C. R. Physique 14 (2013) 2–14

Contents lists available at SciVerse ScienceDirect

Comptes Rendus Physique

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Physics in High Magnetic Fields / Physique en champ magnétique intense

State of the art and developments of high field magnets at the "Laboratoire National des Champs Magnétiques Intenses"

Etat de l'art et développements au « Laboratoire national des champs magnétiques intenses »

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ARTICLE INFO

Article history:
Available online 11 January 2013

Keywords:
High field magnet
Steady field magnet
Pulsed field magnet
High magnetic field

Mots-clés :
Aimant pour champs intenses
Aimant pour champs pulsés
Aimant pour champs continus
Champ magnétique intense

ABSTRACT

The "Laboratoire National des Champs Magnétiques Intenses" (LNCMI) is the result of the merger of the "Laboratoire des Champs Magnétiques Intenses" in Grenoble specialised in the generation of DC magnetic fields and the "Laboratoire National des Champs Pulsés" in Toulouse specialised in the generation of pulsed magnet fields. DC fields of up to 35 T, pulsed fields up to 80 T and single-shot pulsed fields up to 170 T are provided to an international community of users. In the present paper we present the current state of our installations and the developments which are pursued in the context of an increasing international competition.

RÉSUMÉ

Le Laboratoire national des champs magnétiques intenses (LNCMI) est issu de la fusion du Laboratoire des champs magnétiques intenses de Grenoble spécialisé dans la production de champs magnétiques continus et du Laboratoire national des champs pulsés de Toulouse spécialisé dans la production de champs magnétiques pulsés. Le LNCMI accueille une large communauté internationale de chercheurs pour la réalisation de projets scientifiques ou technologiques nécessitant l'utilisation de champs magnétiques intenses. Des champs magnétiques de 35 T en continu, 80 T en pulsé et 170 T à l'aide bobine explosive ont ainsi été développés au laboratoire et mis à disposition des chercheurs. Nous présentons dans cet article l'état de l'art et les perspectives de développements en situant le laboratoire vis-à-vis d'une compétition internationale de plus en plus acharnée.

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1. Introduction

The usefulness of high magnetic fields to change thermodynamic variables in fundamental and applied physics is clearly documented by the scientific papers contained in this edition of C. R. Physique. The magnetic field necessary to create new phases or to observe new effects depends on the particular type of physics as well as on the sample quality. The general tendency is that "higher is better", either to have a more extended access to parameter space or to have a better signal

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1631-0705/$ – see front matter
http://dx.doi.org/10.1016/j.crhy.2012.11.002

to noise ratio. In some peculiar cases, once a phenomenon is discovered, improvement of the samples can make the effect visible at lower fields, as happened for instance with the quantum Hall effect.

Magnetic fields existing in nature vary over several orders of magnitude: the field generated by our brain (10^{-9} T), the Earth's magnetic field (4×10^{-5} T), the magnetic field at the pole of a strong permanent magnet (1 T), the field of a medical resonance imaging (MRI) device in a hospital (3 to 5 T), the field of a Nb_3Sn superconducting magnet (23 T), the highest man-made field (explosive flux compression $\sim 2 \times 10^3$ T), the field of a magnetic white star sun (10^4 T) and the field of a neutron star (10^8 T). Strictly speaking the magnetic field should be expressed in A/m, but it is customary to use the magnetic induction with the unit tesla (T) (and equal to the product of the permeability of the vacuum ($\mu_0 = 4\pi \times 10^{-7}$ in SI units) multiplied by the magnetic field: $B = \mu_0 H$ in the absence of matter). To produce a magnetic field the standard method is to have a circulating electrical current, either by a wire-wound coil, Bitter plates or helix type of structures. The magnetic field depends linearly on the current density and on its distribution in space. This current density generates a force density proportional to the product of the current density j and the magnetic field, i.e. proportional to B^2. For all conductors, except for superconductors, Joule losses occur when a stationary current density is present in their volume. These losses generate a power density proportional to j^2, i.e. also proportional to B^2. In this article we will explain which technological solutions are available to handle these problems and in which ways the maximum field, the duration and the useful volume are restricted.

At the time of writing some records are 23.5 T for an all-superconducting magnet, 45 T for the highest steady field (> 1 h), 100 T for the highest repetitive (> 2×) pulsed field, ∼ 300 T for the highest single-shot field and ∼ 2000 T for the highest destructive (explosive flux compression) field. The major part of the measurements is however performed in fields 10–20% lower than these record values. Hereinafter, we will adopt the practical, but arbitrary, definition of a high magnetic field being a field that cannot be generated with a superconducting coil alone.

2. The technical constraints that limit the generation of high magnetic fields

2.1. Lorentz forces

The force per length (F_l) on a linear current (I) in a constant magnetic field (B) is $F_l = B \times I$, this can easily be transformed into a local expression that only contains a force density (F_v) and the current density: $F_v = B \times j$. For homogeneous cylindrical current distributions this force is the highest in the midplane and directed radially outward causing a tangential (hoop) stress. In order to calculate the stresses and strain for such a coil several analytic codes and finite element approaches are available with various degrees of complexity. For independent turns and for the above mentioned type of coil this results in a tangential (hoop) stress that is equal to Bjr (Fig. 1A) with a maximum close to halfway the outer radius. Detailed finite element calculations (Fig. 1B) confirm that the highest stresses are indeed close to the midplane halfway the coil thickness.

If the windings are glued together, or if there is a mechanical continuity, as for "Bitter" plates for instance, this region with the highest force density will pull on the material closer to the inside resulting in the maximum stress close to the inner bore. This effect is believed not to exist in wire-wound coils (the wires are supposed to separate under radial tension), but exists in "Bitter" plates where it was very elegantly reduced by reducing the radial stiffness of the Bitter plates [1].

When leaving the midplane and off the main magnetic axis the radial component of the magnetic field will result in an axial compressive force density. This force will cause a compressive axial pressure in the midplane equal to the integral of the axial force density over a path parallel to the axis from the coil-end to the midplane. This integral can be simply expressed in terms of the vector potential [2].

Both forces are proportional to B^2 and are the main limiting mechanical factors in magnet design. To contain these forces several options exist: the use of strong materials (but this increases the resistivity and hence the Joule losses), external reinforcement (but this is limited due to plastic backflow [3]) or distributed reinforcement (but this reduces the so-called filling factor [4]: the ratio between the volume where the electrical current flows and the total coil volume). Another possibility is to tailor the current density in such a way that the stresses are equal everywhere (at the expense of efficiency). All three approaches are used to build coils, the last one specifically in the so-called poly-helix design developed in Grenoble [5]. In theory this method could be used to make any magnetic field with a fixed arbitrary low stress level by adapting the current density everywhere [6]. Although this approach is mathematically correct it can be easily shown that such a coil built from soft copper would have for a field of 50 T dimensions of the order of several km! The only practical way to make magnetic fields higher than what would be allowed by the mechanical strength of the material is to rely on the inertia of the coil to contain the Lorentz force (and hence the current path) during a very short time. These are the single-shot coils that fail during the pulse, but in some designs the sample and cryostat survive (most of the time). In this way one can produce fields from 100 to 350 T [7], or even higher if the loss of sample and cryostat is accepted.

