratory, others had to be developed.

A major triumph of the ISR vacuum system has been the successful marrying of many hitherto specialised laboratory techniques into one very large and very complex system without loss in reliability or performance. It is still not unusual to find ultra-high vacuum laboratories which have difficulty in working at 10^{-11} torr – in the ISR there are hundreds of metres at this pressure and soon it is expected to extend to the full 2 kilometres of the rings.

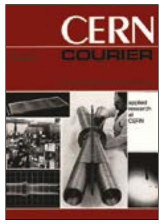
This article will try to sketch some of the problems encountered in meeting the requirements of the vacuum system and how the applied research in this field led to their solution.

Sources of gas

The pressure in a vacuum system, in the simplest analysis, is given by the balance between the residual gas inflow rate and the exhaust rate. The latter, determined by the size and speed of the vacuum pumps, is limited by available space and cost. The former is the sum of several sources including leaks from the surrounding atmosphere, desorption of gas which has been adsorbed on the interior surface of the vacuum chamber and the permeation of gas through the chamber material itself.

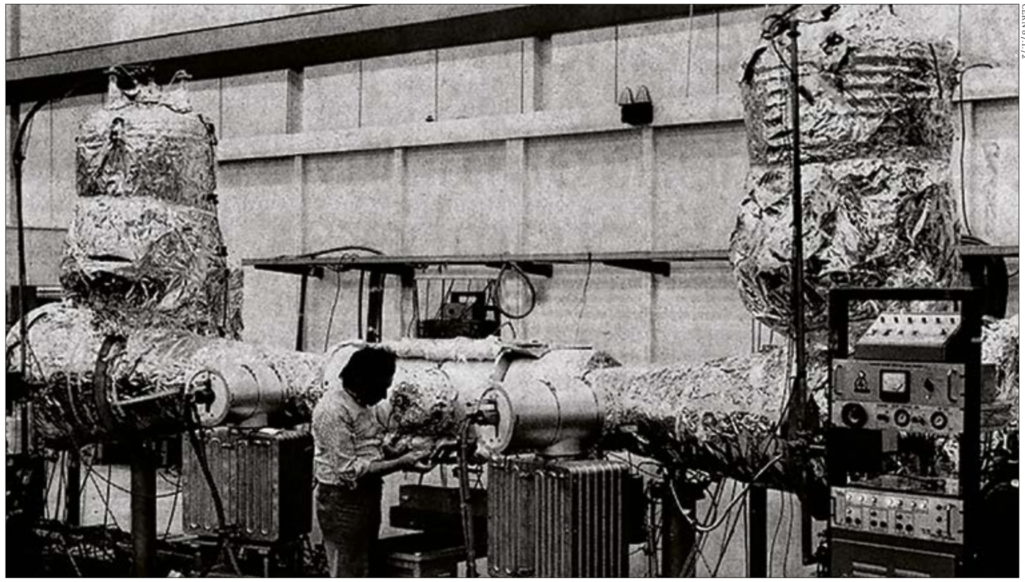
Assuming that all leaks have been eliminated – in itself not a trivial problem since these may range from leaky joints to microscopic pores via slag inclusions in the chamber material – and that surface desorption has been reduced to a negligible value by in situ bakeout of the vacuum system at 300 °C, there is left what perhaps appears the negligible possibility of gas permeating through the metal chambers. In fact, this constitutes the major limitation in a vacuum system such as the ISR where the available pumping speed is severely restricted by the low conductance of the chamber.

The chamber material is a nitrogen enriched austenitic stainless steel chosen on the basis of mechanical strength, low permeability, good vacuum properties, etc. Careful measurements showed that this material, even after an in situ bakeout at 300 °C, was releasing hydrogen gas at the rate of about 3.10^{-12} torr litre per second per cm^2 (equivalent to about 10^8 hydrogen molecules per second per cm^2). The measurements also showed that this hydrogen appeared to be diffusing out of the bulk of the material (rather than desorbing from the surface) and the constancy of the rate over long times suggested a virtually infinite reservoir of hydrogen. This was confirmed by chemical analysis which showed the hydrogen impurity to be about 0.001% or 10^{19}



This article was adapted from text in *CERN Courier* vol. 12, November 1972, pp359–362

The same chamber installed in the storage rings with two cryopumps (the vertical, foil-covered cylinders). With the cryopumps it has been possible to take the pressure in the intersection region down to the 10^{-13} torr range.



molecules per cm^3 of steel.

