

IN FOCUS
MAGNETS

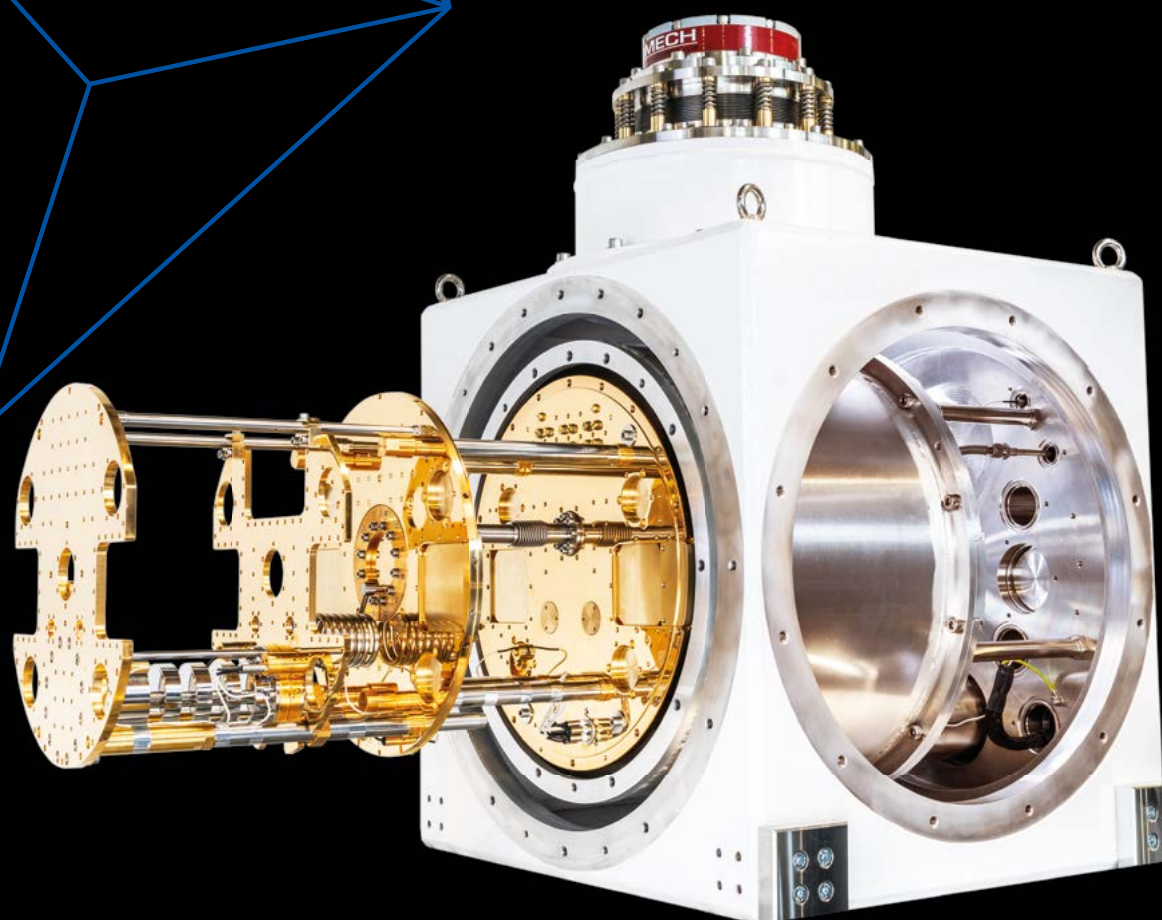
A retrospective of 60 years' coverage of magnet technology

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COIL HITS THE ROAD**1987:** ALEPH's solenoid demanded bespoke design and production methods**LHC INSERTIONS****2001:** the specialised magnets to focus, inject and extract the LHC beams**CONSTRUCTING HERA****2008:** the magnets behind the world's first and only electron–proton collider**MASSIVE MAGNETS****2017:** ITER demonstrates superconductor technology on a gigantic scale

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IN THIS ISSUE

CERN COURIER IN FOCUS **MAGNETS**

FROM THE EDITOR



Welcome to this special CERN Courier retrospective, our third limited-production supplement this year to mark the

magazine's 60th anniversary. It collates a few of the magazine's best articles about magnet technology, which has driven progress in detectors and accelerators for more than half a century. Situated inside detectors, large solenoids allow physicists to determine the charge and momentum of particles with high accuracy. For accelerators, magnets provide the fields that keep charged particles on circular trajectories. The advent of superconducting accelerator magnets in the 1970s led to a jump in the energy and performance of colliders, culminating with the LHC. But going to higher energies demands next-generation conductors such as niobium tin or even more advanced high-temperature superconductors. As our special foreword describes, CERN and other institutes worldwide are making important progress towards these technologies, and the magnets for the high-luminosity LHC provide a springboard to future colliders.

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Published by CERN, 1211 Geneva 23, Switzerland
Tel +41 (0) 22 767 61 11
Printed by Warners (Midlands) plc, Bourne, Lincolnshire, UK
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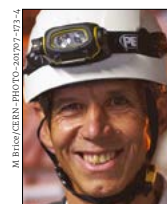
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SPECIAL FOREWORD

Accelerating magnet technology

Superconducting magnet technology has fuelled some of the greatest discoveries in high-energy physics and is at the core of existing and next-generation circular particle accelerators, writes Luca Bottura.



Luca Bottura is head of CERN's magnets, superconductors and cryostats group. Before joining CERN in 1995, he was part of the conceptual and engineering design team for ITER. He has worked on the magnets for the LHC and now undertakes R&D for high-field future accelerator magnets.

The steady increase in the energy of colliders during the past 40 years was possible thanks to progress in superconducting materials and accelerator magnets. The highest particle energies have been reached by proton–proton colliders, where beams of high-rigidity travelling on a piecewise circular trajectory require magnetic fields largely in excess of those that can be produced using resistive electromagnets. Starting from the Tevatron in 1983, through HERA in 1991 (p16), RHIC in 2000 and finally the LHC in 2008 (p10 and 23), all large-scale hadron colliders were built using superconducting magnets.

Large superconducting magnets for detectors are just as important to large high-energy physics experiments as beamline magnets are to particle accelerators. In fact, detector magnets are where superconductivity took its stronghold, right from the infancy of the technology in the 1960s, with major installations such as the large bubble-chamber solenoid at Argonne National Laboratory, followed by the giant BEBC solenoid at CERN, which held the record for the highest stored energy for many years. A long line of superconducting magnets has provided the field to the detectors of all large-scale high-energy physics colliders (p9 and 20), with the last and largest realisation being the LHC experiments, CMS and ATLAS.

All past accelerator and detector magnets have one thing in common: they were built using composite Nb–Ti/Cu wires and cables. Nb–Ti is a ductile alloy with a critical field of 14.5 T and critical temperature of 9.2 K, made from almost equal parts of the two constituents and discovered to be superconducting in 1962. Its performance, quality and cost have



Wiring the future A Nb₃Sn cable, showing the single strands and the glass-fibre insulation, partially unwrapped.

been optimised over more than half a century of research, development and large-scale industrial production. Indeed, it is unlikely that the performance of the LHC dipole magnets, operated so far at 7.7 T and expected to reach nominal conditions at 8.33 T, can be surpassed using the same superconducting material, or any foreseeable improvement of this alloy.

The HL-LHC springboard

And yet, approved projects and studies for future circular machines are all calling for the development of superconducting magnets that produce fields beyond those produced for the LHC. These include the High-Luminosity LHC (HL-LHC), which is currently taking place, and the Future Circular Collider design study (FCC), both at CERN, together with studies and programmes outside Europe, such as the Super proton–proton Collider in China (SppC) or the past studies of a Very Large Hadron Collider at Fermilab and the US–DOE Muon Accelerator

Program. This requires that we turn to other superconducting materials and novel magnet technology.

To reach its main objective, to increase the levelled LHC luminosity at ATLAS and CMS by a factor of five and the integrated one by a factor of 10, HL-LHC requires very large-aperture quadrupoles, with field levels at the coil in the range of 12 T in the interaction regions. These quadrupoles, currently being produced, are the main fruit of the 10-year US–DOE LHC Accelerator Research Program (US–LARP) – a joint venture between CERN, Brookhaven National Laboratory, Fermilab and Lawrence Berkeley National Laboratory. In addition, the increased beam intensity calls for collimators to be inserted in locations within the LHC “dispersion suppressor”, the portion of the accelerator where the regular magnet lattice is modified to ensure that off-momentum particles are centered in the interaction points. To gain the required space, standard arc dipoles



FRESCA2 The large-bore Nb₃Sn dipole FRESCA2 at CERN, built in collaboration with CEA-Saclay, reached a record dipole field of 14.6 T at 1.9 K in 2018. FRESCA2 is planned to be used as the background field magnet for a new, high-field test station at CERN.

Beyond its prime physics objective, HL-LHC is the springboard into the future of high-field accelerator magnets

will be substituted by dipoles of shorter length and higher field, approximately 11 T. As described earlier, such fields require the use of new materials. For HL-LHC, the material of choice is the inter-metallic compound of niobium and tin Nb₃Sn, which was discovered in 1954. Nb₃Sn has a critical field of 30 T and a critical temperature of 18 K, outperforming Nb-Ti by a factor two. Though discovered before Nb-Ti, and exhibiting better performance, Nb₃Sn has not been used for accelerator magnets so far because in its final form it is brittle and cannot withstand large stress and strain without special precautions.

In fact, Nb₃Sn was one of the candidate materials considered for the LHC in the late 1980s and mid 1990s. Already at that time it was demonstrated that accelerator magnets could be built with

Nb₃Sn, but it was also clear that the technology was complex, with a number of critical steps, and not ripe for large-scale production. A good 20 years of progress in basic material performance, cable

development, magnet engineering and industrial process control was necessary to reach the present state, during which time the success of the production of Nb₃Sn for ITER (p29) has given confidence in the credibility of this material for large-scale applications. As a result, magnet experts are now convinced that

Nb₃Sn technology is sufficiently mature to satisfy the challenging field levels required by HL-LHC.

The present manufacturing recipe for Nb₃Sn accelerator magnets consists of winding the magnet coil with glass-fibre insulated cables made of multi-filamentary wires that contain Nb and Sn precursors in a Cu matrix. In this form the cables can be handled and plastically deformed without breakage. The coils then undergo heat treatment, typically at a temperature of around 600 to 700 °C, during which the precursor elements react chemically and form the desired Nb₃Sn superconducting phase. At this stage, the reacted coil is extremely fragile and needs to be protected from any mechanical action. This is done by injecting a polymer, which fills the interstitial spaces among cables, and is subsequently cured to become a matrix of hardened plastic providing cohesion and support to the cables.

The above process, though conceptually simple, has a number of technical difficulties that call for top-of-the-line engineering and production control. To give some examples, the electrical insulation consisting of a few tenths of mm of glass-fibre needs to be able to withstand the high-temperature heat-treatment step, but also retain dielectric and mechanical properties at liquid helium temperatures 1000 degrees lower. The superconducting wire also changes its dimensions by a few percent, which is orders of magnitude larger than the dimensional accuracy requested for field quality and therefore must be predicted and accommodated for by appropriate magnet and tooling design. The finished coil, even if it is made solid by the poly-

mer cast, still remains stress and strain sensitive. The level of stress that can be tolerated without breakage can be up to 150 MPa, to be compared to the electromagnetic stress of optimised magnets operating at 12 T that can reach levels in the range of 100 MPa. This does not leave much headroom for engineering margins and manufacturing tolerances. Finally, protecting high-field magnets from quench, with their large stored energy, requires that the protection system has a very fast reaction – three times faster than at the LHC – and excellent noise rejection to avoid false trips related to flux jumps in the large Nb₃Sn filaments.

The CERN magnet group, in collaboration with the US-DOE laboratories participating in the LHC Accelerator Upgrade Project, is in the process of addressing these and other challenges, finding solutions suitable for a magnet production on the scale required for HL-LHC. A total of six 11 T dipoles (each about 6 m long) and 20 inner triplet quadrupoles (up to 7.5 m long) are in production. And yet, it is clear that we are not ready to extrapolate such production on a much larger scale, i.e. to the thousands of magnets required for a future hadron collider such as FCC-hh. This is exactly why HL-LHC is so critical to the development of high-field magnets for future accelerators: not only will it be the first demonstration of Nb₃Sn magnets in operation, steering and colliding beams, but by building it on a scale that can be managed at the laboratory level we have a unique opportunity to identify all the areas of necessary development, and the open technology issues, to allow the next jump. Beyond its prime physics objective, HL-LHC is the springboard into the future of high-field accelerator magnets.