Maximal stress values in 30 T direct current (DC) Bitter and poly-helix coils are around 300 MPa which is compatible with high-conductivity copper alloys, whereas for pulsed-field coils typical values are around 1000 MPa at 60 T. These stresses are contained with "exotic" low-conductivity copper alloys (highly cold-deformed alloys with Ag or Nb for instance) or with fibre or steel reinforcement (typically 2000–3000 MPa) or a mixture of these two. The relatively low stress level for the 60 T coil (one would expect 300 MPa $\times (60/30)^2 = 1200$ MPa, since forces and hence stresses scale as B^2, when scaling the stress of a 30 T DC coil to the 60 T level) is due to the fact that pulsed coils have a better filling factor since they do not need cooling channels.

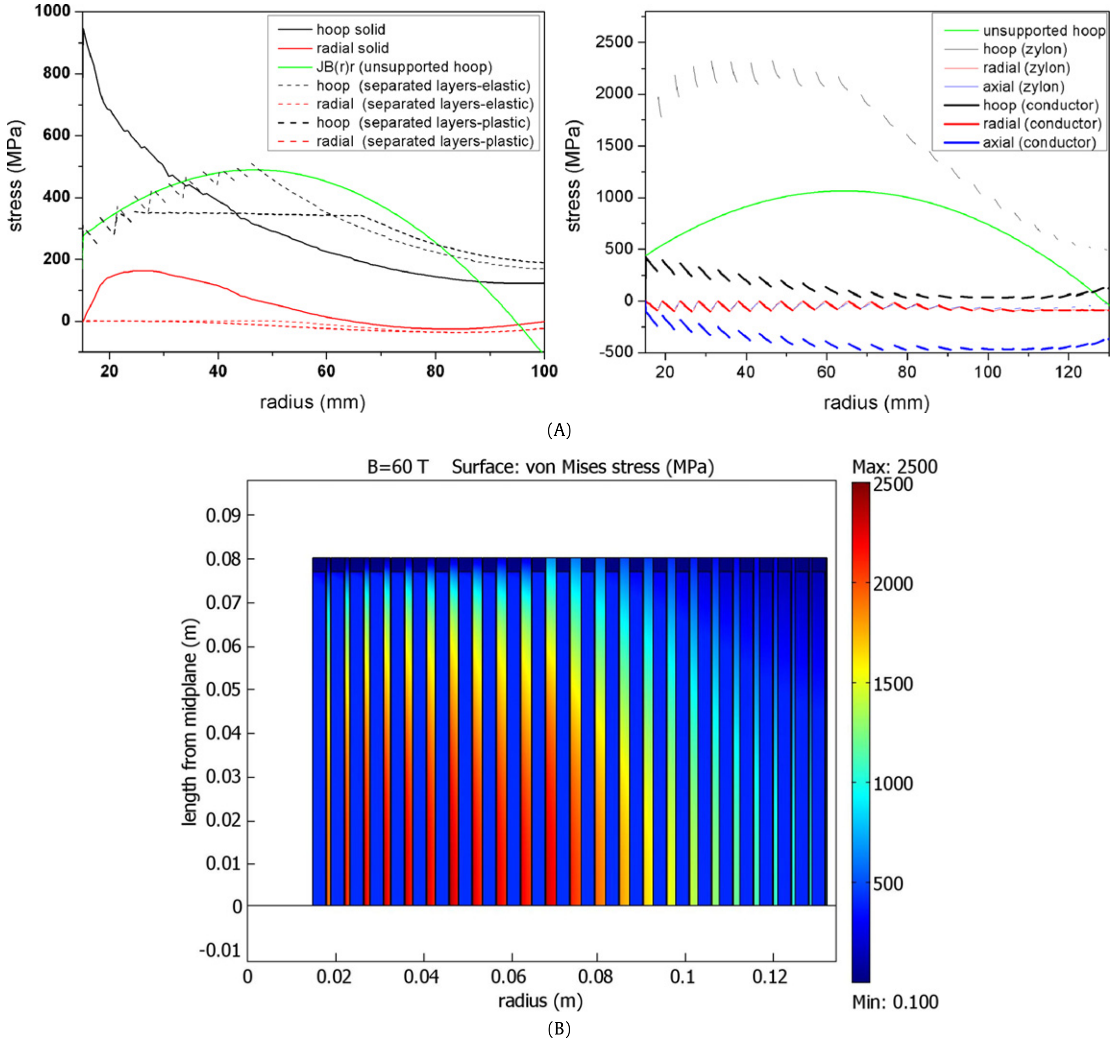

Fig. 1. (A) Left: typical radial [red] and tangential [black] (elastic) stresses in the midplane in a "thick-walled" solenoid at 40 T as a function of the radial position between inner and outer radii, with constant current density for three different situations: totally independent layers [green line], a completely monolithic coil [solid line] and the most realistic case where there is radial stress transmission between the layers under compression but no stress transmission under tension [dashed lines]. For the last case stresses are also shown in case of plastic deformation in a part of the coil as would be observed for a coil wound with hard-drawn copper [long dashed lines]. Right: a 60 T coil, wound also from hard-drawn copper, with the same number of layers and internally reinforced with Zylon at variable thickness (thickness such that the stress in the Zylon is constant, but with a minimum thickness of 0.3 mm). (B) The von Mises stress in the section of a "thick-walled" solenoid reinforced by distributed Zylon at 60 T.

2.2. Heating

The resistive losses in a coil are, except for eddy-current losses in pulsed coils, proportional to the current squared and the electrical resistance. The power loss density $P_v = j^2\rho$ is, for a given coil dimension and field, independent of the wire section and the current. The thermal load is (as the mechanical load) proportional to B^2. To cope with this heat load is an essential task when designing pulsed or DC coils. And since the electrical resistivity rises with increasing mechanical strength, in an optimised coil design one should target to hit the mechanical and thermal limits at the same time.

For DC coils the only solution is the removal of the heat generated in the coil at the same rate as it is produced. This imposes cooling channels. This cooling is in nearly all cases done with water, typically at temperatures of around 30 °C, taking advantage of its large specific heat. Typical power densities found in DC coils amount to 2 W/mm^3.