This outgassing rate would have caused unacceptably large pressures in the beam pipe between pumping stations – pressures which could not be reduced by larger pumps but only by reducing the outgassing rate by one to two orders of magnitude. Laboratory measurements showed that the diffusion rate, and hence the outgassing rate, was very temperature dependent. This suggested a way of removing the source of hydrogen – the steel was subjected to a heat treatment of about 1000 °C in a vacuum furnace before being used. At this temperature the hydrogen release is so fast that the concentration of dissolved hydrogen falls rapidly to a value determined by the partial pressure in the vacuum furnace. In this way it was possible to obtain the tons of stainless steel with special low outgassing rates which were needed for the ultra-high vacuum system of the ISR.

Cryopumping for even lower pressure

In addition to the ultra-high vacuum requirement of 10^{-10} to 10^{-11} torr all around the ISR rings, dictated essentially by beam life-time considerations, the experimenters would like the intersection regions with pressures in the 10^{-12} torr range or better. Such low pressures reduce the ratio of the background signals due to proton–gas molecule collisions compared to the true proton–proton collisions. Pressures even into the 10^{-13} torr range have been obtained, notably in intersection region 1–6, using cryopumping techniques.

In a cryopumped intersection region a surface is cooled to a low temperature and acts as a trap to 'solidify' any gas molecule which strikes it. The speed of the pump depends on the area of the cooled surface (12 l/s and 45 l/s per cm^2 of surface are possible pumping rates for nitrogen and hydrogen respectively) and the pressure limit depends on the temperature of the surface and the gas (lower temperatures are needed the lower the boiling point of the gas).

Hydrogen, as described above, is the major gas load in the ISR; unfortunately it is the most difficult gas to condense apart from helium. The theoretical low pressure limit of a cryopump is given by the saturated vapour pressure of the gas being condensed at the temperature of the pumping surface. For hydrogen this is still about 10^{-6} torr at 4.2 K (a convenient refrigeration temperature using liquid helium as coolant) but it should fall to an extrapolated value of 10^{-13} torr at 2.5 K. In practice, however, it proved impossible to condense hydrogen to pressures below about 10^{-10} torr, independently of what temperature was used. This anomaly was traced to an interaction between the (black body) thermal radiation coming from the vacuum chambers at room temperature and the condensed hydrogen layer – the latter being continually desorbed by this thermal bombardment. The interaction is not one of simple heating but depends in a complex way on the thickness and purity of the condensed layer and on the characteristics of the cold substrate carrying the condensed layer.

Although it was possible to operate a liquid helium cooled cryopump down to 10^{-13} torr in the laboratory even when exposed to thermal radiation by modifying the substrate (e.g. by the precondensation of an inert gas layer of argon or neon) a more practical solution has been developed and used in the ISR. This involves using optically and almost thermally opaque chevron baffles at 77 K which are optimised for molecular transmission. This is a compromise involving a considerable loss of conductance, and hence pumping speed, to the vacuum chamber. The pump and baffles are thus designed to achieve a given pressure and then dimensioned to give the required pumping speed. Two liquid helium cooled cryopumps have been installed in 1–6. Each has a speed of about 15 000 l/s and a limit pressure of about 2.10^{-13} torr. They have operated for several months in the upper 10^{-13} torr range.

Measuring very low pressures

An advance in one technique often exposes a weakness in another. It was noticed that laboratory systems, designed to extend knowledge of very low pressures, frequently appeared to be limited at about 1 to 2.10^{-12} torr. Nearly all very low pressure gauges use a tungsten filament heated to about 2300 °C to provide a source of ionising electrons. The apparent limit pressures were traced to an artefact introduced by the gauge itself – the vapour pressure of tungsten evaporated from the heated tungsten filament. Operating the filament at a carefully chosen and reduced temperature can extend the useful range of the gauge by almost an order of magnitude.

The hot tungsten filament is at the root of another problem. It produces heating in the surrounding vacuum chamber causing an increase of hydrogen desorption and a real increase of the system pressure. Recent development work has shown that it will be possible to construct an extremely sensitive gauge using the high gain of an integral channel electron multiplier. The gauge should be useful down to 10^{-15} torr and, since it uses an extremely low ionising current of a few nanoamperes, it will produce practically no heating or disturbance to the vacuum system.

Beam induced vacuum problems

'Pressure bumps' in the ISR have been in the news before (see vol. 11, page 245). They are the major obstacle to achieving the design stored beams of 20 A and the design luminosity. They are localised regions of about 10 m in which the pressure, normally stable at about 10^{-10} torr in the absence of the beam, begins to rise when the stacked proton beam current exceeds a certain value. Pressure bumps may occur anywhere around either ring at one or several points simultaneously. The mechanism is one of gas release from the wall of the vacuum chamber under ion bombardment. The ions, formed by the ionising effect of the proton beam on the 10^{-10} torr of residual gas, are ejected out of the space charge potential of the beam onto the wall with an energy of about 1 keV. The released gas increases the local pressure and thus gives, in turn, more ions. Hence we have the makings of an avalanche effect and the pressure may stabilise at some higher value or increase without limit until it destroys the stacked beam.