The climb to higher peak fields

For future circular colliders, the target dipole field has been set at 16 T for FCC-hh, allowing proton-proton collisions at an energy of 100 TeV, while the SppC aims at a 12 T dipole field as a first step, to be followed by a 20 T dipole. Are these field levels realistic? And based on which technology?

Looking at the dipole fields produced by Nb₃Sn development magnets during the past 40 years (figure 1), fields up to 16 T have been achieved in R&D demonstrators, suggesting that the FCC target can be reached. In 2018 “FRESCA2” – a large-aperture dipole developed over the past decade through a collaboration between CERN and CEA-Saclay in the framework of the European Union project EuCARD – attained a record field of

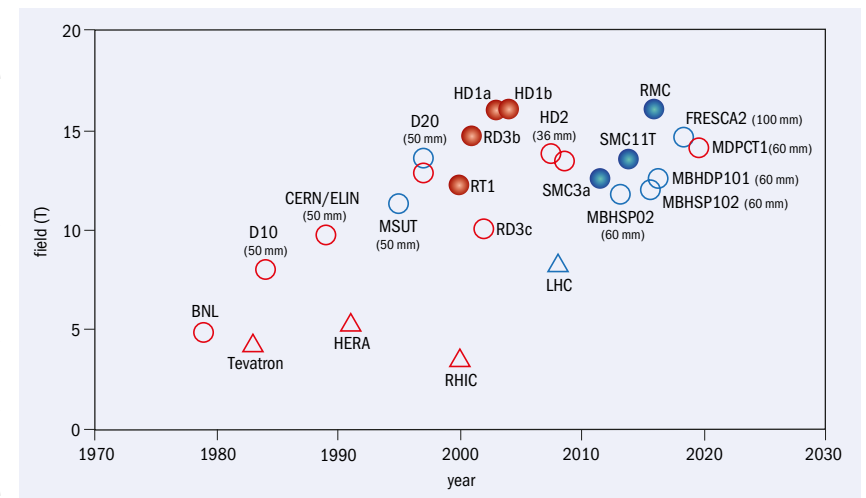
14.6 T at 1.9 K (13.9 T at 4.5 K). Another very relevant recent result is the successful test at Fermilab of the high-field dipole MDPCT1, which reached a field of 14.1 T at 4.5 K earlier this year.

A field of 16 T seems to be the upper limit that can be reached with Nb₃Sn. Indeed, though the conductor performance can still be improved, as demonstrated by recent results obtained at NHMFL, OSU and FNAL within the scope of the US-DOE Magnet Development Program, this is the point at which the material itself will run out of steam: as for any other superconductor, the critical current density drops as the field is increased, requiring an increasing amount of material to carry a given current. This effect becomes dramatic approaching a significant fraction of the critical field. Akin to Nb-Ti in the range of 8 T, a further field increase with Nb₃Sn beyond 16 T would require an exceedingly large coil and an impractical amount of conductor. Reaching the ultimate performance of Nb₃Sn, which will be situated between the present 12 T and the expected maximum of 16 T, still requires much work. The technology issues identified by the ongoing work on the HL-LHC magnets are exacerbated by the increase in field, electro-magnetic force and stored energy. Innovative industrial solutions will be needed, and the conductor itself brought to a level of maturity comparable to Nb-Ti in terms of performance, quality and cost. This work is the core of the ongoing FCC magnet development programme that CERN is pursuing in collaboration with laboratories, universities and industries worldwide.

As the limit of Nb₃Sn comes into view, we see history repeating itself: the only way to push beyond it to higher fields will be to resort to new materials. Since Nb₃Sn is technically the low-temperature superconductor (LTS) with the highest performance, this will require a transition to high-temperature superconductors (HTS).

Brave new world of HTS

High-temperature superconductors, discovered in 1986, are of great relevance in the quest for high fields. When operated at low temperature (the same liquid-helium range as LTS), they have exceedingly large critical fields in the range of 100 T and above. And yet, only recently the material and magnet engineering has reached the point where HTS materials can generate magnetic fields in excess of LTS ones. The first user applications coming to fruition are ultra-high-field NMR magnets, as recently delivered



by Bruker Biospin, and the intense magnetic fields required by material science, for example the 32 T all-superconducting user facility built by the US National High Magnetic Field Laboratory.

As for their application in accelerator magnets, the potential of HTS to make a quantum leap is enormous. But it is also clear that the tough challenges that needed to be solved for Nb₃Sn will escalate to a formidable level in HTS accelerator magnets. The magnetic force scales with the square of the field produced by the magnet, and for HTS the problem will no longer be whether the material can carry the super-currents, but rather how to manage stresses approaching structural material limits. Stored energy has the same square dependence on the field, and quench detection and protection in large HTS magnets are still a spectacular challenge. In fact, HTS magnet engineering will probably differ so much from the LTS paradigm that it is fair to say that we do not yet know whether we have identified all the issues that need to be solved. HTS is the most exciting class of material to work with; the new world for brave explorers. But it is still too early to count on practical applications, not least because the production cost for this rather complex class of ceramic materials is about two orders of magnitude higher than that of good old Nb-Ti.

It is quite logical to expect the near future to be based mainly on Nb₃Sn. With the first demonstration to come imminently, in the LHC, we need to consolidate the technology and bring it to the maturity necessary on a large-scale production. This may likely take place in steps – exploring 12 T territory first, while

seeking the solutions to the challenges of ultimate Nb₃Sn performance towards 16 T – and could take as long as a decade.

Meanwhile, nurtured by novel ideas and innovative solutions, HTS could grow from the present state of a material of great potential to its first applications. The grand challenges posed by HTS will likely require a revolution rather than an evolution of magnet technology, and significant technology advancement leading to large-scale application in accelerators can only be imagined on the 25-year horizon.

Road to the future

There are two important messages to retain from this rather simplified perspective on high-field magnets for accelerators. Firstly, given the long lead times of this technology, and even in times of uncertainty, it is important to maintain a healthy and ambitious programme so that the next step in technology is at hand when critical decisions on the accelerators of the future are due. The second message is that with such long development cycles and very specific technology, it is not realistic to rely on the private sector to advance and sustain the specific demands of HEP. In fact, the business model of high-energy physics is very peculiar, involving long investment times followed by short production bursts, and not sustainable by present industry standards. So, without taking the place of industry, it is crucial to secure critical know-how and infrastructure within the field to meet development needs and ensure the long-term future of our accelerators, present and to come. ●

Fig. 1. Record fields attained with Nb₃Sn dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature. Solid symbols are short (<1 m) demonstrator “racetracks” with no bore, while open symbols are short models (>1 m) and long magnets with bore. For comparison, superconducting colliders past and present are shown as triangles.

Development of a FLASH-ready Dose Delivery System

In recent years, FLASH radiotherapy has emerged as a novel mode of radiotherapy beam delivery. The first studies showed a significant reduction in normal tissue toxicity, with comparable tumour control, when irradiating mice tumours with ultrahigh dose rates higher than 40 Gy/s. Subsequently, the FLASH effect and dose rates have also been demonstrated using particle therapy machines. Due to the hypo-fractionation nature of FLASH, when compared to conventional RT and PT and delivered in 1–2 Gy fractions over a few weeks, it has the potential to greatly decrease treatment costs and increase the number of patients that can be treated in a facility per year.

But there are many challenges ahead of the scientific community before successful translation into clinics. The radiobiology behind the FLASH effect is still largely unknown and will have to be researched further to be able to generate effective and safe treatment plans. Effective beam control and monitoring mechanisms will also have to be developed to ensure safe dose delivery at FLASH dose rates. Cosylab is developing a new dose delivery control system, the C-DDS, that will implement FLASH requirements and thus enable research into the FLASH effect and translation of the mechanism into clinics.

To support research into the FLASH effect, several important features of the delivery system have been identified and integrated into the design of the C-DDS. Modularity is one of the main design principles of C-DDS.

By designing the system to be highly modular and open to modifications, this will allow adaptation to the new mechanisms and equipment that will be required to control and monitor the ultra-high FLASH

dose rates. For example, the system can be built up to perform scattering, uniform scanning or scanning, allowing researchers to experiment with different delivery modes, and the modular design of the system is not just beneficial for the further development of FLASH. This means that the system can be integrated more easily into a target PT facility, either in clinical or research rooms, by allowing the support of different equipment (for example, scanning magnet power supplies, ionisation chambers, accelerator and beamline control systems, and motion mitigation equipment). The system is, however, developed and preconfigured with default interfaces and the core functionality of a modern scanning system.

Achieving the required dose rates in a clinically relevant 3-D volume will require the development of advanced control algorithms, which should run on fast FPGAs. The default interfaces and functionality of the C-DDS include a spot-wise variable beam intensity algorithm, allowing the C-DDS to optimise the intensity of the beam being delivered on the individually planned spot weights. This, in combination with advanced delivery modes such as continuous line scanning, will be required to achieve and understand the FLASH effect and the role of the temporal structure of the beam.

The monitoring of FLASH dose rates will need the development of new detectors, as it is predicted that ionisation chambers will not be fast enough due to ion drift and the integration times of the detectors. Having a control system that is adaptable enough to integrate new types of detectors will be crucial for further development. In addition, the default beam monitoring algorithms of the C-DDS have been designed to react to beam errors as quickly as possible, with

all the data-processing algorithms being implemented on fast FPGA circuits.

Certain research features have been included in the C-DDS, which will allow it to be useful for work on FLASH. The system can be synchronised to external equipment, such as beam monitors, by allowing it to trigger the start of beam delivery or by producing external triggers on events connected to the beam delivery. Detailed logs of all operations in the C-DDS are available during and after delivery, allowing researchers to characterise new beam monitors and beam delivery mechanisms.

As the C-DDS has been developed with both clinical and research functions in mind, this allows for integration into both clinical and research rooms at PT facilities, allowing dual programme (clinical and research) facilities to use the same system for both patient treatment and ongoing research, simplifying the translation of new technologies to the clinical workflow.

In conclusion, Cosylab is developing an advanced dose delivery system that will enable faster development of FLASH therapy and its integration into the clinical workflow. The modularity of the system will allow for the testing of advanced beam monitors and beam control approaches. The default integrated algorithms also allow fast control and monitoring of the delivered beam. The research features of the system have been designed to allow control and access to low-level data and configurations of the system. All of these features are essential for research programmes to understand the promise of FLASH and to translate it into a clinical reality.