For pulsed coils one can use the heat capacity of the conductor to temporarily cope with the power density, and switch off the current before the coil becomes too hot. In fact this is the main reason why these coils are pulsed. The gain in using pulsed coils is that one can build electrically more efficient coils (since we do not need cooling channels) although one might need more electrical power. Since we use the heat capacity to temporarily store the energy before the coil becomes too hot, it is evident that starting at a low temperature will allow for longer pulse durations. Moreover the resistivity of a metal decreases when going to lower temperature, so in cooling down one gains twice: the power density for a given field

Table 1
The effects of linear scaling of the coil dimensions by a factor λ keeping the magnetic field constant (r_i = inner radius, j = current density, R^* and L^* are the normalised (i.e. divided by the number of turns squared) resistance and self-inductance, E_{magn} is the magnetic energy at maximum field and P_{loss} is the power loss, τ is the rise-time to maximum field).

r_i	vol.	stress	j	R^*	L^*	E_{magn}	P_{loss}	τ
λ^1	λ^3	λ^0	λ^{-1}	λ^{-1}	λ^1	λ^3	λ^1	λ^2

Table 2
Approximate scaling effects when increasing the coil size with a factor α while keeping the maximum field and the radius of the bore fixed (r_o = outer radius).

r_o	vol.	stress	j	R^*	L^*	E_{magn}	P_{loss}	τ
α	$\alpha^{3.1}$	$\alpha^{\sim -0.2}$	$\alpha^{-1.2}$	$\alpha^{-1.4}$	$\alpha^{0.7}$	$\alpha^{2.7}$	$\alpha^{0.7}$	$\alpha^{2.4}$

Table 3
Approximate effect on the maximum field of reducing the inner bore radius while keeping the current density constant, with the field B_0 for $r_i = 0$, $\gamma = \frac{(r_o - r_i)}{r_0}$ and $B_{max} = \gamma B_0$.

r_i	vol.	stress	j	B_{max}	E_{magn}	P_{loss}	τ
$(1-\gamma)r_o$	$\gamma^{\sim 0}$	γ^0	γ^0	γ^1	$\gamma^{\sim 0}$	$\gamma^{\sim 0}$	$\gamma^{\sim 0}$

(i.e. given current density) decreases because of the decreasing ρ and secondly we can dissipate more energy before the coil becomes too hot. It can be easily shown that the end temperature is only depending on the "action integral" and the temperature dependence of the ratio of C and ρ [3]:

$$\int_{t_{start}}^{t_{end}} j(t)^2 \,\mathrm{d}t = \int_{T_{start}}^{T_{end}} \frac{C_p(T)}{\rho(T)} \,\mathrm{d}T \tag{1}$$

where C_p is the specific heat per volume and ρ is the resistivity as a function of temperature; t is the time duration of the pulse.

As the specific heat also decreases with decreasing temperature, very low temperatures (i.e. below 77 K) do not bring much gain.

Most pulsed coils are cooled by liquid nitrogen to 77 K and are heated during the pulse to approximately room temperature. Typical pulse durations are of the order of 100 ms with cooldown times of 1 to 2 hours. Typical power densities for pulsed coils are 10 W/mm^3 for the conductor only and 5 W/mm^3 for the overall structure.

2.3. Scaling

Since the losses and stresses depend only on the current density and the coil shape but not on the wire section or the number of turns one can easily deduce scaling laws. These scaling laws are exact as far as every parameter in a coil changes with the same scaling factor (including for instance the insulator thickness) keeping the filling factor (the fraction of the coil-section where there is actual current flowing) and the current density distribution homogeneous (i.e. no eddy-current effects). These exact scaling laws are given in Table 1.

Under some realistic assumptions one can also deduce some approximate scaling behaviour [8] for changing the ratio of outer to inner radius (α) and fixed inner radius and maximum field (Table 2).

Fixing the outer radius and the current density results in the approximate scaling relations, with the field B_0 for $r_i = 0$ shown in Table 3.

The bottom line is that for constant field and stress the energy goes as λ^3 and the resistive power as λ. So it is, from engineering and investment viewpoint, a good idea to have the inner bore as small as possible, especially for installations that are energy limited (as are most pulsed-field installations).

3. Power and energy requirements for high magnetic fields

3.1. Power and energy limitation

The power and energy available for generating high magnetic fields are limited due to several reasons. For DC magnets the power is limited in an absolute way by the electrical power available for a magnet at a given high field facility (from 10 to 56 MW). The second limitation comes from the availability of the cooling power. Up to 300 l/s of cold water are needed to cool a 35 T magnet. To obtain a steady field all the dissipated power has to be extracted in real time, however creating a reservoir with (pre)cooled water permits to install less cooling power than electrical power. The DC field installation can then be considered as a sort of pulsed installation with a very long pulse. This is the case for all DC facilities worldwide except for the Grenoble facility which takes its cooling power from the nearby "Drac" river.