The danger is obviously greatest where the residual pressure is greatest, where the pumping speed is lowest or where the vacuum chamber wall is contaminated and there is a large gas yield per incident ion. It is now clear that, even after the elaborate cleaning and degassing procedures, the vacuum chamber is not as clean as was thought. On the basis of thermally induced desorption, it had been concluded that hydrogen dissolved in the metal is the only source of gas. But now it is apparent that the surface is covered with a layer of strongly adsorbed contaminants (H_2, H_2O, CO, CO_2, CH_4, hydrocarbons etc.) which are only released under energetic ion bombardment.

During the initial operation of the ISR the critical current for run-away pressure bumps was about 4 A. At that time the 10^{-10} torr operating pressure was achieved after an in situ bakeout of about 4 hours at 200 °C. Since then the temperature has been raised to 300 °C and the bakeout time lengthened to about 24 hours – the critical currents have climbed to 10 to 12 A. The normal operating pressure is still about 10^{-10} torr but clearly the surfaces now appear much cleaner under ion bombardment.

Why stop there? Because many components of the ISR were designed for a maximum bakeout temperature of 300 °C, and further increase of the bakeout times at constant temperature seems to give practically no advantage. Other parameters have to be attacked – those of residual pressure and pumping speed. All the intersection regions were initially equipped with titanium sublimation pumps in addition to the normal sputter-ion pumps, which are the standard pumping element around the ISR. Pressures at the intersections were typically around 2.10^{-11} torr and the 'pressure bump' phenomenon rarely occurred in these regions.

A vacuum improvement programme is therefore under way to equip the whole of the ISR with additional sublimation pumps. They are installed in eleven of the 24 sectors which operate regularly at 2.10^{-11} torr. Pressure bumps in the unimproved sectors still limit the performance but there are high hopes of reaching the design current early next year when the whole vacuum system is improved and running at 2.10^{-11} torr.

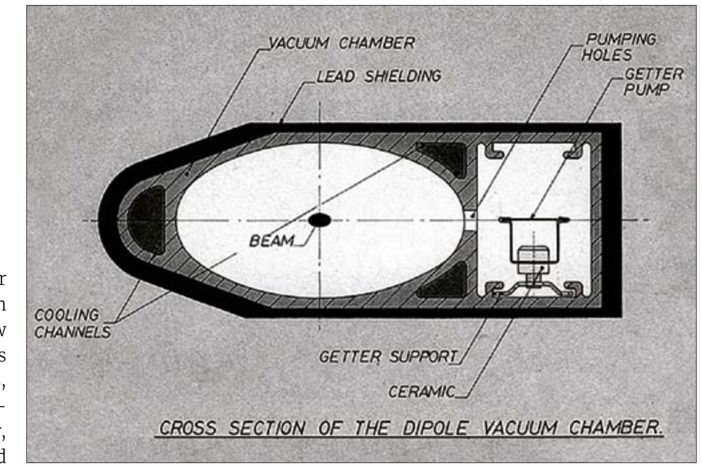
In the meantime extensive laboratory investigations are under way to find ways of eliminating surface contamination. The most promising approach at the moment seems to be to simulate and accelerate the ion-induced desorption by running a high pressure (10^{-2} torr) inert gas discharge in the vacuum chamber. Subsequent gas release rates on test samples have been reduced by two or even three orders of magnitude by this technique. But there is a technical problem – how to propagate and control a gas discharge around 2 kilometres of ISR vacuum chamber. At the same time, more sophisticated cleaning and bakeout techniques, new surface treatments or even the possibility of a new chamber of an altogether different material is under study.

Possibly the most important achievement of the ISR vacuum system is the extremely high reliability of many apparently commonplace components

The results of applied research in the fields of materials science, low temperature physics, ultra-high vacuum technology and engineering have helped to create in the ISR the largest ultra-high vacuum system ever built. Exciting specialised techniques, such as cryopumping at 2.5 K have been integrated with everyday nuts and bolts in their thousands. Possibly the most important achievement of the ISR vacuum system is the extremely high reliability of many apparently commonplace components – there are over 10 000 demountable flanges, for example, which must all be leak-tight simultaneously. This reliability is the result of careful and thorough applied research. There are still problems – such as the pressure bumps but, to (mis-) quote from the Shakespeare play which gave us our title, 'Think not on it till tomorrow: we'll devise thee brave punishments for it'. ●

HIGH VACUUM

While the 27 km tunnel for the LEP electron–positron collider at CERN was being prepared for commissioning of the machine the following year, the Courier *described non-evaporable getters and other technologies used for its vacuum system.*



Cross-section of the vacuum chamber for the 27 km LEP electron–positron ring being constructed at CERN. Such big high vacuum systems provide a challenge for industry.