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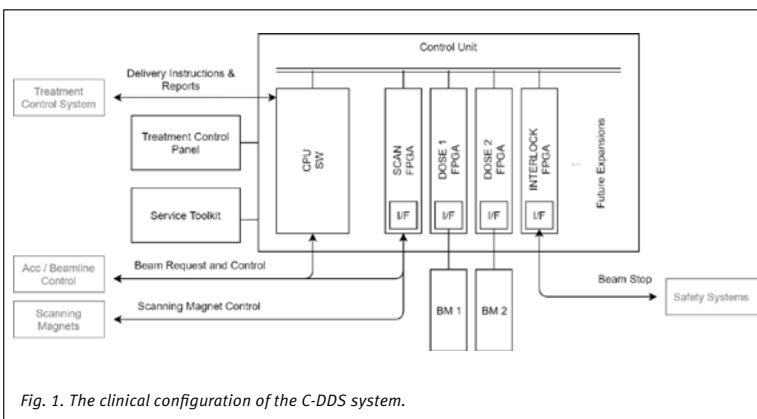
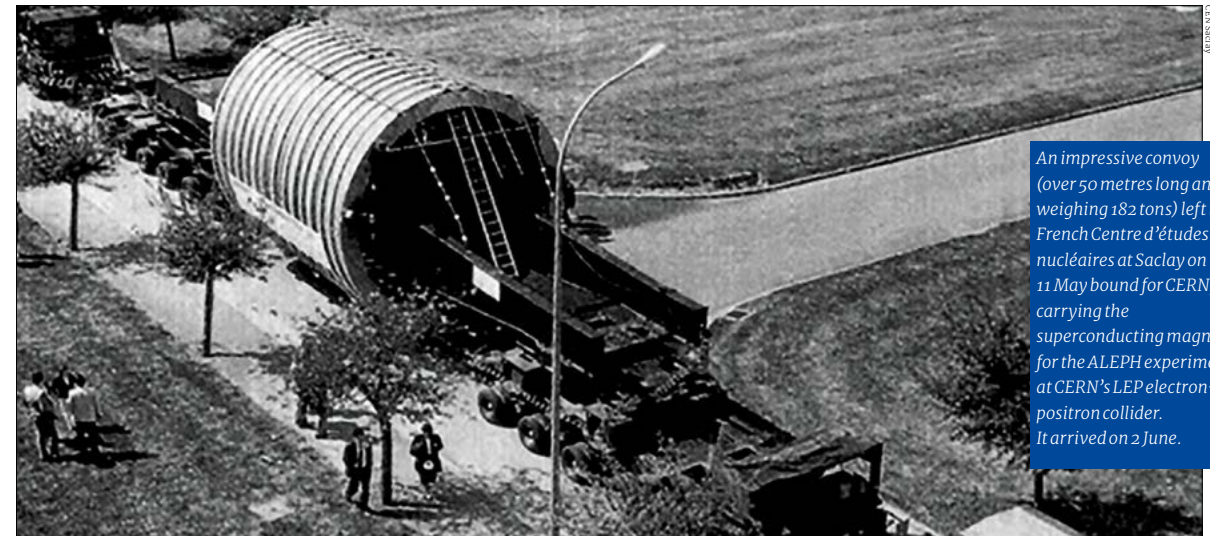


Fig. 1. The clinical configuration of the C-DDS system.

ALEPH COIL HITS THE ROAD

The giant 1.5 T superconducting solenoid for the ALEPH experiment at LEP demanded special tooling for winding, impregnation, fitting and transport, as the July 1987 issue reported.



An impressive convoy (over 50 metres long and weighing 182 tons) left the French Centre d'études nucléaires at Saclay on 11 May bound for CERN, carrying the superconducting magnet for the ALEPH experiment at CERN's LEP electron-positron collider. It arrived on 2 June.

The size and precision of components for the four big experiments being prepared for CERN's new LEP electron-positron collider make special demands on designers and manufacturers.

An example is the superconducting solenoid for the ALEPH experiment at CERN's LEP electron-positron collider, contracted to the Institut de recherche fondamentale de la Commission de l'Énergie Atomique (CEA) in 1983.

It was designed and built by engineers and technicians of the Department of Elementary Particle Physics of the CERN's Saclay Laboratory. Recent tests at Saclay were highly successful, with current attaining 60 per cent of its design value, the (temporary) absence of shielding not permitting it to go any higher.

Weighing 60 tons, 5 metres across and 7 metres long, the ALEPH solenoid produces a magnetic field of 15 kilogauss (1.5 tesla) in a volume of 130 m³. The use of a superconducting coil reduces electric power requirements by a factor of 40 and overall weight by a factor of four. Producing the required field involves 9 million ampere-turns and a stored magnetic energy of 130 million joules.

Special technology had to be developed for its man-

ufacture in view of the dimensions of the coil and the constraints imposed by the detector design – minimum weight and a minimum of material to be traversed by the particles produced by LEP.

Applying this technology on the required scale called for special tooling for winding, impregnation, fitting and transport. Tests at Saclay checked that the adopted solutions could reach the required performance levels.

Special features of the coil also include: almost exclusive use of aluminium; superconducting niobium-titanium cable coextruded in a pure aluminium sheath (30 kilometres to handle a current of 5000 amperes); the collar constraining the magnetic forces being used as the winding mandrel – the conductor being wound inside the collar; vacuum impregnation of the coil; and indirect coil cooling through tubes welded on the collar.

Meanwhile the barrel yoke for the ALEPH magnet has been reassembled at CERN after initial assembly by Ferriera-Cattaneo and INNSE in Milan.

The coil for the other superconducting coil for a LEP experiment, that for DELPHI, is undergoing tests at Rutherford Appleton Laboratory, UK, while the barrel yoke using Soviet steel is being assembled at CERN. ●



This article was adapted from text in CERN Courier vol. 27, July/August 1987, p14

LHC INSERTIONS: THE KEY TO CERN'S NEW ACCELERATOR

In October 2001, production of the specialised magnets that perform specific tasks, such as final focus, and injection and extraction of beams, was in full swing. The magnets would soon be installed in the eight "insertion regions" between the LHC's arcs.

When the machine runs in collider mode, one should forget the lattice," said Norbert Siegel. "Where it all happens is at the interaction points." Siegel is leader of the CERN group responsible for Large Hadron Collider LHC superconducting magnets other than those of the machine's main lattice. Like other accelerators and colliders, the LHC's magnets can be divided into two categories. Lattice magnets keep protons on course and are responsible for maintaining stable circulating beams. The rest go by the name of insertion magnets, performing specific tasks such as final focus before collision, beam cleaning, injection and extraction.

Inner triplets

For the LHC, the most complex insertion magnets are the eight so-called inner triplets that will squeeze the proton beams and bring them into collision in the centre of the four LHC experiments. The inner triplets are placed symmetrically at a distance of 23 m on either side of the interaction points, and each forms a cryogenic unit about 30 m long. They consist of four low-beta quadrupole magnets, so-named because their job is to minimize the beta-function, which is proportional to beam size, at the interaction point. Because of the special job they have to do and their proximity to the interaction points, the inner triplet magnets will be subject to unusually high heat loads. This means that a superfluid helium heat exchanger of unprecedented scale is required to keep them at their 1.9 K operating temperature.

The inner triplets are being provided as part of the US and Japanese contributions to the LHC project. They will use two types of quadrupole, along with various corrector magnets that are being supplied by CERN. One type of quadrupole is being developed at Japan's KEK laboratory, the other at the US Fermilab, which also has the task of integrating all of the components into their cryostats. After a successful development programme using short model magnets, full-size low-beta quadrupoles have been made and were tested in May.

The first piece of hardware built by the US-LHC project, which coordinates the US contribution to the accelerator, arrived at CERN from Fermilab last year (*CERN Courier* November 2000 p40). A heat exchanger test unit, it had the job of verifying the design of the inner triplet cooling system. Existing data on heat exchangers of this scale being scarce, the final inner triplet design had to wait until the test unit was put through its paces at CERN, one of the few places in the world with the capacity to provide superfluid helium at the necessary flow rate. With the tests



US contribution to the LHC – superconducting separator dipole made by the US Brookhaven Laboratory.



Canada: the first series production twin-aperture quadrupole produced by the TRIUMF laboratory, Vancouver, with ALSTOM Canada.

reaching a successful conclusion, the design has now been frozen and inner triplet production started at Fermilab in July. The first inner triplet is scheduled to arrive at CERN by the end of 2002.

Dedicated separators

As well as bringing the accelerator's counter-rotating beams together, LHC insertion magnets also have to separate them after collision. This is the job of dedicated separators, and the US Brookhaven Laboratory is develop-



Japan: the first KEK-built, full-length prototype low-beta quadrupole on the test bench.



US: a cryostated full-length low-beta quadrupole ready for measurements at Fermilab.

ing superconducting magnets for this purpose. Brookhaven is drawing on its experience of building the Relativistic Heavy Ion Collider (RHIC), which like the LHC is a superconducting machine. Consequently, these magnets will bear a close resemblance to RHIC's main dipoles. Following a prototyping phase, full-scale manufacture has started at Brookhaven and delivery of the first superconducting separator magnets to CERN is fore seen before the end of the year.

All LHC insertions include dispersion suppressors and

matching sections. The dispersion suppressors will limit the variation of beam position at the collision points caused by a spread in particle momenta, while the matching sections tailor the beam size in the insertions to the acceptance of the machine's lattice. Dedicated insertion quadrupoles of various designs have been developed and optimized by CERN to fulfil the aperture, space and magnetic strength requirements for these tasks. All are now at the production stage in European industry, with the first due for delivery at the beginning of 2002.

Other magnets

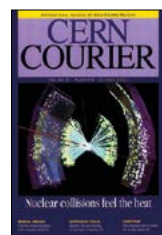
All of the magnets discussed above are superconducting. The LHC will, however, make use of room-temperature magnets in several of its insertions. These are being provided as part of the Russian and Canadian contributions to the LHC, and they include special quadrupoles and dipoles for the beam-cleaning insertions, and beam injection and ejection magnet systems that include fast kicker magnets and steel septum magnets. The septa are all being provided by the Russian IHEP laboratory in Protvino near Moscow, where production is well under way. In the cleaning insertions, which remove beam halo particles from the circulating beams, magnets must operate at room temperature due to the harsh radiation environment. Separation dipoles for these insertions are being made by the Russian Budker Institute of Nuclear Physics in Novosibirsk, while double-aperture quadrupoles are being provided by Canada's TRIUMF laboratory.

Finally, there is one kind of insertion magnet that plays no role in the effective working of the LHC as a collider – the huge magnet systems of the four experiments. Their magnetic fields have an influence on the beams' trajectories and have to be compensated for by orbit compensation magnets.

Production of all of the LHC insertion magnets is now well under way. Their preparation and installation in the tunnel, along with integration with other LHC systems, such as cryogenics, vacuum and power, provide challenging work for the years ahead. When that is over and the LHC is complete, it will be a phenomenally complex machine. However, as Norbert Siegel points out, once the LHC is running, attention will be diverted from the machine, as all eyes turn to the four main experimental insertions – the key to a better understanding of our universe. ●

Further reading

"LHC lattice magnets enter production" *CERN Courier* June 2001, p15.



This article was adapted from text in *CERN Courier* vol. 41, October 2001, pp28–30

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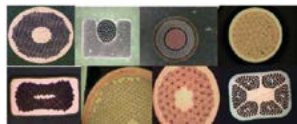
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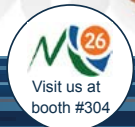
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SUPERBENDS EXPAND THE SCOPE OF BERKELEY'S ALS

David S Robin, Arthur L Robinson and Lori S Tamura describe the first-ever retrofit of superconducting bend magnets into the storage ring of an operating synchrotron radiation source, which extended the spectrum of Lawrence Berkeley National Laboratory's Advanced Light Source into the hard-X-ray region.

At first it was a perfect match. The physical constraints of its site at the Lawrence Berkeley National Laboratory on a hillside above the University of California's Berkeley campus, the research interests of its initial proponents and the fiscal realities of the times all pointed to the same conclusion in the early 1980s: the Advanced Light Source (ALS) should be a third-generation, but low-energy, synchrotron radiation source designed for highest brightness in the soft-X-ray and vacuum-ultraviolet spectral regions.

While the ALS has turned out to be a world leader in providing beams of soft X-rays – indeed, furnishing these beams remains its core mission – there has nonetheless been a steadily growing demand from synchrotron radiation users for harder X-rays with higher photon energies. The clamour has been strongest from protein crystallographers whose seemingly insatiable appetite for solving structures of biological macromolecules could not be satisfied by the number of crystallography beamlines available worldwide.

The question was how to provide these X-rays in a cost-effective way without disrupting the thriving research programmes of existing ALS users. Superconducting bend magnets (superbends) provided the answer for the ALS and a proposal was adopted (a proposal that was originally made in 1993 by Alan Jackson of Berkeley and Werner Joho of Switzerland's Paul Scherrer Institute) to replace some of the normal combined-function (gradient) magnets in the curved arcs of the storage ring with superconducting dipoles that could generate higher magnetic fields and, thus, synchrotron light with a higher critical energy.

A team headed by David Robin, the leader of the ALS Accelerator Physics Group, took on the pioneering task of retrofitting superconducting bend magnets into the magnet lattice of an operating synchrotron light source. In particular, three 5 Tesla superbends were to replace the 1.3 Tesla centre gradient magnets in Sectors 4, 8, and 12 of the 12-fold symmetric ALS triple-bend achromat



US contribution to the LHC – superconducting separator dipole made by the US Brookhaven Laboratory.