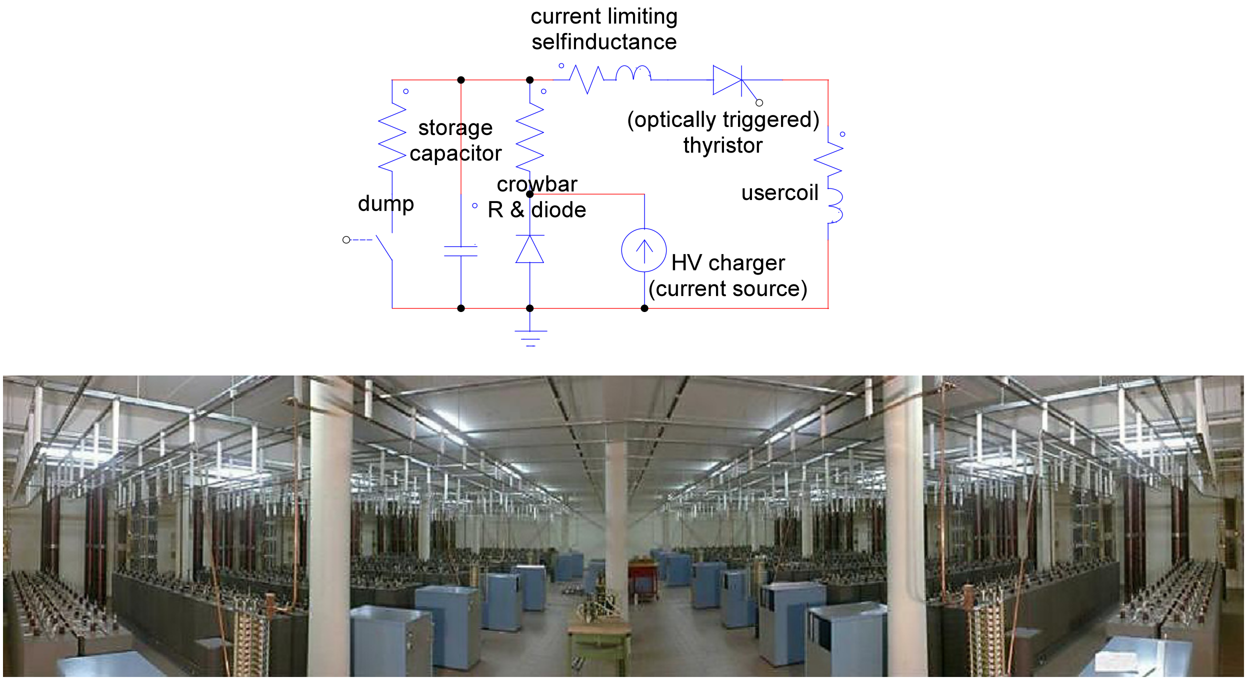

Fig. 2. Top: the basic circuit of a capacitor bank showing the main components: a dump resistor with a discharge switch, the storage capacitors protected by a fuse (fuse not shown, normally a large number of capacitors is in parallel and every capacitor is protected by a fuse), a crowbar diode and its resistor to create an exponentially decaying field and to limit the voltage reversal on the capacitors, a self-inductance to limit the current in the installation in case of a short, the high-voltage charger (normally a voltage limited current source), a switch (in nearly all cases a thyristor, except for single-turn coils) to connect the stored energy to the user coil, and finally the user coil that has an inductance and a history dependent resistance. Bottom: a fish-eye view of the 14 MJ capacitor bank as installed at the pulsed facility LNCMI-Toulouse (blue cabinets are the chargers, grey boxes are the capacitors and the cylindrical structures at the back are the protecting self-inductances). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For pulsed magnets, the situation is reversed. Since typical pulse rise-times are of the order of 10–50 ms and the magnetic energy of the order of 1 to 5 MJ, it is obvious that one needs an electrical power of the order of 100 MW but only for a very short time. Installing a classical supply would be very expensive and since the required energy is limited (the magnetic energy plus the energy to heat the coil from liquid nitrogen temperature to the room temperature) another way of energising the magnet is possible. To reduce the electrical power required from the public grid one can store energy for a relatively long time (several minutes) and release it during the pulse. An average power to peak power ratio of 5000 can easily be obtained. There are several solutions to store the energy: magnetically in a big self-inductance, mechanically in a flywheel [9,10], chemically in a battery [11] or electrically in a capacitor. For practical reasons, the latter solution is used as the resistive and inductive load of the high field coil is then combined with a capacitance giving automatically a sinusoidal pulse. Fig. 2 (top) shows the principle of the corresponding electric circuit and on the bottom a photograph of the 14 MJ capacitor bank as installed at the Toulouse site of the LNCMI. The three other options of energy storage are or have been used as well, especially for longer pulse shapes or controlled pulses [12–15]. Examples are the former Amsterdam 40 T installation that had a unique controlled pulse form and was directly energised by a 5 MW supply connected to the public mains [3] and a similar installation in Vienna [16].

3.2. Cooling

DC and pulsed magnets need cooling to remove the dissipated heat. For DC magnets this heat has to be removed at the same rate as it is dissipated to run at a constant temperature. Consequently DC magnets include cooling channels. In poly-helix magnets, the annular space between two consecutive helices (or the spacing between the turns of the helices in the case of radially cooled helices first developed at the MIT in Boston [17]) constitutes the cooling channel. For Bitter magnets elongated holes are machined along the azimuthal direction and at different radii in each copper alloy disk and insulation foil. When stacked together, hydraulic channels are formed parallel to the main axis of the solenoid. Pulsed magnets rely on the heat capacity of the conductor to temporarily store the dissipated energy during the pulse that is removed after the pulse. Pulsed magnets had historically no dedicated cooling channels as this was thought to weaken the structure and to reduce the filling factor. The development of distributed reinforcement coils, where in principle all the layers are mechanically independent, has permitted to include annular cooling channels (i.e. a cylindrical cooling space similar in shape to a layer of turns) at the expense of a very limited reduction in filling factor since cooling channels of 3 mm radial thickness turn out to be more than sufficient. It can be shown that for n cooling channels one gains theoretically a reduction by a factor $(n+1)^2$ of the cooldown time for infinitely long coils with cooling channels that are so wide that the surface of the channel remains at 77 K. In practice this factor amounts to ~ 3.5 for one cooling channel and to ~ 7 for 2 channels [18]. This gain is of enormous importance for a user of a high field facility since it reduces typical cooling times below ~ 1 h. In pursuing this approach one can imagine poly-helix coils, that are normally cooled by water for producing DC magnets, cooled by liquid nitrogen to produce rapid-cooling (high duty-cycle) pulsed-field coils to be used e.g. in X-ray or neutron scattering experiments.

It should be noted that DC magnets are cooled by increasing the temperature of liquid water (typically with a $\Delta T \sim 30$ K that corresponds to ~ 125 kJ/l) that circulates in a closed loop connected though a heat exchanger to a primary cooling source coming from a river or from chilled water reservoir, whereas pulsed-field coils are cooled by (mainly) evaporation of liquid nitrogen (heat of evaporation ~ 159 kJ/l).

4. Materials

4.1. Conductors

From what has been mentioned before it should be clear that the mechanical strength and electrical conductivity are the key parameters for the choice of the conductor. For DC magnets these two competing requirements are taken into account in such a way that when the maximum magnetic field is reached the conductor strength at any position of the different conductors constituting the magnet the strength is just sufficient to contain the local Lorentz force. This strategy permits to construct the most economic magnet as the conductivity of copper alloy is increasing with decreasing mechanical properties. In practice DC magnets use high-conductivity copper alloys as conductor with a conductivity ranging from 45 to 58 MS.

For pulsed fields the strength and conductivity are in principle decoupled, since the amount of dissipated heat can always be limited by reducing the pulse duration. However in a well-balanced design (to have the highest field and longest pulse for a given energy supply and magnet bore) we should choose materials such that we are equally limited by the thermal and mechanical constraints. For the material choice one has at least two possible routes: either the combination of a good conductor (i.e. copper) with a strong but less conducting material, a so-called macro-composite where the composite conductor properties show the weighted average of the two constituents [19,20] or a micro-composite. A micro-composite [21–24] is a mixture of two materials on a very fine scale that is prepared in such a way (mostly by applying a lot of cold deformation) that the final properties can be superior to what would be deduced from the weighted average of the properties of the two constituents. For all high-strength materials (typical strength of the order of 1 GPa) a serious limitation is the limited additional plastic deformation that can be supported and hence the “windability”. The limited additional plastic deformation is also a problem when combining these materials with internal or external reinforcements. It turns out that most of the metals used become stronger at lower temperatures, a welcome feature that allows some safety margin in the design. Additional important characteristics of a conductor are (apart from evident economic aspects) the fact whether the material has still some degree of plastic deformation (useful in order to avoid catastrophic failure due to locally high stresses in case of small irregularities in the coil structure), its availability in relatively large quantities (~ 20 to 40 kg) and with a section of several mm^2 (most micro-composites require a lot of cold work and are thus practically hard to obtain in large sections).