Particles circulating in a particle accelerator near the speed of light cover enormous distances. In synchrotrons, where beams are only held for a few seconds at the most, the tube containing the particles has to be evacuated down to at least 10^{-6} mbar. In storage rings, where the particles have to circulate for hours and sometimes days, pressures need to be taken down still further, to about 10^{-12} mbar, to minimize beam-gas collisions and maximize machine output.

The development of light bulbs and electronic tubes earlier this century provided the first big boost to vacuum technology, and further impetus came in the 1950s where the development of the first big particle accelerators and of space simulation chambers called for industrial participation in both prototype development and actual construction.

In this work, the need for 'clean' vacuum free of hydrocarbons pushed the performance of oil and mercury diffusion pumps. Later, the more exacting demands of storage rings led to a swing to turbomolecular and sputter ion pumps. The first major series of turbopumps from Pfeiffer (Germany) was installed in CERN's PS proton synchrotron and ISR Intersecting Storage Rings, while sputter ion pumps, requiring little maintenance, with no moving parts and with almost infinite lifetime, have become the preferred pump for the high reliability large systems needed for particle physics.

Ion pumps initially had difficulties both at high pressures and in handling chemically inert gases (helium, argon, etc.) but continuous 'pressure' from the accelerator sector led to improved performance, such as in the Leybold (Germany) differential diode developed for CERN's SPS Super Proton Synchrotron and the Varian (Italy) Starcell triode ion pump, developed from the stringent rare gas pumping specifications for the 27 km LEP storage ring at CERN.

Particle accelerators underlined the importance of surface cleanliness in reducing desorption. Pioneering work at the ISR on the famous 'pressure bump instability' led to increased understanding of particle-surface interactions, and the curing techniques have benefited other vacuum applications (plasma fusion devices, thin film technology, microelectronics,...).

Experience from particle physics has also stressed the importance of 'outgassing' from the myriad of materials in contact with the vacuum system. Now a wide range of materials (stainless steel, ceramics, ferrites, aluminium, alloys, plastics,...) has been specially studied for high vacuum applications, while in situ bakeout at high temperatures is standard practice.

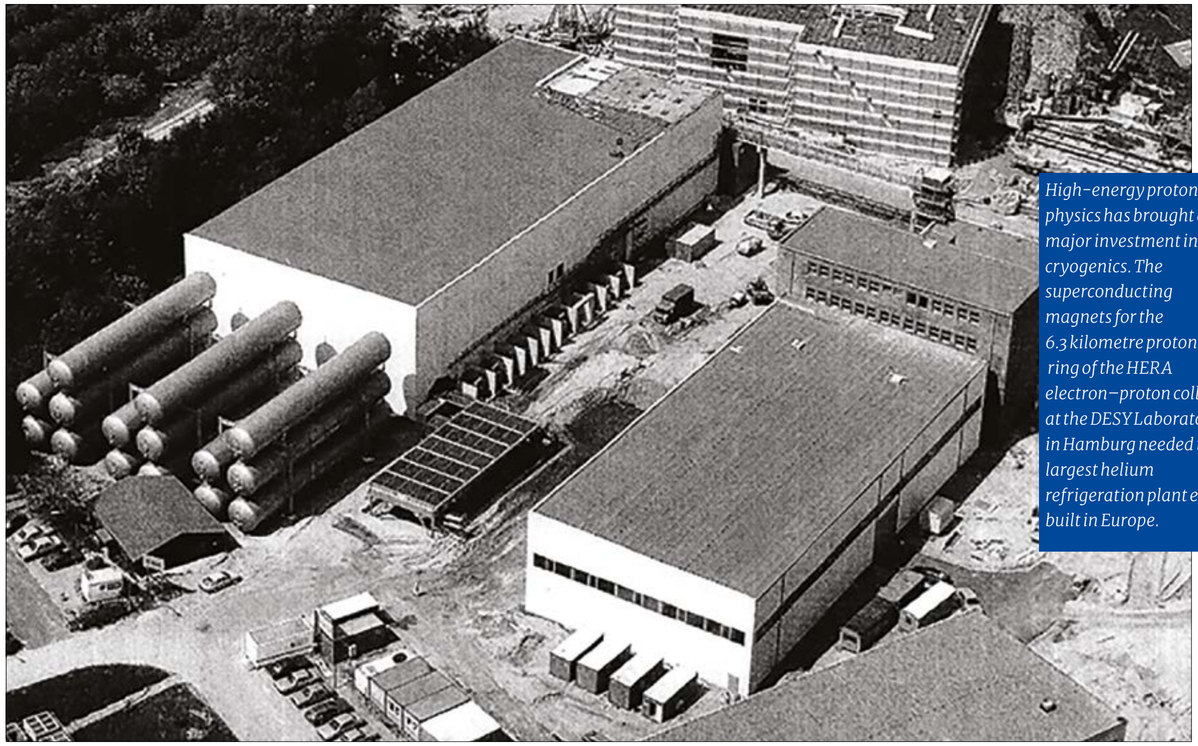
A special problem in accelerators, typically using a narrow but very long vacuum pipe, is that of conductance – ensuring a uniform vacuum with grouped pumping systems. One approach is to reduce the space between pumps, or even have one long continuous pump.