This article is adapted from text in *CERN Courier* vol. 42, March 2002, pp28-31

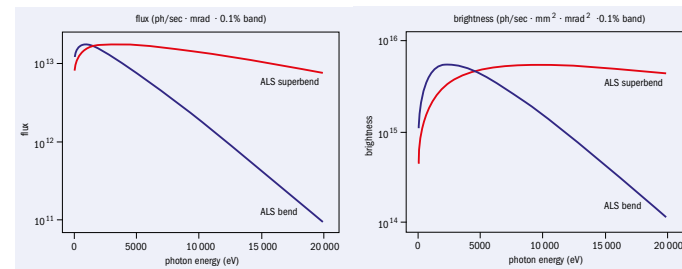
storage-ring lattice. The long project culminated early last October when, after a six-week shutdown to install and commission the superbends, the ALS reopened for users with a new set of capabilities.

The superbends have extended the spectral range of the ALS to 40 keV for hard-X-ray experiments. They do not degrade the high brightness of the ALS in the soft-X-ray region, for which the ALS was originally designed, nor do they degrade other performance specifications, such as beam stability, lifetime and reliability. They do not require that any straight sections normally occupied by high-brightness undulators be sacrificed to obtain high photon energies by filling them with high-field, multipole wigglers. Superbend magnets are already serving the first of a new set of protein crystallography beamlines. Ultimately, 12 new beamlines for crystallography and other applications, such as microtomography and diamond-anvil-cell high-pressure experiments, will be constructed.

SEPTEMBER 2019

13

CERN COURIER IN FOCUS MAGNETS



The flux and brightness of the ALS superbends (red) show a dramatic increase at higher photon energies relative to those of the normal bend magnets (blue).

Superbend history

The ALS was originally based on an electron storage ring with a 198 m circumference and a maximum beam energy of 1.9 GeV to provide peak performance in the vacuum-ultraviolet and soft-X-ray spectral regions. One way for the ALS to respond to the demand that arose in later years for higher photon energies would have been to use some of its scarce straight sections for high-field, multipole wigglers. Later, in 1997 the ALS did install one such wiggler – a device that provides the hard X-rays for an extremely productive protein crystallography beamline (Beamline 5.0.2) operated by the Berkeley Center for Structural Biology.

However, the drawback of the wiggler route was immediately obvious: many wigglers would limit the number of high-brightness undulators that give the ALS its state-of-the-art, soft-X-ray performance and that justified its construction in the first place. Moreover, a wiggler cannot readily service more than one beamline capable of the demanding multiwavelength anomalous diffraction experiments that many crystallographers want to perform, whereas a bend magnet can. In the end, the ALS adopted the superbend alternative proposed by Jackson and Joho – a choice that brought along some imposing challenges.

Superconductivity is no stranger to synchrotron light sources, where superconducting bend magnets have been used in small (mini) synchrotrons dedicated to X-ray lithography. In addition superconducting insertion devices in straight sections are, if not common, a venerable technology. Unlike wigglers and undulators in straight sections, however, superbends would be an integral part of the storage-ring lattice in a large multi-user facility and could not simply be turned off in case of failure or malfunction. So, the stakes were very high – the pay-off would be an expanded spectrum of photons to offer users; the risks included the possibility of ruining a perfectly good light source or, at the very least, causing unacceptable downtime.

In 1993, newly hired accelerator physicist Robin was set to work on preliminary modelling studies to see how superbends could fit into the storage ring's magnetic lattice and to determine whether the lattice symmetry would be broken as a result. He concluded that three superbends with fields of 5 Tesla, deflecting the electron beam through 10° each, could be successfully incorporated into the storage ring. Later, beginning in 1995, Clyde Taylor of Berkeley's Accelerator and Fusion Research Division (AFRD) led a laboratory-directed R&D project to design and build a superbend prototype.

By 1998 the collaboration (which included the ALS Accel-

erator Physics Group, the AFRD Superconducting Magnet Program and Wang NMR Inc) had produced a robust magnet that reached the design current and field without quenching. The basic design has remained unchanged through the production phase. It includes a C-shaped iron yoke with two oval poles protruding into the gap. A mile-long length of superconducting wire made of niobium-titanium alloy in a copper matrix winds more than 2000 times round each pole. The operating temperature is about 4 K.

With the strong support of ALS advisory committees and Berkeley laboratory director Charles Shank, Brian Kincaid – at that time the ALS director – made the decision to proceed with the superbend upgrade, and his successor, Daniel Chemla, made the commitment to follow through. The superbend project team, now including members of Berkeley's engineering division, held a kick-off meeting in September 1998 with Robin as project leader, Jim Krupnick as project manager and Ross Schlueter as lead engineer. Christoph Steier then joined the team a year later as lead physicist.

Subsequently, the success of wiggler Beamline 5.0.2, combined with some pioneering work on normal bend-magnet beamlines by Howard Padmore and members of his ALS Experimental Systems Group, led to the formation of user groups from the University of California, the Howard Hughes Medical Institute and elsewhere that were willing to help finance superbend beamlines, further adding to the momentum of the project.

Superbend team work pays off

For the next three years, the superbend team worked towards making the ALS storage ring the best understood such ring in the world. In every dimension of the project, from beam dynamics to the cryosystem, from the physical layout inside the ring to the timing of the shutdowns, there was very little margin for error. To study the beam dynamics, the accelerator physicists adapted an analytical technique used in astronomy called frequency mapping (CERN Courier January 2001 p15). This provided a way to "experiment" with the superbends' effect on beam dynamics both theoretically and experimentally before the superbends were installed.

Another technical challenge was to design a reliable, efficient and economical cryosystem capable of maintaining a 1.5 ton cold mass at 4 K with a heat leakage of less than 1 watt. Wang NMR was contracted to construct the superbend systems (three plus one spare). Wang designed a self-sustaining cryogenic system based on a commercial cryocooler, leads made of high-temperature superconductors and a back-up cryogenic reservoir.

Following some preparatory work during previous shutdowns, the installation of the superbends began in August 2001. The initial installation plan was very tight. In one 11-day period, the superbend team removed three normal gradient magnets and a portion of the electron-beam injection line in straight section 1 just upstream of Sector 12; installed the superbends; modified cryogenic systems; and completed extensive control system upgrades. They also installed many other storage-ring items and prepared for start-up with a beam.

After the installation phase, the goal was to commission

the ALS with superbends and return the beam to users by 4 October. This schedule allowed the month of September to commission the ring (with the exception of a four-day break for the installation of the front ends for two superbend beamlines) and a three-day period for beamline realignment. However, commissioning proceeded much faster than had been expected and it was less than two weeks after the start of the installation when the machine was ramped up to full strength, and the effects of the superbends on the performance of the storage ring were fully evaluated.

Because so much was at stake, the storage ring had been studied and modelled down to the level of individual bolts and screws to ensure a smooth, problem-free installation into the very confined space within the storage ring. This attention to detail also paid off in the rapid commissioning. To take one example, the superbends were very well aligned, as demonstrated by a stored beam with little orbit distortion and small corrector-magnet strengths.

At the end of the first day, a current of 100 mA and an energy of 1.9 GeV were attained. At the end of the first week-end, the injection rate and beam stability were near normal. By the end of the first week, the full 400 mA beam current was ramped to 1.9 GeV and studies of a new, low-emittance lattice with a non-zero dispersion in the straight sections (designed to retain the high brightness that the storage ring had without superbends) were begun. By the end of the

second week, test spectra taken in some beamlines showed no change in quality due to the presence of superbends.

Since reopening for business in October, the ALS has not experienced any significant glitches that might be associated with such a major change. Overall the ALS has made good on its promises to users of installing and commissioning the superbends without disrupting or delaying their research programmes and operating them with no adverse effects on performance in the bread-and-butter soft-X-ray spectral region, as demonstrated by the values of the storage-ring parameters.

Superbend beamlines are already taking data and more are under construction or planned. Three superbend protein-crystallography beamlines are now taking data, and researchers at the first of these to come on line have already solved 15 structures. Three more crystallography beamlines are on the way. Non-crystallography beamlines currently in the works include one for tomography and one for high-pressure research with diamond-anvil cells, two areas for which superbends are even more advantageous than they are for protein crystallography, because they more fully exploit the higher photon energies that superbends can generate. Many other areas, including microfocus diffraction and spectroscopy, would also benefit enormously through the use of the superbend sources.

In summary, a new era at Berkeley's ALS is under way. ●

By 1998 the collaboration had produced a robust magnet that reached the design current and field without quenching

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CONSTRUCTING HERA: RISING TO THE CHALLENGE

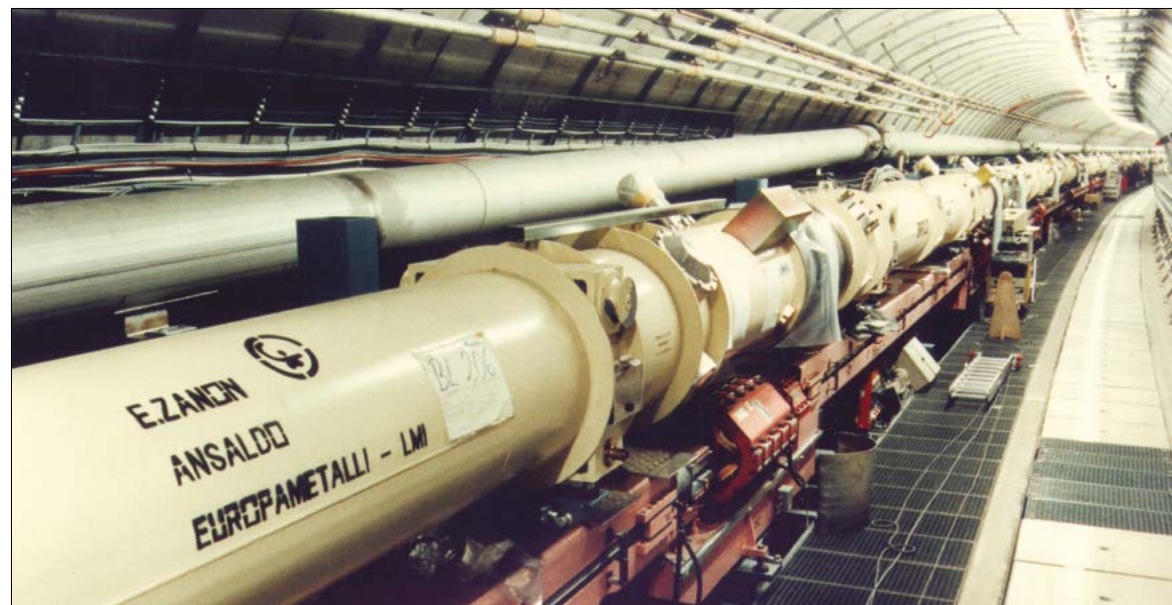
At 11.28 p.m. on 30 June 2007, DESY's HERA collider was shut down after almost 16 years of operation. In this article, Dieter Trines looked back at the challenge of building the first and only electron-proton collider, based on a superconducting-magnet ring.

Ideas for an electron-proton collider based on storage rings first arose after the famous experimental results on deep inelastic electron-proton scattering from SLAC in 1969, which indicated a granular structure for the proton. Using two storage rings to collide electrons and protons head-on, rather than directing an electron beam at a proton target, would allow for higher centre-of-mass energies. This would in turn result in a better resolution for measurements of the internal structure of the proton. So, in the early 1970s, several laboratories – Brookhaven, CERN, DESY, Fermilab, IHEP (Moscow), Rutherford Laboratory, SLAC and TRIUMF – began to think about building an electron-proton collider.

At DESY, Björn Wiik in particular was a major advocate for the construction of an electron-proton collider. In 1972, Horst Gerke, Helmut Wiedemann, Günter Wolf and Wiik wrote a first report in which they proposed using the existing double-storage ring DORIS for electron-proton collisions. Then, in 1981, after several workshops organized by the European Committee for Future Accelerators (ECFA), DESY submitted a proposal to the government of the Federal Republic of Germany (FRG) for the construction of a completely new machine called HERA. It was to be an electron-proton collider with a circumference of 6.3 km and it had the strong support of the European high-energy physics community and ECFA.

Early discussions on electron-proton colliders had already considered the use of superconducting magnets for the proton ring. Then, in the 1980s, this demanding technology became feasible for large systems, thanks to the courageous and pioneering work at Fermilab on superconducting magnets for the construction of the Tevatron. When it came into operation in 1983, the Tevatron was the world's first superconducting synchrotron at high energies.