4.2. Insulators

Interlayer and interturn voltage seem, at first sight, relatively low, less than 100 V for DC magnets and less than a few kV for pulsed magnets. A typical polyimide (Kapton) type insulator has a dielectric strength of 200 V/μm so 20 μm of Kapton should be sufficient as insulation and most of the wires are insulated by two layers of 25 μm such that in between any two conductors there is 100 μm of Kapton allowing for a voltage difference of 20 kV. However, in practice, coil failure is quite often a combination of mechanical and electrical failures in a chicken-and-egg situation! It is assumed that the Kapton insulation suffers from the repeated and rapid mechanical and thermal loads and this would account, at least partly, for the fact that a typical highest-field pulsed coil has a lifetime of the order of 500–1000 pulses and that bigger coils (for similar wire section and maximum field) tend, unfortunately, to have shorter lifetimes. Several other types of insulation have been tried. Several types of coatings or varnishes that work well with soft copper are difficult to apply to high-strength conductors. A mechanical reason is that it is hard to control the layer thickness of the varnish on a rigid (and sometimes twisted) wire. A physical one is that all strong conductors have integrated a lot of cold work and are thus prone to annealing when the varnish is applied or dried at higher temperature. Moreover, it is quite difficult to have a good adhesion to the steel surface of a copper stainless steel macro-composite wire for chemical reasons. Impregnated glass fibre insulation tends to develop cracks due to bending during coil-winding as well as differential thermal contraction. Moreover, glassfibre insulation results in a very poor filling factor.

4.3. Reinforcement

Another way of increasing the field would be to include reinforcement. The most evident way to apply reinforcement would be to put an external reinforcing cylinder at the outside of the coil since this would contain the main component

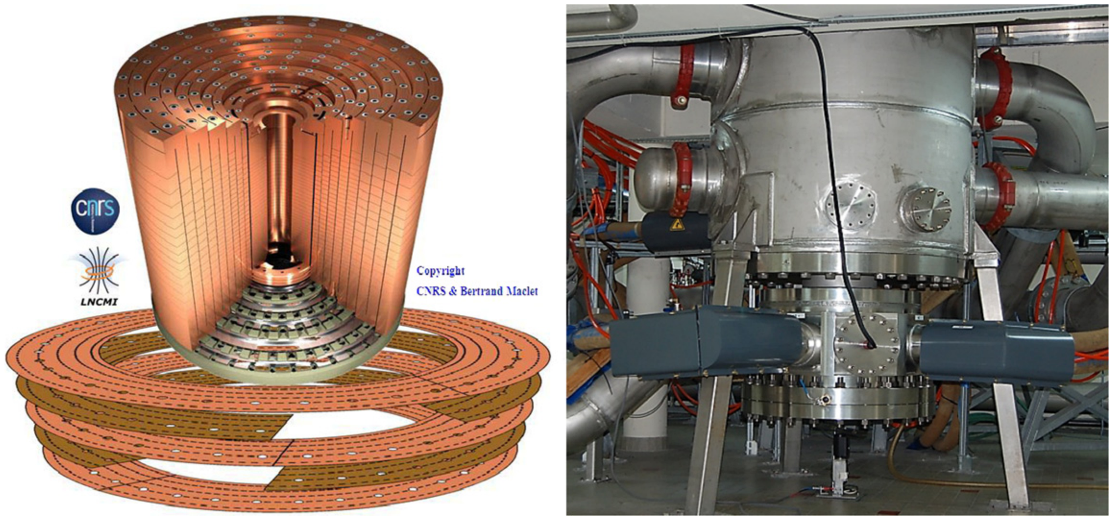

Fig. 3. Left: the two main technologies used for DC high field magnets. For Bitter magnet type, the external diameter can reach one meter. For sake of understanding, only three copper alloy disks and two insulator sectors have been represented. The innermost magnets can consist of either Bitter or poly-helix coils. A poly-helix coil is made of a set of concentric copper alloy tubes which have been cut in a helix shape. This arrangement permits to divide the high field magnet in different sub-coils (10 on this figure) giving a new degree of freedom for the optimisation process. Typical current supplying these magnets is 30 000 A with a corresponding current density of 300 A/mm^2. Right: general view of a 35 T magnet in operation at the LNCMI-Grenoble DC facility, the height of the structure visible in the picture is approximately 2 m.

of the Lorentz force that is radially outwards and at the same time would not influence the coil efficiency or filling factor. However one can show that even with an infinitely stiff and strong reinforcing cylinder one would not be able to generate very high fields in a repetitive way since the conductor would be deformed plastically at every cycle. A more efficient approach is the use of one, relatively thin reinforcing cylinder at approximately halfway the coil thickness [3].

A sophisticated way to apply reinforcement is the use of distributed reinforcement at every layer, where the amount of reinforcement can be adapted to the local load, as was first proposed in [4]. Ultra-strong fibres are the preferred reinforcing material since they can easily be applied in tangential direction. An impressive number of record fields has been obtained with this method pioneered in Leuven [25–29]. However the unidirectional composite (fibre plus epoxy) produced in this way has the disadvantage of negligible strength in any other direction than the tangential direction. If one could overcome this problem without losing strength in the tangential direction it is very likely that a significant gain in maximum field could be obtained.

5. Continuous magnetic fields

5.1. Resistive magnets

As classically wound coils do not allow for sufficient cooling, specific technologies have been developed, that use either a copper alloy disk or helix as the elementary building block for construction. These geometries are suitable for withstanding the electromagnetic forces and allow circulation of cooling water at sufficient high speed to retrieve Joule losses.

Fig. 3 displays the principle of the two technologies. 35 teslas in a 34 mm room temperature bore available for the experiments is the magnetic field record when applying those principles to design high field solenoid magnets. To understand the challenges for designing such magnets, the following figures are noteworthy: DC currents used to power the windings classically range from 20 to 30 kA with a typical turn section of 1 cm^2. Consequently high power densities of the order of 1 to 2 W/mm^3 are found in the conductor as well as high heat fluxes (3 to 5 W/mm^2) at their surface. These values are one order of magnitude higher than what can be found in the core of boiling or pressurised water nuclear reactors. For a 35 T magnet in a 34 mm bore, the electromagnetic forces generate a maximal tensile stress in the windings of the order of 400 MPa. The corresponding Joule power is of the order of 20 MW. Consequently the production of even higher magnetic field will be mainly limited by two factors: the material available to cope with high stress and high power density and the maximal electrical power available for the magnetic field production. At the world level, only five facilities have power available in excess of 10 MW for DC field production (Table 4): Tallahassee (Florida, US), Grenoble (France), Nijmegen (the Netherlands), Tsukuba (Japan), and the new facility of Hefei (China) under construction. The magnetic field increases with the current and consequently only with the square root of the electrical power. A 50 MW facility could permit to approach a magnetic field of 50 T. Nevertheless, in Tallahassee, the only place where this power is available, no project exists up to now to use this power for a single magnet. A kind of international consensus appears as a consequence of the rising energy costs, that magnetic fields in excess of 40 T should be obtained either by “hybrid” magnets or by pulsed magnets.

Table 4
Maximum magnetic fields available and planned at the main DC high field facilities. Only five high field facilities worldwide have electrical power available higher than 10 MW, giving access to magnetic field ranging between 33 and 45 T.