For LEP, a non-evaporable getter (NEG) pump was designed in close collaboration with industry (SAES Getters, Italy). Although getters had been used for 30 years to evacuate lamps and electronic tubes, the 27 km LEP tube provided a new challenge.

Built to handle protons, CERN's seven kilometre SPS proton synchrotron faced new problems when called on to store antiprotons in CERN's antiproton project, launched ten years ago. Flashed titanium sublimation getter pumps for the SPS and for the AC and LEAR antiproton rings were designed to meet CERN specifications (Vacuum Generators, UK, and Balzers, Switzerland), and improvements to such sublimators have gone on to be available commercially from industry.

Physics demands for high reliability and efficiency have also brought in their wake much new vacuum hardware (seals, flanges, joints, all-metal valves, etc.). ●

This article was adapted from text in *CERN Courier* vol. 28, November 1988, pp15–17



High-energy proton physics has brought a major investment in cryogenics. The superconducting magnets for the 6.3 kilometre proton ring of the HERA electron–proton collider at the DESY Laboratory in Hamburg needed the largest helium refrigeration plant ever built in Europe.

TECHNOLOGICAL SPINOFFS FROM ACCELERATORS

The May 1994 issue of the Courier*, continuing a theme that year on the applications arising from fundamental physics, featured an article by Oscar Barbalat about the industrial benefits of particle accelerators.*

Accelerator technologies

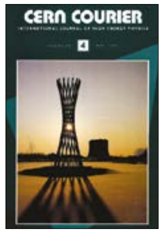
Particle-accelerator performance depends critically on the underlying technology. Thus the construction of larger, more powerful and more sophisticated accelerators has resulted in technological progress, yielding applications in other areas.

The basic particle accelerator technologies are electrical and radiofrequency engineering, for the powerful electric and magnetic fields needed respectively to accelerate the particles and control the beams.

Superconductivity, with its suppression of ohmic losses, makes the generation of these fields more efficient. With present superconducting materials requiring extremely low temperatures, cryogenics has also become a key accelerator technology.

Beams also need a high vacuum to minimize unwanted collisions. Mechanical engineering appears in the design of nearly every component, while another essential ingredient is the particle source.

Finally, accelerators have led to the development of a variety of monitoring and controlling techniques, both for their construction (high-precision surveying) and for their operation.



This article was adapted from text in *CERN Courier* vol. 34, May 1994, pp6–10.

Superconductivity

Large-scale applications of superconductivity have been pioneered by particle accelerator engineers. Improved accelerator performance needed increased magnetic fields and electric fields while keeping the energy consumption within acceptable limits.

This has stimulated the development of superconducting dipole and quadrupole magnets and of superconducting radiofrequency accelerating cavities. The first super-conducting cables (for bubble chambers and nuclear magnetic resonance – NMR – spectrometers) were capable only of d.c. operation. Accelerator requirements seeded the development of superconducting cables for a.c. operation, at the heart of all major ongoing applications. These cables are made of intrinsically stable conductors, twisted thin strands of superconducting wires embedded in a copper matrix and suitable for ramped fields.

The implementation of a fusion reactor, either based on magnetic or inertial confinement, will probably rely on superconductivity. In the case of magnetic confinement, a net energy gain can only be achieved if the confining magnetic field does not require excessive power. Furthermore, the high magnetic fields permitted by superconductivity may allow the design of more compact machines. ITER, the future large international research tokamak, will be designed around superconducting magnets.