DESY had no major experience in this technology, so



Inside the HERA tunnel: the proton accelerator with its superconducting magnets (beige) lies above the normally conducting magnets of the electron ring.

in 1979 Hartwig Kaiser and Siegfried Wolff were sent to work with colleagues at Fermilab and profit from their know-how. The successful dipole and quadrupole magnets developed at Fermilab naturally influenced the design of the superconducting accelerator magnets for HERA, and the first dipoles built at DESY were basically copies of the Fermilab magnets. However, with increasing experience, the physicists and engineers at DESY started to add major improvements of their own, leading to the characteristic design of the HERA magnets, which proved extremely successful over the lifetime of the accelerator. As the superconducting magnet ring was the most challenging part of HERA, this article will focus on its design in particular.

The superconducting coil is the most critical component of a superconducting magnet. Coils several metres long are fabricated with cross-sections accurate to a few hundredths of a millimetre. This demanding task was solved at Fermilab by using laminated tooling for the production and curing of the coils. These are surrounded by collars

punched from stainless-steel sheets, which provide the precise coil geometry and sustain the huge magnetic forces. Only special types of steel, which do not become brittle or magnetic at cryogenic temperatures, are suitable. For the coils of the HERA dipoles, the collars are made from an aluminium alloy with high yield-strength, thus eliminating magnetic effects.

In the HERA dipoles, this collaring is reinforced by the iron yoke, which, unlike its Fermilab counterpart, is located inside the cryostat. This "cold iron" concept has several advantages. First, it leads to an additional gain of 12% in the central magnetic field, as the iron is closer to the coil. Second, the cryogenic load at 4 K is reduced as a result of the longer support rods. Finally, a passive protection scheme with parallel diodes can protect the coil against damage from the stored energy should it become normally conducting (quench). The resulting larger cold mass leads to longer cool-down and warm-up times of about five days. However, this turned out to be no drawback as



Björn Wiik in the HERA tunnel. The "father" of the HERA electron-proton collider went on to become director of DESY.

there were only a few occasions during the whole lifetime of HERA, outside regular shutdowns, when the magnets had to be warmed up. Hartwig Kaiser, Karl Hubert Mess and Peter Schmüser were the main people responsible for this development.

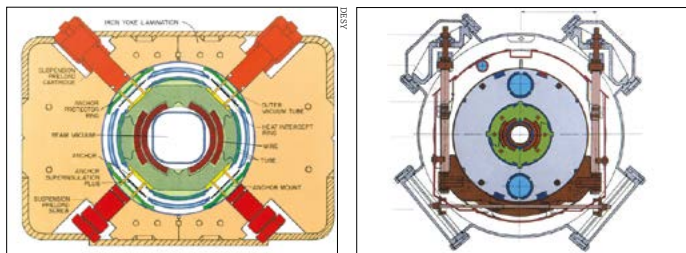
In a superconducting magnet ring, the protection of the coils against quenches is of utmost importance and is a challenging technology in itself. It involves both the detection of a quench (by monitoring the voltage over the coils) and the installation of quench heaters to force the quenching coil to become normally conducting, thus distributing the energy deposited by the magnet current over its whole length. As many magnet coils are powered serially in long strings, the current coming from the power supply has to be bypassed around the quenching magnet and its stored energy safely dissipated in a resistive load. A switch is required to bypass the magnet. At Fermilab, this was in the form of a thyristor mounted outside the vacuum vessel, which had to be triggered in case of a quench. The



This article is adapted from text in CERN Courier vol. 48, January/February 2008, pp30-33



In the accelerator control room Björn Wiik (centre) and Gustav-Adolf Voss (centre right) raise their glasses to celebrate the first electron-proton collisions in HERA on 19 October 1991.



These schematics show how the Tevatron dipole (left) served as a model for the development of the dipoles in the proton ring at HERA (right).

current leads to the thyristor were connected to the coil at 4 K, thus adding to the cryogenic load.

For the HERA magnets, Mess applied a different idea, first considered at Brookhaven, in which a “cold” diode inside the cryostat at 4 K automatically switches the current of about 5000 A in case of a quench. This was one of the most innovative and courageous technological steps of the HERA project. First, a suitable diode had to be found. Of course, no commercially available diodes were made for such an application. Mess did eventually find one that promised to be up to the task, but only after extensive searching and testing. Then, the mechanical mounting and electrical connections of the diodes had to be devised in such a way as to guarantee their reliable operation inside the helium, where they were exposed to rapid and extreme thermal cycles. Comprehensive tests of all of the diodes were carried out to qualify them and validate the design of the mounting – an example of innovative engineering at its best.

To save costs and keep the cryogenic load at 4 K as low as possible, the various corrector magnets were connected via superconducting cables inside the 4 K helium pipe over an octant of the ring. The cables were held in a special fixture between the magnets and had to be soldered together before the 4 K helium tubes were joined by a welding sleeve. To make sure that all of the 20 or so cables were correctly connected, clever clamping devices – which supplied electrical contact to all of the wires simultaneously – were installed at two intersections. By applying voltages to the various contacts, a computerized central measuring station determined whether the cables were connected correctly in a time-effective way. There are many other cases that required ingenious ideas, such as solving the problem with persistent currents in the superconducting coils as Schmüser and his students did, but unfortunately it is impossible to cover these in a short article.

There were many systems for the superconducting magnet ring where little or no experience existed at DESY. One example is the huge cryogenic system with the cryogenic plant and the magnet cryostats, various cryogenic boxes, and transfer lines and pipes for cold and room-temperature helium, respectively. One pipe, the quench gas-collection pipe, was connected to the 4 K helium volume of the dipole magnets but separated by a special valve, named the Kautzky valve after its inventor at Fermilab. This valve opens automatically when the pressure inside the cryostat exceeds

a preset value. It is sealed by a conical plastic piece inside a conical body. However, some of these valves would start to rattle during a quench, indicating that they were closing and opening in rapid succession. This effect quite often cracked the plastic cone, so the valves would no longer seal for normal operation and had to be exchanged. Despite intensive studies and tests of various materials – the high radiation level in the HERA tunnel meant that the Teflon of the original design could not be used – the problem was never solved. It did not become an operational problem thanks to the small number of quenches. This was an example where the work on HERA did not evolve from the heritage of Fermilab.

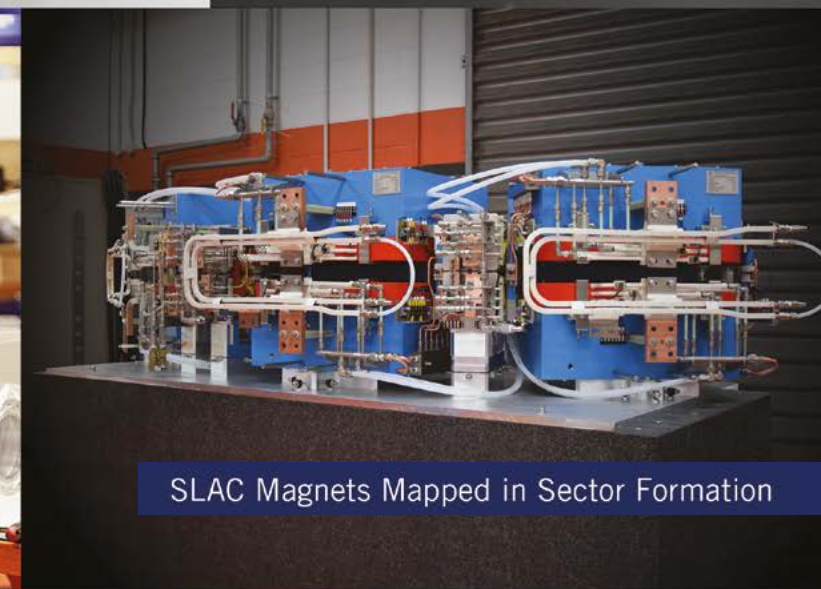
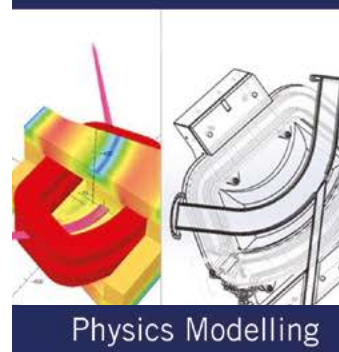
One clear evolutionary step, however, was the strong involvement of industry in the production of the superconducting magnets for HERA. For European industry in particular, HERA presented a unique opportunity: it was the first time that companies had an opportunity to gain experience in superconducting technologies and cryogenics on such a large scale. This step was beneficial for both DESY and the industrial companies, and also for later projects using superconducting-magnet technology.

Another step forward, this time in terms of financing and organizing large research projects, was the construction of HERA in collaboration with research laboratories from other countries: the so-called “HERA model”. It is to the credit of both Wiik and Volker Soergel that they brought the collaboration together with contributions from Canada, France, Israel, Italy, the Netherlands and the US, with additional manpower provided by institutes in China, Czechoslovakia, Poland, Switzerland, the UK, and USSR as well as institutes from both the FRG and the German Democratic Republic. The particularly large contribution by Italy of half of the superconducting dipoles cannot be overemphasized, and was to the great merit of Antonino Zichichi, who made this happen.

At DESY, we clearly stood on the shoulders of Fermilab’s pioneering work when realizing HERA, and the experiences and technological advancements made at HERA were valuable for later projects, such as RHIC at Brookhaven and the LHC at CERN. When DESY began the adventure of constructing the superconducting magnet ring for HERA, several people were worried that there would be problems with such a novel system and that its operation would become very difficult. Fortunately, none of the worries were substantiated and the operation of the “cold” ring essentially went without problems. I am sure that people at CERN now have similar worries concerning the LHC. I would like to express my best wishes to them, with the hope that they might be as fortunate and successful with the LHC as we were with HERA. ●



WORLD LEADERS IN MANUFACTURING HIGH PRECISION ELECTROMAGNETS AND ASSOCIATED ACCELERATOR COMPONENTS



MAGNETS UHV VACUUM CHAMBERS RF RESONATORS
BEAMLINE INSTRUMENTS ION SOURCES PHYSICS DESIGN
MECHANICAL DESIGN MANUFACTURE VERIFICATION



CMS: A SUPER SOLENOID IS READY FOR BUSINESS

In the spring of 2007, as described by Domenico Campi and David Stickland, the powerful superconducting solenoid for the CMS experiment had passed its commissioning tests with flying colours and was ready for routine operation.

For seven years, Point 5 on the LHC has been the site of intense activity, as the CMS detector has taken shape above ground at the same time as excavation of the experimental cavern below. Last year saw an important step in the preparations on the surface, as the huge CMS superconducting solenoid – the S in CMS – was cooled down, turned on and tested.

The CMS coil is the largest thin solenoid, in terms of stored energy, ever constructed. With a length of 12.5 m and an inner diameter of 6 m, it weighs 220 tonnes and delivers a maximum magnetic field of 4 T. A segmented 12 500 t iron yoke provides the path for the magnetic flux return. Such a complex device necessarily requires extensive tests to bring it into stable operation – a major goal of the CMS Magnet Test and Cosmic Challenge (MTCC) that took place in two phases between July and November in 2006.

From the start, the idea was to assemble and test the CMS magnet – and the whole detector structure – on the surface prior to lowering it 90 m below ground to its final position. The solenoid consists of five modules that make up a single cylinder (figure 1), while the yoke comprises 11 large pieces that form a barrel with two endcaps. There are six endcap disks and five barrel wheels, and their weight varies from 400 t for the lightest to 1920 t for the central wheel, which includes the coil and its cryostat.

The CMS solenoid has several innovative features



Fig. 1. The assembly of the solenoid nears completion at CERN.



This article is adapted from text in CERN Courier vol. 47, March 2007, pp22–25

compared with previous magnets used in particle-physics experiments. These are necessary to cope with the high ampere turns needed to generate the 4 T field – 46.5 MA around a 6 m diameter. The most distinctive feature is the four-layer coil winding, reinforced to withstand the huge forces at play. The niobium titanium conductor is in the form of Rutherford cable co-extruded with pure aluminium and mechanically reinforced with aluminium alloy (figure 2). The layers of this self-supporting conductor bear 70% of the magnetic stress of 130 MPa while the cylindrical support structure, or mandrel, takes the remaining 30%.