Copper alloy coils	*In operation in* 2012:	
	Grenoble, France	35 T in 34 mm
	Nijmegen, the Netherlands	33 T in 32 mm
	Tallahassee, the United States	35 T in 32 mm
Hybrid magnets (> 35 T)	*In operation in* 2012:	
NbTi and/or Nb_3Sn outer coils	Tallahassee, the United States	45 T = 11 T (Nb_3Sn) + 34 T (30 MW)
&	Tsukuba, Japan[a]	38 T = 14 T (Nb_3Sn) + 24 T (14 MW)
Copper alloy inner coils		
	Under construction, available in 2014–2018:	
	Grenoble, France	44 T = 9 T (NbTi) + 35 T (24 MW)
	Nijmegen, the Netherlands	44 T = 11 T (Nb_3Sn) + 33 T (22 MW)
	Hefei, China	40 T = 11 T (Nb_3Sn) + 29 T (20 MW)
	Tallahassee, the United States[b]	36 T = 14 T (Nb_3Sn) + 22 T (12 MW)

[a] Not available since March 2011, a new project is under definition in collaboration with the Sendai laboratory.
[b] Highly homogeneous magnet where the resistive and the superconducting parts are electrically powered in series. Will be mainly dedicated to Nuclear Magnetic Resonance experiments.

5.2. Hybrid magnets

The principle of a hybrid magnet is to add the magnetic field produced by a superconducting solenoid to the one produced by a copper based solenoid. The superconducting solenoid is always the outer magnet so that the superconductors are not exposed to the high magnetic field in order to preserve their superconducting properties. For a given power available it is the way to achieve the highest magnetic field. Consequently almost every DC high magnetic field facility has its own program of developing a hybrid magnet. The superconducting part of such a hybrid configuration encounters additional constraints as compared to a comparable (in size and field) stand-alone superconducting magnet since electromagnetic coupling between the copper and the superconducting coils reduces the superconductor safety margin. This reduction is due to the induced currents when ramping the inner magnet or (even worse) if the insert has an emergency shut down. Cryogenics and safety are critical issues for these machines which store magnetic energies as high as 50 to 100 MJ. State of the art hybrid magnet construction shows that for a comparable diameter the superconducting contribution to the total magnetic field of a hybrid magnet is around 30% less than what could have been obtained with an equivalent stand-alone superconducting magnet. There are only two hybrid magnets worldwide that provided a magnetic field higher than 35 T as can be seen from Table 4. Older hybrid systems that have produced fields in the range of 25 to 30 T have been progressively dismantled and replaced by 15 to 20 MW copper based magnets that permit much higher sweeping rate suitable for a large part of condensed matter physics experiments. Some of these hybrids are still available in Boston and Sendai but not mentioned in Table 4. New high field hybrid projects are ongoing at the different high field facilities located in China, Florida, France, the Netherlands and Japan. They have the double aim to reach record magnetic fields and to lower running costs when long time measurements are needed at constant field (for example in the case of NMR or levitation experiments). Table 4 summarises the main characteristics of these projects. Using Nb_3Sn alloy for the superconducting outer part of a magnet approaching 20 T in a large bore (200 to 400 mm) seems to be the ultimate goal, at the limit of the physical properties of this material. Consequently when using the classical hybrid configuration it seems difficult to imagine magnetic field in excess of 60 T (it would be easier with a copper based magnet but a 100 MW power supply will be needed for a typical bore size of 30 mm). That leads us to consider, in the next paragraph, pulsed magnetic fields that allow one to reach higher field at the detriment of the duty cycle. Another “hybrid approach” is to use a low temperature (and relatively low cost) superconductor for the outer magnet and high temperature superconductors taking advantage of their high critical magnetic field for the inner part. Numerous small size coil prototypes have been fabricated and tested in a magnetic environment available in high field facilities. Different R&D programs are now carried out in high field facilities and companies specialised in NMR magnets in order to be able to reach superconducting fields in the range of 25 to 30 T. Nevertheless a lot of technical issues need still to be solved such as detection of a quench in the high temperature superconductors or the anisotropy of the $YBa_2Cu_3O_7$ superconducting properties (one of the most realistic candidates for high magnetic field applications). In Europe, these developments are pushed by European programs such as EUCARD that has the mission to organise the R&D for a possible upgrade of the LHC at the 2025 horizon.

In 2009, a first 30 T all-superconducting magnet project has been launched at the NHMFL, Tallahassee. In Europe, the Dresden and the Grenoble facilities are asking funds to start with a similar project in order to stay competitive at the global level. Such a project will boost the development of the high temperature superconductor technology in Europe.

6. Pulsed magnetic fields

At the Toulouse site of the LNCMI standard coils up to 70 T are installed and available to users. All coils for field of 60 T or above are reinforced by distributed layers of Zylon [4] fibre (Table 5). Most of the coils are now equipped with annular cooling slits that reduce the typical cool down time by more than a factor of three.

Table 5
An overview of the available coils at the Toulouse site of the LNCMI, t_{max} is the time between the beginning of the pulse and the time when the field reaches the maximum, t_{cool} is the time needed to cool the magnet again in order to allow another pulse at maximum field after a pulse at maximum field.

Cooling: N = normal, R = rapid	t_{max}	B_{max}	Bore (mm) at 77 K	t_{cool} (min) after B_{max}	Remarks
N	~ 70 ms	35	26	90	copper coil
R	27 ms	60	11.2	≪ 45	
N	~ 26 ms	60	12	90	copper stainless coil
N	27 ms	60	12	75	
N	28 ms	60	13	75	
N	54 ms	60	28	240	
R	54 ms	60	28	75	gain of 240/75 = 3.2 × in cooldown time!
N	31 ms	70	12	180	
N	31 ms	70	13	180	
N&R	~ 27 ms	81	13	75	prototype dual coil magnet
–	2.5 µs	~ 200	10	–	single-turn coil

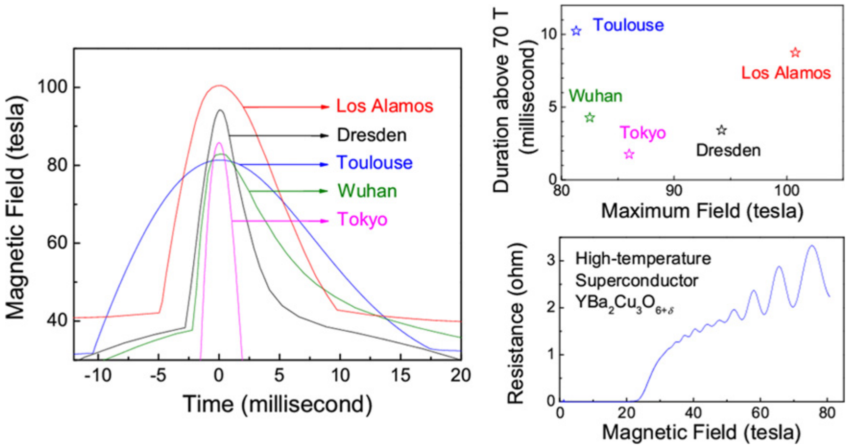

Fig. 4. Various maximum field–time profiles at the major pulsed-field installations, the top right frame shows the field duration above 70 T and the lower right frame shows a resistance measurement up to 81 T realised in Toulouse [26–30].