Research on inertial confinement fusion explores several ways of imploding the fuel pellet. Particle beam fusion systems are based on ideas resulting directly from particle physics research, while the most promising laser system, the free electron laser, also derives from particle accelerator technology.

The output of electric power generators has grown considerably in recent decades, performance also having been boosted by improved cooling, allowing higher current densities. However this also produces a rise in ohmic losses and a corresponding reduction in efficiency, prompting a closer look at superconductivity.

Transmission of electric power is another possible application of superconductivity. The prospect of replacing the vast electrical highways feeding large cities by underground superconducting cables is an attractive proposition. Successful tests of a twin-conductor 60 Hz 115 m-long flexible cable transporting triple-phase 1000 MVA at Brookhaven National Laboratory in the 1970s have opened the way to longer transmission lines. Increased environmental consciousness will strongly encourage the development of compact underground power lines.

Another potentially far-reaching application of superconductivity in power engineering is the large scale storage of electricity. Large coal-fired and nuclear power plants are designed to operate close to full capacity. Their efficiency and expected lifetime is decreased significantly if they have to suppress large fractions of their capacity. On the other hand electricity demand has large seasonal, weekly and daily variations. A variety of technologies, ranging from gas turbines to pumped hydroelectricity, are currently used to handle these variations. Reducing unwanted gas emission and the difficulty of finding suitable hydrostorage sites would make new techniques such as SMES (Superconducting Magnetic Energy Storage) attractive.

One of its main advantages is that energy is stored in its electrical form and requires no intermediate conversion from or into thermal or kinetic energy. Reference systems for 5 GVA have been designed in the US and Japan. The feasibility of the concept has successfully been tested in a 30 MJ system installed in 1982 to stabilize the electric power transmission between the Pacific Northwest and Southern California.

High speed ground transportation could also become a large scale application of superconductivity. Prototypes have been demonstrated in Germany and Japan. A 10 ton Japanese test vehicle, using levitation from eddy currents created by an electromagnet moving above a conducting rail, has exceeded 500 km/h. Superconducting coils fulfil the three functions of suspension, guiding and propelling the vehicle.

Research on the application of superconducting magnetic coils for marine propulsion is also underway in Japan and a prototype boat has recently been tested successfully.

Another industrial application of superconductivity is magnetic separation for mineral and scrap metal processing – requiring high magnetic forces over large volumes.

Eddy currents induced by superconducting magnets could slow convection currents during the crystallization process of silicon for semiconductor production. This would lead to more homogeneous crystals and open up the manufacture of larger single chip devices.

Another avenue worth exploring is ultra-fast computers based on the rapid switching of Josephson diodes.

Superconducting magnets are used all over the world for the characterization and identification of chemical compounds by nuclear magnetic resonance spectroscopy. While some 10 years ago typical systems used magnets in the 5 Tesla range, commercial devices now use magnets operating near 10 Tesla, with correspondingly increased performance.

The construction of CERN's Large Electron–Positron collider has further stimulated progress in vacuum technology

Superconductivity is also finding applications in medical diagnosis through magnetic resonance imaging scanners, less invasive than classical X-ray diagnosis. Again, performance improvements would follow from higher field magnets.

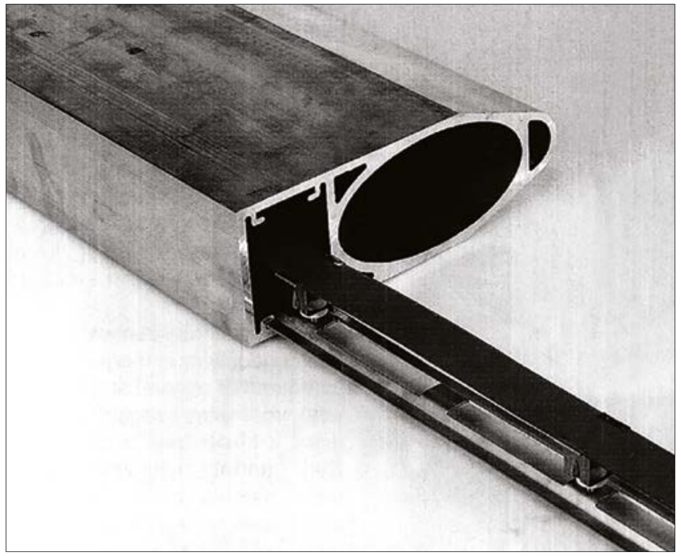
The high temperature superconductors discovered only a few years ago have not yet found their way into accelerator technology as they can neither be made into high density current-carrying cables for magnet coils nor deposited on large surfaces for radiofrequency cavities. However, this rapidly developing field is being closely monitored. Any materials breakthrough would open the way to wider applications.