Constructing the coil has been a *tour de force* in international collaboration involving suppliers in several countries. The basic element, the superconducting wire, originated with Luvata in Finland, and passed to Switzerland, where Brugg Kabelwerk made the Rutherford cable,



and Nexans co-extruded it with pure aluminium. The cable then went to Techmeta in France for electron-beam welding onto two sections of high-strength aluminium alloy to allow the conductor to support the high magnetic stress. Finally ASG Superconductors in Italy wound the coils for the five sections of the solenoid, which travelled individually by sea, river and land to Point 5 for assembly into a single coil. The division into sections, and the chosen outer diameter of 7.2 m, ensured that transport could be by road without widening or rebuilding.

By August 2005 the solenoid was ready to be inserted into the cryostat that keeps it at its operating temperature of 4.5 K (figure 3). Cooling requires a helium refrigeration plant with a capacity of 800 W at 4.5 K and 4500 W in the range 60–80 K. The cryoplant was first commissioned with a temporary heat load to simulate the coil and its cryostat, and then early in 2006 the real coil was ready for cool-down. In an exceptionally smooth operation the temperature of the 220 t cold mass was lowered to 4.5 K over 28 days.

The next stage was to close the magnet yoke in preparation for the MTCC. The massive elements of the yoke move on heavy-duty air pads with grease pads for the final 100 mm of approach. Once an element touches the appropriate stop it is pre-stressed with 80 t to the adjacent



Fig. 2. (left) A model of the CMS solenoid coil, showing its four-layer coil-winding structure.

Fig. 3. (above right) The solenoid, right, about to be inserted into the cryostat barrel.

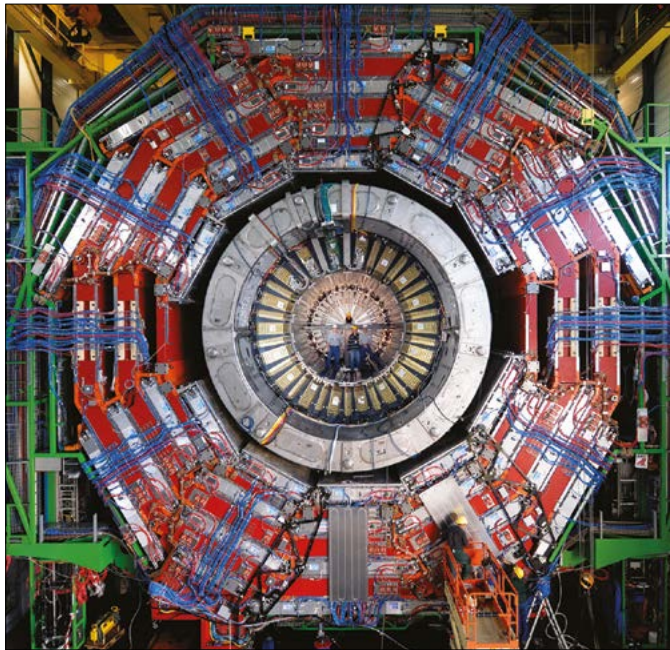
element to ensure a good contact before switching on the magnet. To assure good alignment, a precise reference network of some 70 points was set up in the assembly hall, with the result that all elements could be aligned to within 1 mm of the ideal coil axis. The first closure of the whole yoke took some 30 days, and was completed on 24 July (CERN Courier September 2006 cover and p7). The MTCC could now begin.

Testing the magnet took place in two phases, with the initial tests in August 2006 and further tests and field mapping in October. The cosmic challenge, to test detectors and data-acquisition systems with cosmic rays, took place simultaneously. Each step in current ended with a fast discharge into external dump-resistor banks. Depending on the current level at the time of the fast discharge, it could take up to three days to re-cool the coil.

A key feature with any superconducting magnet system is to protect against high thermal gradients occurring in the coil if the system switches suddenly from being superconducting to normally (resistively) conducting with a sudden loss of magnetic field and release of stored energy – a quench. The aim is to dissipate the energy into as large a part of the cold mass as possible. For this reason the CMS solenoid is coupled inductively to its external mandrel, so that in the case of a quench eddy currents in the mandrel heat up the whole coil, dissipating the energy throughout the whole cold mass.

The tests showed that when the magnet discharges the dump resistance warms up by as much as 240°. At the same time the internal electrical resistance of the coil increases, up to as much as 0.1 Ω after a fast discharge at 19 kA.

The tests also showed that after a fast discharge at 19 kA the average temperature of the whole cold mass rises to 70 K, with a maximum temperature difference of 32.3° measured between the warmest part, on the inside of the central section of the coil, and the coldest part, on the outside of the mandrel. It then takes about two hours for the temperature to equalize across the whole coil. About



half of the total energy (1250 MJ) dissipates as heat in the external dump resistor, which takes less than two hours to return to its normal temperature.

Monitoring the magnet's mechanical parameters was also an important feature of the tests, to check for example the coil shrinkage and the stresses on the coil-supporting tie rods during cool-down. The measured values proved to be in excellent agreement with calculations. Powering the cold mass step-by-step allowed also for measurements of any misalignment of the coil. This showed that the axial displacement of the coil's geometric centre is less than 0.4 mm, indicating a magnetic misalignment of less than 2 mm in the positive z direction.

A major goal of Phase II of the MTCC was to map and reconstruct the central field volume with 5×10^{-4} precision. The measurements took place in three zones, with flux-loop measurements in the steel yoke, check-point measurements near the yoke elements, and a detailed scan of the entire central volume of the detector – essentially the whole space inside the hadron calorimeter.

Measuring the average magnetic flux density in key regions of the yoke by an integration technique involved 22 flux loops of 405 turns installed around selected plates. The flux loops enclosed areas of 0.3–1.58 m² on the barrel wheels and 0.48–1.1 m² on the endcap disks. The flux loops measure the variations of the magnetic flux induced in the steel when the field in the solenoid is changed during the fast (190 s time constant) discharge. A system of 76 3D B-sensors developed at NIKHEF measured the field on the steel-air interface of the disks and wheels to adjust the 3D magnetic model and reconstruct the field inside the iron yoke elements, which are part of the muon absorbers.

A special R&D programme with sample disks made of

Fig. 4. The solid steel yoke (red) comprising three concentric layers interspersed with muon chambers (silver) surround the superconducting solenoid (silver-coloured ring). The field mapper is installed across the centre of the hadron calorimeter (gold coloured).

The electrical tests of the solenoid have demonstrated its excellent performance, as well as the functioning of its ancillary systems

the CMS yoke steel from different melts investigated if the measurements of the average magnetic flux density in the yoke plates could be done with accuracy of a few per cent using flux loops. These studies showed that the contribution of eddy currents to the voltages induced in the test flux loop is negligible.

The precise measurement of the magnetic field in the tracking volume inside the CMS coil used a field-mapper designed and produced at Fermilab. This incorporated 10 more 3D B-sensors, developed at NIKHEF and calibrated at CERN to 5×10^{-4} precision for a nominal field of 4 T. To map a cylindrical volume inside the coil, this instrument moved along the rails installed inside the hadronic barrel calorimeter, stopping in 5 cm steps at points where the sensor arms could be rotated through 360°, and at predefined angles with azimuth steps of 7.5°. Figure 4 shows the final position of the mapper before closure of the positive endcap. It mapped a cylindrical volume 1.724 m in radius and 7 m long.

The CMS magnet has six NMR probes near the inner wall of the superconducting coil cryostat to monitor the magnetic field. These were also used in the field-mapping to measure the field on the coil axis and on the cylindrical surface of the measured volume.

The actual field-mapping in October involved a series of measurements at 0 T, 2 T, 3 T, 3.8 T (twice to study systematics), 3.5 T and 4 T. The flux-loop measurements were made during fast-discharges of the coil at various current values. While the detailed analysis of the data is still ongoing, preliminary studies are very encouraging. The field distribution behaves very much as the simulation predicted – though more detailed simulation of the extra iron in the feet of CMS is necessary to account for it fully.

The azimuthal component of the field is nominally zero, but as the plot shows it takes on small values with a sinusoidal dependence on the rotation angle. This is now fully understood as coming from small tilts of the plane in which the mapper moves with respect to the nominal z axis of the magnetic field; this couples the magnetic field components and also gives rise to the small variations seen in the radial component. In addition, the team now understands some even smaller variations in the sinusoidal behaviour of the azimuthal field as a function of the z step following a careful survey of the tilts induced on the mapper arms as it traversed the length of the coil on its (almost) straight rails.

The electrical tests of the solenoid have demonstrated its excellent performance, as well as the functioning of its ancillary systems, and its readiness for smooth operation. The detailed mapping was equally successful and final analysis is now underway to ensure that the best possible parameterization of the field for analysis of real data in autumn 2007. As soon as the tests were over, the huge sections of yoke were pulled apart again, and the descent to the cavern could at last begin.

Many institutes participating in CMS took part in the design, construction and procurement of the magnet, as members of the CMS Coil Collaboration, including CEA Saclay, ETH Zurich, Fermilab, INFN Genoa, ITEP Moscow, the University of Wisconsin and CERN. ●

SUPERCONDUCTIVITY AND THE LHC: THE EARLY DAYS

With 9 T dipole magnets of a new “twin” design and superfluid helium cooling, the LHC took the use of superconductivity in accelerators to a new level. In 2011, Lucio Rossi looked at some of the first challenges that had to be overcome.

As the 1970s turned into the 1980s, two projects at the technology frontier were battling it out in the US accelerator community: the Energy Doubler, based on Robert Wilson's vision to double the energy of the Main Ring collider at Fermilab; and Isabelle (later the Colliding Beam Accelerator) in Brookhaven. The latter was put in question by the difficulty in increasing the magnetic field from 4 T to 5 T – which turned out to be much harder than originally thought – and eventually gave way to Carlo Rubbia's idea to transform CERN's Super Proton Synchrotron into a p-p collider, allowing the first detection of W and Z particles. Fermilab's project, however, became a reality. Based on 800 superconducting dipole magnets with a field in excess of 4 T, it involved the first ever mass-production of superconductor and represented a real breakthrough in accelerator technology. For the first time, a circular accelerator had been built to work at a higher energy without increasing its radius.

When the Tevatron began operation at 540 GeV in 1983, Europe was just starting to build HERA at DESY. This electron-proton collider included a 6 km ring of superconducting magnets for the 820 GeV protons and it came into operation in 1989. The 5 T dipoles for HERA were the first to feature cold iron and – unlike the Tevatron magnets, which were built in house – they were produced by external companies, thus marking the industrialization of superconductivity.

Meanwhile the USSR was striving to build a 3 TeV superconducting proton synchrotron (UNK), which was later halted by the collapse of the Soviet Union, while at CERN the idea was emerging to build a Large Hadron Collider in the tunnel constructed for the Large Electron-Positron (LEP) collider (CERN Courier October 2008 p9). However, the US raised the bid with a study for the “definitive machine”. The Superconducting Super Collider (SSC), which was strongly supported by the US Department of

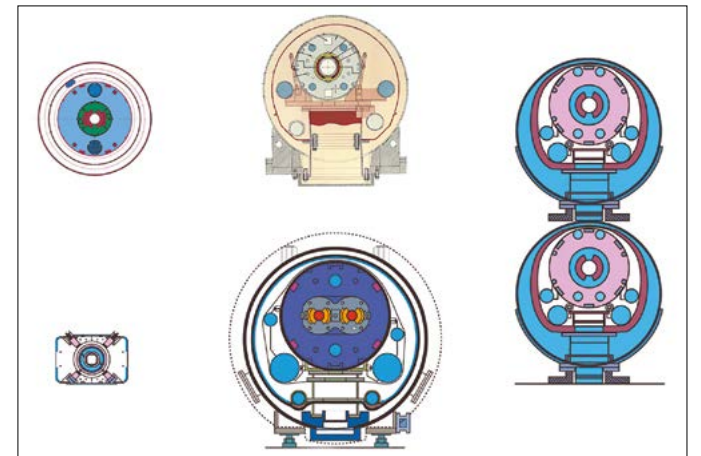


Fig. 1. Comparison of dipoles from the Tevatron to the LHC.

CERN COURIER
Superconductivity and accelerators
This article is adapted from text in CERN Courier vol. 51, November 2011, pp21-27

Energy and by President Reagan, would accelerate two proton beams to 20 TeV in a ring of 87 km circumference with 6.6 T superconducting dipoles. With this size and magnetic field, the SSC would require decisive advances in superconductors as well as in other technologies. When the then director-general of CERN, Herwig Schopper, attended a high-level official meeting in the US and asked what influence on the scientific and technical goals the Europeans could have by joining the project, he was told “none, either you join the project as it is or you are out”. This ended the possibility of collaboration and the competition began.