For fields above 70 T we have a dual coil system, similar to the system developed in the European "ARMS" [8] project, that can be used for experiments at fields up to 81 T and has a bore (at liquid nitrogen temperature) of 13 mm. A typical pulse shape of this system compared to various other states of the art installations is given in Fig. 4.

For even higher fields a single-shot, rapid pulse installation is available for fields up to 200 T in a bore of 10 mm.

Finally, apart from the coils for neutron and X-ray diffraction that will be discussed below, some specialised coils that are optimised not for the highest field but to have the highest integral of B^2l (with the magnetic field B and the path l in the field, $B^2l \sim 150$ T^2m) are available (Fig. 5), such coils are used in the BMV ("Biréfringence Magnétique du Vide" – the vacuum magnetic birefringence) experiment [31,32]. These coils are mainly dedicated to optical experiments.

7. High magnetic fields in combination with other experimental techniques

7.1. Introduction

High magnetic fields are one of the most powerful tools available to scientists for the study, modification and control of the state of matter. Consequently different scientific communities are pushing to make high magnetic fields available in combination with other powerful tools like free electron lasers (FEL), X-ray or neutron facilities. For example the project of the new European Spallation source for the production of neutrons to be implemented in Lund in Sweden, integrates the possibility to perform experiments under high magnetic fields and takes into account the energy concerns at the very beginning of the project. A short-term approach is to try to integrate high magnetic fields in existing facilities. A mid- and far-infrared FEL can now be used at the Dresden facility for pulsed fields and another is under construction at the Nijmegen facility for continuous fields. These projects allow the combined use of powerful THz waves with high magnetic fields. Concerning the link with X-ray or neutron facilities, the NHMFL has proposed to the National Science Foundation the construction of a new synchrotron source near the high field facility or the installation of new power supplies near the Advanced Photon Source, the synchrotron part of the Argonne National Laboratory. Up to now, the highest steady magnetic field available for experiments at a synchrotron radiation facility is 15 T at Spring 8 near Osaka, by means of a commercial

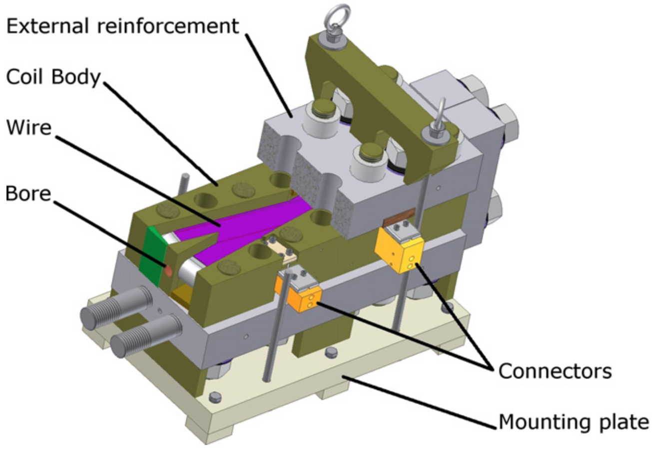

Fig. 5. Model of a coil optimised for maximal field, perpendicular to the bore over a long distance (the bore is parallel to the longest dimension of the structure and inbetween the two coils).

superconducting magnet. This value can also be found in the neutron facilities located in Oak Ridge, Berlin and in Grenoble. A project to reach higher continuous magnetic field is pursued by the Helmholtz Zentrum in Berlin. It aims at reaching 25 T to perform scattering experiments at the neutron facility over an angle up to 30 degrees in forward or backward configuration. It will use a horizontal hybrid configuration derived from the series connected hybrid under construction in Tallahassee that has the peculiarity that the copper based central solenoid is electrically in series with the superconducting Nb_3Sn outer magnet. In Grenoble, the only place worldwide where a neutron source (ILL), a synchrotron (ESRF), and a high magnetic field facility (LNCMI) are grouped within less than 1 km, a 40 T compact horizontal hybrid project is under study, that will be based on the ongoing LNCMI hybrid project and its 25 MW DC power supply. The validation of the technology to be used for a split magnet for scattering experiments has been obtained in the framework of the construction of a prototype of a powerful ion source that is presented below.

7.2. High intensity ion sources

An intense stable accelerated ion beam is an extremely powerful tool for fundamental research in physics and biology, allowing new discoveries essential for many scientific areas like fusion plasmas, astrophysics, hadron therapy, super heavy elements and atomic physics. Worldwide, almost all accelerators for nuclear physics are equipped with electron cyclotron resonance ion sources (ECRIS), a device invented at CEA-Grenoble, where multi-charged ion beams are extracted from a magnetically confined plasma. Most accelerators would benefit from higher average electric charge and higher intensities of the ion beams. To reach this goal, it is necessary to get the highest plasma density using the highest possible ECR frequency, the plasma density varying like the square of this frequency. This frequency increase must be obtained keeping various physical parameters, like the confinement time, in a certain range, allowing the optimisation of the ion beams to be extracted. To reach these characteristics, it is necessary to produce higher magnetic fields with complex topologies and high gradients, the present record being established at an ECR frequency of 28 GHz (about 4 T required) with superconducting technologies. The doubling of this frequency (i.e. magnetic field) is under study worldwide. To build such a structure with superconductors is difficult and expensive, and the risk of failure in the realisation is high. To elaborate an R&D program with such a device, the Laboratoire de Physique Subatomique et de Cosmologie (LPSC) (a joint CNRS and Université de Grenoble laboratory in charge of ion source development) and the high field facility in Grenoble have adapted the poly-helix magnet technology to the ECRIS requirements. This collaboration has designed and constructed a 60 GHz ECRIS prototype (Fig. 6) using radially cooled poly-helices [33], the same technology chosen for the development of a split magnet prototype for ILL and ESRF [34].

Fig. 6 shows the prototype of the source in operation at the LNCMI-Grenoble. The main magnetic feature is a closed loop of field ("cusp" configuration) for plasma confinement. The radially cooled technology, characterised by the main cooling flow direction perpendicular to the magnetic axis permits to construct the device as the assembly of two sub-magnets that can be powered independently. The first stable continuous plasma was obtained in September 2012 [35].

7.3. Pulsed high magnetic field for diffraction and absorption

Since continuous high magnetic fields above 16 T will only become available after major investments at neutron and X-ray facilities, the use of combined pulsed magnetic fields and X-rays has been developed at the ESRF [36] to show the unique results that can be obtained when using high magnetic fields. This project is currently being extended to single-crystal diffraction. Recently a project has started to produce 40 T for neutron diffraction. All these experiments are possible due to the transportable pulsed generators that can deliver 150 kJ (Fig. 7) and 1 MJ.