Cryogenics

Cryogenics, the technique of low temperature, goes hand in hand with superconductivity. Classical superconductors operate at a few degrees K, provided by liquid helium cooling. Physicists had become familiar with large-scale low temperature work through the liquid hydrogen bubble chamber, one of the most widely used detectors of the 1960s and early 70s.

Most superconducting magnets now use niobium-titanium wire and operate at temperatures close to 4.2 K, the boiling point of helium. At this temperature, the field achievable with NbTi is limited to about 6.5 Tesla.

In the quest for higher magnetic fields, superconductors with better magnetic properties, such as niobium-tin, are troublesomely brittle. For its next accelerator project,



The construction of CERN's LEP electron–positron collider has pushed vacuum technology. The problems of evacuating a 27-kilometre ring led to the development of a linear non-evaporable getter (NEG) pump using an aluminium–zirconium alloy bonded in powder form on a constantan ribbon, seen here alongside a piece of LEP vacuum chamber.

the LHC proton collider, CERN thus prefers to exploit the improved NbTi performance at lower temperatures (2 K).

Such temperatures offer attractive features: liquid helium becomes superfluid, with an enormous increase in thermal conductivity and reduction of viscosity and much practical payoff.

Cryogenics is applied in other fields, for instance in vacuum and space science and for sensitive instrumentation such as low noise amplifiers and infra-red night vision devices.

The NMR superconducting magnets used both in the laboratory and for medical diagnostics employ cryogenics technology developed for accelerator magnets. What used to be delicate, fragile and complex systems requiring continuous attention have today become a reliable technology.

Another cryogenics outlet is the production through liquefaction of extremely pure gases, useful in any industrial processes (e.g. in the semiconductor industry) requiring extreme cleanliness or purity.

Vacuum and surface science

Particle acceleration requires a good vacuum to avoid scattering the beam on residual gas. Pressures in the region of 10^{-6} – 10^{-7} Torr are generally sufficient for synchrotrons, where acceleration lasts only a few seconds. However storage rings and colliders which must hold beams over several days have more critical requirements, calling for the 10^{-10} – 10^{-11} Torr range. Even lower pressures are needed near the detectors to reduce background.

The valuable experience at CERN's Intersecting Storage Rings (ISR) brought considerable progress in this field. The ISR was the first large machine to be operated using the advanced technology of ultra-high vacuum systems (UHV), eventually reaching 10^{-12} Torr. This catalysed the vacuum industry to develop UHV components (e.g. sputter ion pumps, all-metal valves, seals, gauges).

Equally important for UHV systems is the cleanliness of all surfaces. Techniques for cleaning and preparing surfaces – chemical treatments, bakeout and glow discharge to reduce gas desorption – were developed.

The construction of CERN's Large Electron Positron collider (LEP) has further stimulated progress in vacuum technology. Although the vacuum level is less than the ISR, evacuating a 27-kilometre ring posed special problems. This led to the development of a linear non-evaporable getter (NEG) pump using an aluminium-zirconium alloy bonded in powder form on a constantan ribbon. Another development has been the all-aluminium vacuum chamber with better thermal conductivity and lower residual radioactivity than stainless steel and which can be extruded into complicated shapes.

Other vacuum components have been developed following accelerator experience, particularly where mechanical motion under vacuum is needed. As pressure falls, lubrication is inhibited and friction increases dramatically. Ingenious solutions had to be found for fast closing valves, beam diagnostic devices or shutters and movable sensing electrodes and deflectors.

Vacuum seals have also undergone considerable improvements. Elastomers can sustain neither high radiation nor bakeout at 300–400C, and metal joints have now generally been introduced.

This progress in vacuum technology is finding direct applications in space science and fusion test facilities, and in industry, for example in the technologies for semiconductor manufacture.

Even when extremely low pressures are not required, for example in surgery, the pharmaceuticals industry or in food preparation and conservation, the extreme cleanliness of UHV systems and their reliability have brought benefits. Cleanliness and special surface conditions are essential for quality and performance in many high technology areas. Vacuum and surface technology therefore play an increasingly important role.

Particle sources

Accelerators require intense sources of electrons and ions. An important application of such sources is the implantation of ions for semiconductor circuit elements. Ion beams are also used in material preparation such as pre-deposition surface cleaning/conditioning and low energy Ion Beam Assisted Deposition (IBAD). IBAD films have remarkable properties (adhesion, hardness, optical transmission,...). Another important industrial application is the electron beam technique used for precision welding.