To compete with the SSC, the LHC had to fight on two fronts: increase the magnetic field as much as possible so as to reduce the handicap of the relatively small circumference of the LEP tunnel; and increase the luminosity as much as possible to compensate for the inevitable lower energy. In addition, CERN had to cope with a tunnel with a cross-section that was tiny for a hadron collider, which many considered a “poisoned gift” from LEP. However, the interest for young physicists and engineers lay in the “impossible challenges” that the LHC presented.

To begin with, there was the 8–10 T field in a dipole magnet. Such a large step with respect to the Tevatron would require both the use of large superconducting cable to carry 13 kA in operating conditions of 10 T – almost

CERN COURIER IN FOCUS MAGNETS

double the capability of existing technology – and cooling by superfluid helium at 1.8–1.9 K. Never previously used in accelerators, superfluid helium cooling had been developed for TORE Supra, the tokamak project led by Robert Aymar but on a smaller scale. Then, to fit the exiting LEP tunnel, the magnets would have to be of an innovative “two-in-one” design – first proposed by Brookhaven but discarded by US colleagues for the SSC – where two magnetic channels are hosted in the iron yoke within a single cold mass and cryostat. In this way, a 1 m diameter cryostat could house two magnets, while the geometry of the SSC (with separate magnets but with 30% lower field than the LHC) simply could not fit in the LHC tunnel. Figure 1 shows the various main-dipole cross-sections for the various hadron machines.

A critical milestone

In 1986 R&D on the LHC started under the leadership of Giorgio Brianti, quietly addressing the three issues specific to the LHC (high field, superfluid helium and two-in-one), while relying on the development done for HERA and especially for the SSC for almost all of the other items that needed to be improved. The high field was the critical issue and had to be tested immediately. Led by Romeo Perin and Daniel Leroy, CERN produced the first LHC coil layout and provided the first large superconducting cable to Ansaldo Componenti. This company then manufactured on its own a 1-m long dipole model – single bore, without a cryostat – that was tested at CERN in 1987. Reaching a field of 9 T at 1.8 K, it proved the possibility of reaching the region of 8–10 T (*CERN Courier* October 2008 p19). This was arguably the most critical milestone of the project because it gave credibility to the whole plan and began to lay doubt on the strategy for the SSC.

These results were obtained with niobium–titanium alloy (Nb–Ti), the workhorse of superconductivity. CERN had also a parallel development with niobium–tin (Nb₃Sn) that could have produced a slightly higher field at 4.5 K, with standard helium cooling. This development, pursued with the Austrian company Elin and led by CERN’s Fred Asner, produced a 1-m long 9.8 T magnet and also a 10.1 T coil in mirror configuration, the first accelerator coil to break the 10 T wall. However, in 1990 the development work on Nb₃Sn was stopped in favour of the much more advanced and practical Nb–Ti operating at 1.9 K. This was a difficult decision, as Nb₃Sn had a greater potential than Nb–Ti and would avoid the difficulty of using superfluid helium, but it was vitally important to concentrate resources and to have a viable project in a short time. The decision was similar that taken by John Adams in the mid-1970s to abandon the emerging superconducting technology in favour of more robust resistive magnets for CERN’s Super Proton Synchrotron.

For the development of the superconducting cable there were three main issues. First, it should reach a sufficient critical current density with a uniformity of 5–10% over the whole production, which also had to be guaranteed in the ratio between the superconductor and the stabilizing copper matrix, illustrated in figure 2. The critical current was to be optimized at 11 T at 1.9 K, maximizing the gain

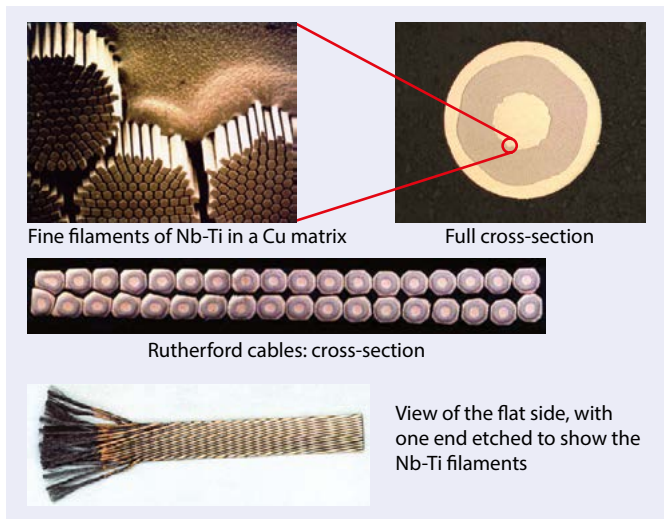


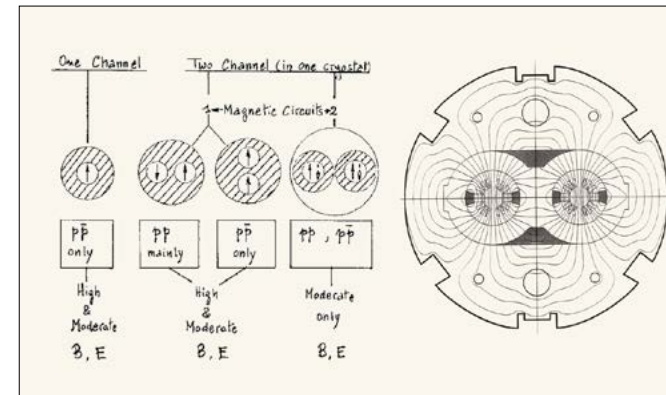
Fig. 2. Structure of the superconducting cable used in the LHC – from Nb–Ti filament to final cable.

when passing from 4.2 to 1.9 K. The second issue was to reduce the size of the superconducting filaments to 5 μ m without compromising the critical current. This required, among other features, the development of a niobium barrier around Nb–Ti ingots. Third was to control the dynamic (ramping up) effect in a large cable, as some effects vary as the cube of the width.

Again, the strategy was to concentrate on specific LHC issues – the large cable, the critical current optimization at 1.9 K – and rely on the SSC’s more advanced development for the other issues. There is, indeed, a large debt that CERN owes to the SSC project for the superconductor development. However, when the SSC project was cancelled in 1993, the problem of eliminating the dynamic effect arising from the resistance between strands composing the cable was still unresolved – but it became urgent in view of the results on the first long magnets in 1994 and after. Later, CERN carried out intense R&D to find a solution suitable for mass production relatively late, at the end of the 1990s. This involved controlled oxidation, after cable formation, of the thin layer of tin–silver alloy with which all the copper/Nb–Ti strands were coated – a technology that was a step beyond the SSC development.

Returning to the magnet development, after the success of the 1987 model magnet, which was replicated by another single-bore magnet that CERN ordered from Ansaldo, the R&D route split into two branches. One concerned the manufacture of 1-m long full-field LHC dipole magnets to prove the concept of high fields in the two-in-one design, with superconducting cable and coil geometry close to the final ones. A few bare magnets, called Magnet Twin Aperture (MTA), were commissioned from European Industry (Ansaldo, Jeumont–Scheinder consortium, Elin, Holec) under the supervision of Leroy at CERN.

The second line of development lay in proving the two-in-one concept in long magnets and a superfluid–helium cryostat. This involved assembling superconducting coils from the HERA dipole production, which had ended in



1988, in a single cold mass and cryostat, the Twin Aperture Prototype (TAP). The magnet, under the supervision of Jos Vlogaert with the cryostat and cold-mass, under Philippe Lebrun, tested successfully in 1990, reaching 5.7 T at 4.2 K and 7.3–8.2 T at 1.8 K – thus supporting the choices of the two-in-one magnet design, of the superfluid helium cooling and the new cryostat design.

At the same time, the LHC dipole was designed in the years 1987–1990, featuring an extreme variation: the “twin” concept, where the two coil apertures are fully coupled, i.e. with no iron between the two magnetic channels (figure 3). We now take this design for granted, but at the time there was scepticism within the community (especially across the Atlantic); it was supposed to be much more vulnerable to perturbations because of the coupling and to present an irresolvable issue with field quality. It is to the great credit of the CERN management and especially Perin, who for a long time was head of the magnet group, that they defended this design with great resilience – because among many advantages it also made an important 15% saving in the cost.

The result of the first sets of twin 1-m long magnets came in 1991–1992. Some people were disappointed because they felt that the results fell short of the 10 T field “promised” in the LHC “pink book” of 1990. However, anyone who knows superconductivity greatly appreciated that the first generation of twins went well over 9 T. This was already a high field and only 5–10% less than expected from the so-called “short sample” (the theoretical maximum inferred by measuring the properties of a short 50–70 cm length of the superconducting cable); accelerator magnets normally work at 80%, or less, of the short-sample value. The results of the 1m LHC models also made it clear that the cable’s mechanical and electrical characteristics and the field quality of the magnet (both during ramp and at the flat top) were not far from the quality required for the LHC.

A final step would be to combine the two branches of the development work and put together magnets of the twin design with a 10 m cold mass in a 1.8 K cryostat to demonstrate that full-size, LHC dipoles of the final design were feasible. However, the strict deadline imposed by the then director-general, Rubbia, dictated that the LHC should have the same time-scale as the SSC and be ready

Fig. 3. A workshop in Lausanne in 1984 looked at several early options for the LHC dipole, left, the second of which was retained in the final “twin” design, far right.

at the end of 1999. This meant that CERN was forced to launch the programme for the first full-size LHC prototypes in 1988, i.e. well before the end of the previous step, the construction in parallel of 1 m LHC MTA models and the 10-m long TAP.

At this point, CERN was just finishing construction of LEP and beginning work on industrialization of the components for LEP2; it was a period of shortage of personnel and financial resources (not a new situation). So Brianti and collaborators devised a new strategy: for the first time CERN would seek strong participation from national institutes in member states in the accelerator R&D and construction. In 1987–1988 the president of INFN, Nicola Cabibbo, and CERN’s director-general, Schopper, agreed – with a simple exchange of letters (everything was easier in those days) – that INFN would give an exceptional contribution to the LHC R&D phase. The total value was about SwFr12 million (1990 values) to be spread over eight years.

Towards real prototypes

In 1988 and 1989, INFN and CERN ordered LHC-type superconducting cables for long magnets and in 1989 INFN ordered two 10-m long twin dipoles from Ansaldo Componenti in Italy, some nine months before CERN had the budget to order three long dipoles, one from Ansaldo and two from Noell, a German company that had been involved in the construction of HERA quadrupoles. A fourth CERN long magnet, without the twin design, was ordered from the newly formed Alstom–Jeumont consortium (even at CERN some people still doubted the effectiveness of the twin design). The effort was decisive in being able by 1993 to have the magnets qualified by individual tests and then put into a string, consisting of dipoles and quadrupoles connected in series to simulate the behaviour of a basic LHC cell.

Parallel to the INFN effort, the French CEA–Saclay institute established collaboration with CERN and took over the construction of the first two full-size superconducting quadrupoles for the LHC. While CERN provided specifications and all of the magnet components (including superconducting cable), CEA did the full design and assembly of these quadrupoles, for a value a few million Swiss francs over the eight years of R&D (*CERN Courier* January/February 2007 p25). This was the start of a long collaboration; the French also continued to support the project after the initial R&D, throughout industrialization and construction phases, with an in-kind contribution on quadrupoles, cryostats and cryogenics for about SwFr50 million (split between CEA and CNRS-IN2P3).

The challenge of the prototyping was hard and covered many aspects. In particular for the dipoles, CERN first had to convince industry to pay enough attention and to invest resources in the LHC; the allure of the SSC, a much larger project (6000 main dipoles of 15 m length, 2000 quadrupoles, etc), was difficult to ignore. CERN’s project was much more challenging technically, with the required accuracy of the tooling a factor of five or so higher than for the HERA magnets. There was also the usual fight in a prototyping phase: good results required building expensive tooling for one or two magnets, with



Fig. 4. A short straight section, containing a prototype LHC main quadrupole from the CEA, on its test bench at CERN.