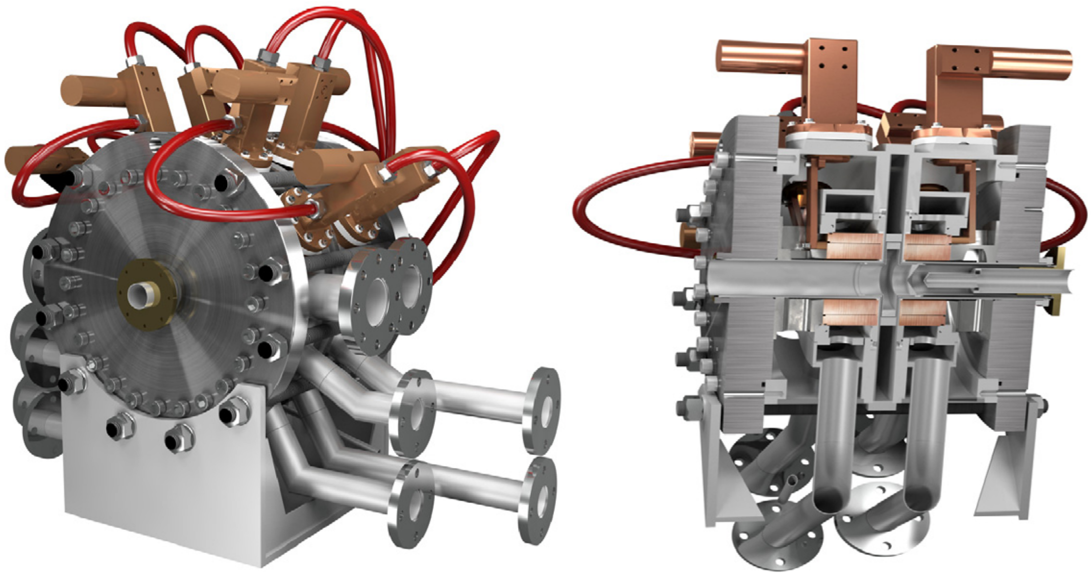

Fig. 6. View of the ion source prototype under qualification at the high field facility in Grenoble. The prototype is one meter high. On the cut view, one can see the split geometry of the magnet. In this "cusp" magnetic configuration the field contribution of each half magnet formed by two concentric radially cooled helices has opposite direction to form a closed loop of magnetic field at the centre necessary for plasma stability. Repulsive forces have to be held by the mechanical structure and this is the opposite of what happens in standard split coil configuration optimised for the highest magnetic field.

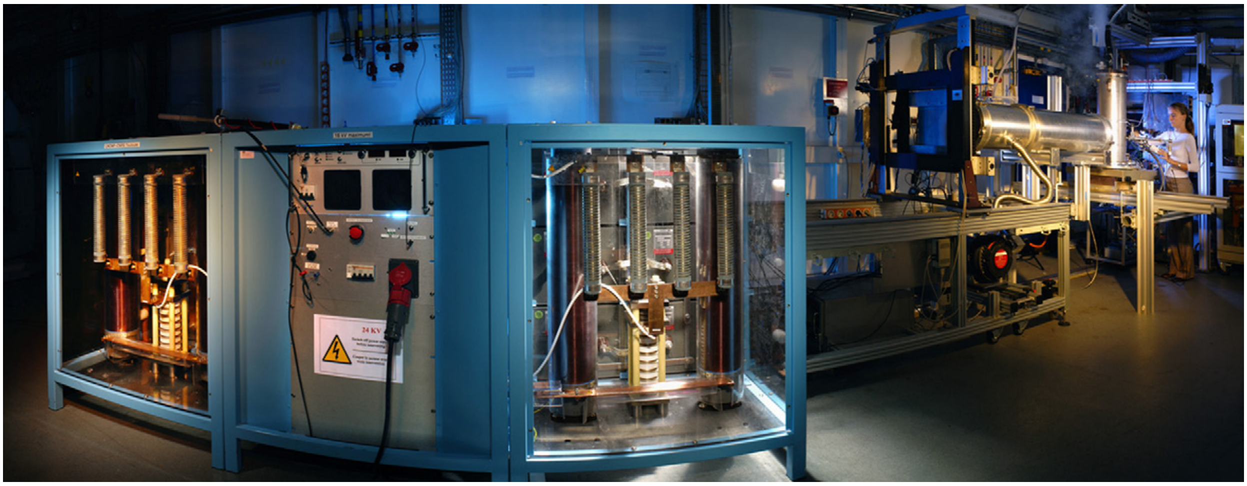

Fig. 7. An example of a transportable capacitor bank. A 150 kJ, 20 kV generator installed inside the BM26 hutch at the ESRF in Grenoble. One can distinguish two identical modules that contain the capacitors and a central module with the chargers and all the controls. The three modules have each a size of $1.3 \times 1.25 \times 0.95$ m^3. A 1.1 MJ transportable generator is available as well, the footprint is only slightly larger due to the use of high-energy density capacitors but the weight increased significantly (2×2 ton + 800 kg) (picture ESRF).

The problems that can be studied by pulsed fields are severely limited by the beam intensity since the data acquisition time is limited by the inherently low duty cycle ($t_{\text{at\_field}}/t_{\text{cooldown}}$ with $t_{\text{at\_field}}$ the time the field is above 90% of its maximum value and t_{cooldown} the time between two pulses in a stationary mode of operation). Typically during a 24 hour day one can acquire only several seconds of data at the highest fields. To improve this value one needs to increase the cooling efficiency and the obvious way to do this is to increase the number of cooling slits. The pulse duration itself seems at first sight not so relevant, however several reasons led us to prefer longer pulses: effect of vibrations, eddy-current heating and coil lifetime (the lifetime of a coil is thought to depend more on the number of pulses than on the total pulse duration). The opportunity to have experience with rapid cooling with liquid nitrogen of pulsed coils at the Toulouse site and the longstanding tradition of poly-helix DC magnets at the Grenoble site suggested the development of pulsed poly-helix magnets cooled by evaporating liquid nitrogen. The project has been started recently and the first results concerning cooling suggest that duty cycles of over 180 s/8 h can be obtained. The more challenging part is to adapt the poly-helix technology to ultra-strong conductors and to manage the high mechanical loads that have to be supported at the envisaged (> 40 T) field levels.

8. Conclusion

The development of the technologies for high magnetic field generation is ongoing: before 2016, the possibilities for researchers to perform measurements in DC fields up to 45 T will be open to a wide community thanks to advanced projects in Europe, Japan, China and the United States. Concerning pulsed magnets, within the same period of time 100 T repetitive pulse will be available to researchers at least in France, Germany and the United States.

Material properties are the main limiting factor in producing higher fields and ongoing efforts on material development could contribute to a more reliable or economic production of even higher fields. However, one should not forget that the required power, energy and volume of the coil scale as the third power of the linear dimensions and hence parallel to investing in ever larger power or energy supplies one should also seriously investigate the possibilities to miniaturise the experiments and thus to reduce the bore size.

The challenge for the future is to combine the use of high DC magnetic fields with other large facilities like synchrotrons or neutron sources. For this purpose, developments of innovative hybrid systems including high temperature superconducting materials are essential. In Europe, these developments are taken in charge by high field facilities and by the R&D activities linked to the preparation of the upgrade of the Large Hadron Collider at CERN.

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