Finally the classic applications example is the range of electron tubes used for telecommunications, broadcasting and radar which derive from the cathode-ray tube protoaccelerator devices developed at the turn of the century for basic physics research. ●

MOLECULAR STICKY TAPE

The 1998 EPS-IGA prize for outstanding work in the accelerator field was awarded to CERN's Cris Benvenuti for "major breakthroughs in achieving ultra-high vacua in storage rings using the NEG system, and for the development of niobium coatings of superconducting radio-frequency cavities in LEP".

Getters are materials with a strong affinity for gases which molecules stick to like fluff to sticky tape. At CERN's Large Electron-Positron collider, LEP, getters provide ultra-high vacuum. Now a new thin-film alloy developed at CERN promises even better vacuum, and could also spell good news for avid television watchers.

Since the advent of particle storage rings, high-energy physics and vacuum technology have advanced hand-in-hand. Storage rings demand high vacuum so particle beams are not lost through collisions with stray gas molecules, and getter pumps are commonly used. The most widely used getters in accelerators work by heating a titanium filament causing sublimation, the direct conversion of titanium metal to gas. This gas is then deposited on the surrounding vacuum vessel where it traps stray gas molecules in the vacuum chamber.

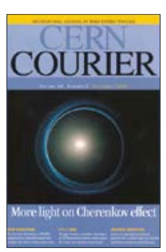
These so-called sublimation pumps provide a localized pumping action, whereas particle accelerators require distributed pumping. In the 1970s Cris Benvenuti addressed this problem by developing a new way of using getters for CERN's LEP. The accelerator's main pumping system is provided by linear strips of non-evaporable getters, NEGs, which cover 23 kilometres of the accelerator's 27 kilometre ring. They are made of a zirconium-aluminium alloy which is activated by heating to 750 °C. Instead of sublimating the gettering material, heating gives the oxygen enough energy to diffuse into the bulk material, leaving a clean surface to trap any residual gas inside LEP's beam pipe.

In LEP, vacuum is established by sealing the accelerator's vacuum chamber, heating to around 150 °C to remove any residual water vapour – the so-called "bake-out", and pumping with conventional suction pumps. Baking out at 750 °C is not possible, however, because it would damage the vacuum chamber. A gettering material which could be activated at a lower temperature would obviate the need for electrical heating, and thus the need for electrical insulation from the beam pipe.

In the 1970s, the world's foremost manufacturer of getters, SAES Getters in Milan, developed a gettering material which is activated at 400 °C. This is now widely used in steel vacuum systems which can withstand a high bake-out temperature. In particle accelerators, however, lighter materials are often required. LEP's vacuum chamber, for example, is made of aluminium and 200 °C is the bake-out limit. Another technology brought to fruition by Benvenuti's team has provided a way forward. The cavities which pump energy into LEP's beams rely on superconducting niobium. Early cavities are made of solid niobium, but since only a thin layer is needed, Benvenuti's team set to work on techniques to coat copper cavities with niobium to the high degree of uniformity required. Their work has resulted in over 90% of the accelerator's superconducting cavities being made from niobium-coated copper, whilst only 20 are made from solid niobium.

Left to right: Sergio Tazzari, Chairman of the European Physical Society's Interdivisional Group on Accelerators (EPS-IGA); Søren Pape Møller of Aarhus, awarded the EPS-IGA prize for a young physicist or engineer; Cris Benvenuti of CERN, awarded the EPS-IGA prize for outstanding work in the accelerator field; Werner Joho, Chairman of the Prize Selection Committee.

With Benvenuti's long association with vacuum, it was not long before his team turned its thin-film experience to the gettering question. Three years of development have resulted in two patents and a zirconium-vanadium-titanium alloy, discovered earlier this year, which is fully activated after 24 hours at 200 °C, low enough for any vacuum chamber's bake-out. Moreover, this new alloy can be used as a thin-film coating of the vacuum chamber walls which gives the added bonus of effectively eliminating or strongly suppressing out-gassing from the underlying vacuum chamber. CERN's next major accelerator project, the Large Hadron Collider, is currently evaluating the new alloy with a view to using it in certain sections of the accelerator. So what of that good news for television fans? Flat-screen displays are a much-touted new technology, but they have yet to make a significant impact on the market. Liquid-crystal displays are currently the most common, but they are expensive. An alternative technology is field-emission displays, FEDs. These work by using a single field-emission diode to illuminate each pixel of the screen, and they require ultra-high vacuum to work. Benvenuti's zirconium-vanadium titanium alloy could be just the ticket. ●



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