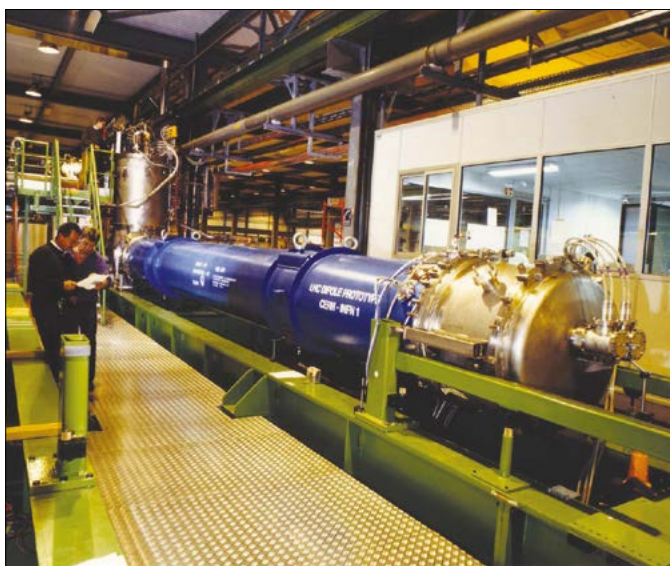


Fig. 5. On 14 April 1994 the first 10 m LHC dipole prototype from INFN was successfully powered at CERN for the first time. This magnet is now operating in the CAST experiment at CERN.

insufficient budget and no certainty that the project would be approved and the tooling cost thus paid for.

A delay of one year was the price to pay for the many developments and adjustments. Meanwhile, in 1993 the project had to pass a tough review devoted to the cryo-magnet system led by Robert Aymar, who as CERN's director-general 10 years later would collect the fruit of the review. With the review over and completion of the long magnet prototypes approaching, the credibility of the LHC project increased. In autumn 1993, the SSC came to a halt – certainly because of high and increasing cost (more than \$12 billion) and the low economic cycle in the US, but also because the LHC now seemed a credible alternative to reach similar goals at a much lower cost (\$2 billion in

CERN accounting). Rubbia, near the end of his mandate as director-general, which was the most critical for the R&D phase, led the project without rival. In a symbolic coincidence, the demise of the SSC occurred at the same as leadership of the LHC project passed from Giorgio Brianti, who had led the project firmly from its birth through the years of uncertainty, to Lyn Evans, who was to be in charge until completion 15 years later. The end of the SSC and the green light for the LHC was marked by the delivery to CERN of the first INFN dipole magnet in December 1993, just in time to be shown to the Council. This was followed four months later by the second INFN magnet and then by the CERN magnets, as well as by the two CEA quadrupoles designed and built by the team of Jacques Perot and later Jean-Michel Rifflet (figure 4).

Returning to the first dipole, which had been delivered from INFN at the end of 1993, a crash programme was necessary to overcome an unexpected problem (a short circuit in the busbar system – a problem that in a different form would later plague the project), so as to test it by in time for a special April session of the Council in 1994. The magnet passed with flying colours, going above the operational field of 8.4 T at the first quench, beyond 9 T in two quenches, and a first quench above 9 T after a thermal cycle i.e. full memory (figure 5). Its better-than-expected performance was actually misleading, giving the idea that construction of the LHC might be easy; in fact, it took a long six years before another equally good magnet was again on the CERN test bench. However, the other 10-m long magnets performed reasonably well and with the two very good CEA quadrupoles (3.5 m long), CERN set up the first LHC magnet string, to test it thoroughly and finally receive the approval of the project in December 1994.

Many other formidable challenges were still to be resolved on the technical, managerial and financial sides. These included: the nonuniformity of quench results and the problem of retraining that plagued the second generation of LHC prototypes; the unresolved question of the inter-strand resistance; the change of aluminium to austenitic steel as the material for the collars, implemented by Carlo Wyss; and the lengthening of the magnets from 10 m to 15 m with the consequent curvature of the cold mass, etc.

Looking back at the period 1985–1994, when the base for the LHC was established, it is clear that a big leap forward was accomplished during those years. The vision initiated by Robert Wilson for the Tevatron was brought to a peak, pushing the limit of Nb–Ti to its extreme on a large scale. New superconducting cables, new superconducting magnet architectures and new cooling schemes were put to the test, in the constant search for economic solutions that would be applicable later to large scale production. This last point is an important heritage that the LHC leaves to the world of superconductivity: the best performing solution is not always going to be really the best. Economics and large-scale production are very important when a magnet is part of a large system and integration is critical. “The best is the enemy of the good” has been the guiding maxim of the LHC project – a lesson from the LHC for the world of superconductivity in this 100th anniversary year. ●

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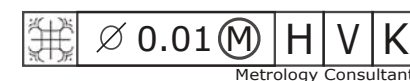
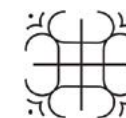


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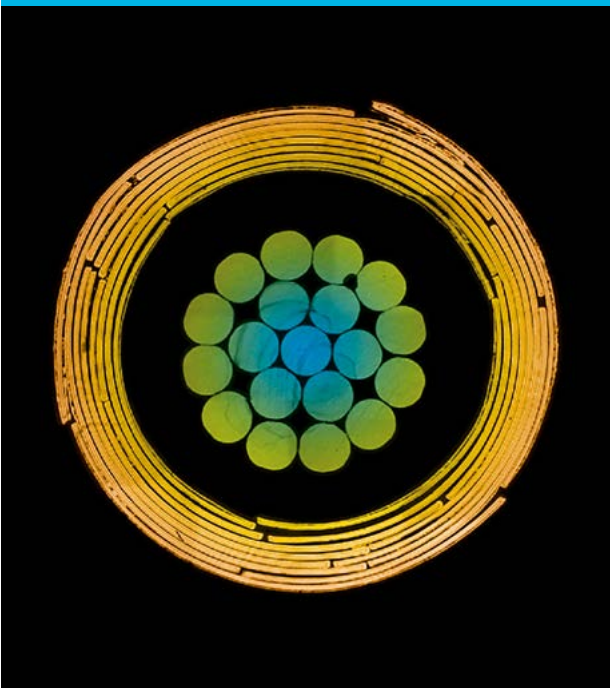


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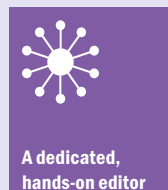
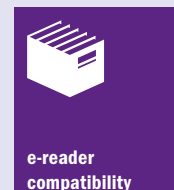
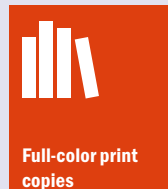
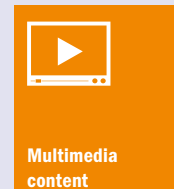
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Top: the encased toroidal-field coil, and winding of the conductor with millimetre precision. Bottom: the ITER site photographed in June 2017.

ITER'S MASSIVE MAGNETS ENTER PRODUCTION

As Matthew Chalmers reported in 2017, completion of the first toroidal-field coil for ITER demonstrates niobium-tin superconductor technology on a gigantic scale.

It is 14 m high, 9 m wide and weighs 110 tonnes. Fresh off a production line at ASG in Italy, and coated in epoxy Kapton-glass panels (image top left), it is the first superconducting toroidal-field coil for the ITER fusion experiment under construction in Cadarache, Southern France. The giant D-shaped ring contains 4.5 km of niobium-tin cable (each containing around 1000 individual superconducting wires) wound into a coil that will carry a current of 68,000 A, generating a peak magnetic field of

11.8 T to confine a plasma at a temperature of 150 million degrees. The coil will soon be joined by 18 others like it, 10 manufactured in Europe and nine in Japan. After completion at ASG, the European coils will be shipped to SIMIC in Italy, where they will be cooled to 78 K, tested and welded shut in a 180 tonne stainless-steel armour. They will then be impregnated with special resin and machined using one of the largest machines in Europe, before being transported to the ITER site.

SEPTEMBER 2019

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IN FOCUS MAGNETS



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Vacuum-pressure impregnation tooling.

Science doesn't get much bigger than this, even by particle-physics standards. ITER's goal is to demonstrate the feasibility of fusion power by maintaining a plasma in a self-sustaining "ignition" phase, and was established by an international agreement ratified in 2007 by China, the European Union (EU), Euratom, India, Japan, Korea, Russia and the US. Following years of delay relating to the preferred site and project costs, ITER entered construction a decade ago and is scheduled to produce first plasma by December 2025. The EU contribution to ITER, corresponding to roughly half the total cost, amounts to €6.6 billion for construction up to 2020.



This article is adapted from text in CERN Courier vol. 57, September 2017, pp34-36

Fusion for energy

The scale of ITER's components is staggering. The vacuum vessel that will sit inside the field coils is 10 times bigger than anything before it, measuring 19.4 m across, 11.4 m high and requiring new welding technology to be invented. The final ITER experiment will weigh 23,000 tonnes, almost twice that of the LHC's CMS experiment. The new toroidal-field coil is the first major magnetic element of ITER to be completed. A series of six further poloidal coils, a central solenoid and a number of correction coils will complete ITER's complex magnetic configuration. The central solenoid (a 1000 tonne superconducting electromagnet in the centre of the machine) must be strong enough to contain a force of 60 MN – twice the thrust of the Space Shuttle at take-off.

Fusion for Energy (F4E), the EU organisation managing Europe's contribution to ITER, has been collaborating with industrial partners such as ASG Superconductors, Iberdrola Ingeniería y Construcción, Elytt Energy, CNIM, SIMIC, ICAS consortium and Airbus CASA to deliver Europe's share of components in the field of magnets. At least 600 people from 26 companies have been involved in the toroid production and the first coil is the result of almost a decade of work. This involved, among other things, developing new ways to jacket superconducting cables based on materials that are brittle and much more difficult to handle than niobium-titanium. In total, 100,000 km of niobium-tin strands are necessary

for ITER's toroidal-field magnets, increasing worldwide production by a factor 10.

Since 2008, F4E has signed ITER-related contracts reaching approximately €5 billion, with the magnets amounting to €0.5 billion. Firms that are involved, such as SIMIC where the coils will be tested and Elytt, which has developed some of the necessary tooling, have much to gain from collaborating in ITER. According to Philippe Lazare, CEO of CNIM Industrial Systems Division: "In order to manufacture our share of ITER components, we had to upgrade our industrial facilities, establish new working methods and train new talent. In return, we have become a French reference in high-precision manufacturing for large components."

CERN connection

Cooling the toroidal-field magnets requires about 5.8 tonnes of helium at a temperature of 4.5 K and a pressure of 6 bar, putting helium in a supercritical phase slightly warmer than it is in the LHC. But ITER's operating environment is totally different to an accelerator, explains head of F4E's magnets project team Alessandro Bonito-Oliva: "The magnets have to operate subject to lots of heat generated by neutron irradiation from the plasma and AC losses generated inside the cable, which has to be removed, whereas at CERN you don't have this problem. So the ITER coolant has to be fairly close to the wire – this is why we used forced-flow of helium inside the cable." A lot of ITER's superconductor technology work was driven by CERN in improving the characteristics of superconductors, says Bonito-Oliva: "High-energy physics mainly looks for very high current performance, while in fusion it is also important to minimise the AC losses, which generally brings a reduction of current performance. This is why Nb₃Sn strands for fusion and accelerators are slightly different."

CERN entered formal collaboration with ITER in March 2008 via a co-operation agreement concerning the design of high-temperature superconducting current leads and other magnet technologies, with CERN's superconducting laboratory in building 163 becoming one of the "reference" laboratories for testing ITER's superconducting strands. Niobium-tin is the same material that CERN is pursuing for the high-field magnets of the High Luminosity LHC and also a possible future circular collider, although the performance demands of accelerator magnets requires significant further R&D. Head of CERN's technology department, Jose Miguel Jimenez, who co-ordinates the collaboration between CERN and ITER, says that in addition to helping with the design of the cable, CERN played a big role in advising for high-voltage testing of the cable insulation and, in particular, with the metallurgical aspect. "Metallurgy is one of the key areas of technology transfer from CERN to ITER. Another is the HTS current leads, which CERN has helped to design in collaboration with the Chinese group working on the ITER tokamak, and in simulating the heat transfer under real conditions," he explains. "We also helped with the cryoplants, magnetic-field quality, and on central interlocks and safety systems based on our experience with the LHC." ●



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