HIGH-FIELD ACCELERATOR MAGNETS BEYOND LHC

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Abstract

The LHC magnet R&D Program has shown that the limit of NbTi technology at 1.8 K was in the range 10 to 10.5 T. Hence, to go beyond the 10-T threshold, it is necessary to change of superconducting material. Given the state of the art in HTS, the only serious candidate is Nb_3Sn. A series of dipole magnet models built at Twente University and LBNL and a vigorous program underway at FNAL have demonstrated the feasibility of Nb_3Sn magnet technology. The next step is to bring this technology to maturity, which requires further conductor and conductor insulation development and a simplification of manufacturing processes. After outlining a roadmap to address outstanding issues, we evoke the US proposal for a second generation of LHC Insertion Region (IR) magnets and the Next European Dipole (NED) initiative promoted by the European Steering Group on Accelerator R&D (ESGARD).

WHY DO WE NEED HIGHER-FIELD ACCELERATOR MAGNETS?

The Push Towards Higher Fields

For a given tunnel size, the energy of a circular machine is limited by the strength of bending magnets. Moreover, for both linear and circular colliders, the luminosity is determined (mainly) by the optics of Interaction Regions (IR's), which is itself limited by the strength and quality of IR magnets. Over the years, there has been a constant push from the High-Energy Physics (HEP) community to keep developing higher-field and higher-field gradient accelerator magnets.

Brief History

The push towards higher fields led naturally to the use of superconductors. Worthy of mention is the pioneer work carried out by W.B. Sampson at Brookhaven National Laboratory (BNL) in the mid 1960's, illustrated in Figure 1 by a 76-mm-aperture, 85-T/m quadrupole magnet model wound from Nb_3Sn ribbons and cold tested in January 1966 [1]. (Note that the aperture and field gradient of this model are similar to those of the HERA quadrupole magnets developed 15 years later [2].)

The first successful use of superconducting magnets in a machine took place at the Tevatron, at Fermi National Accelerator Laboratory (FNAL) [3]. The Tevatron, which relies on 774 6.1-m-long, 76.2-mm-aperture, 4-T arc dipole magnets, was commissioned in 1983 and has been running very reliably since then. It was instrumental in demonstrating the feasibility and reliability of superconducting magnet systems and has paved the way to their commercial applications (such as Magnetic Resonance Imaging or MRI systems).

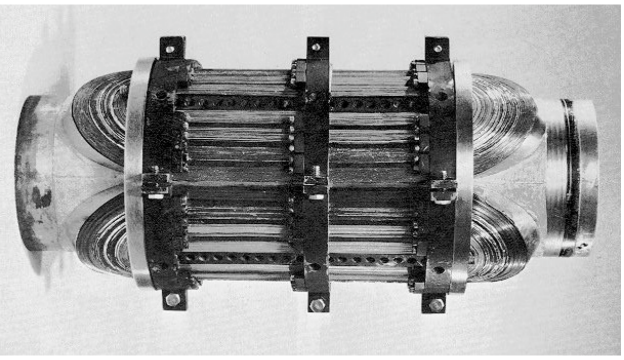

Figure 1: 76-mm-aperture, 85-T/m quadrupole model wound from Nb_3Sn ribbons by W.B. Sampson at BNL in 1965 [1].

Since the time of the Tevatron, significant progress has been made in the design and production of superconductors and accelerator magnets, leading to a gain of a factor ~2 in dipole field. The ongoing superconducting magnet productions for the Large Hadron Collider (LHC) at CERN, which, among others, call for 1232 14.2-m-long, 56-mm-twin-aperture, 8.33-T arc dipole magnets, is the culmination of 20 years of superconducting accelerator magnet development around the world [4]. The idea of building the LHC first emerged in 1982 [5], and the machine is expected to be turned on in the Spring of 2007, a mere 25 years later.

What's next?

In addition to arc dipole and quadrupole magnets, LHC also requires a number of superconducting IR magnets, including triplets of final-focusing quadrupole magnets, which are presently being built at FNAL and KEK [6]. Due to the high radiation doses to which they will be subjected, the life expectancy of these magnets is estimated around 7 years. Hence, it is likely that they will have to be replaced in 2015, thereby offering the opportunity of upgrading LHC IR optics to improve luminosity.

Several scenarios of LHC IR upgrades are already being considered [7], [8]. The most conservative ones keep the present optics layout but rely on stronger final-focusing quadrupole magnets. The most innovative ones call for a different optics layout, where the beam-separation dipole magnets are located in front of the final-focusing quadrupole magnets to reduce long-range, beam-beam interactions, as illustrated in Figure 2. In any case, these various scenarios require the development of large-aperture, high-field or high-field-gradient magnets.

Mid 2010's is also the earliest time frame when one can expect to need final-focusing quadrupole magnets for any of the proposed linear collider projects. In the case of linear colliders, the magnet requirements are very IR-design dependent.

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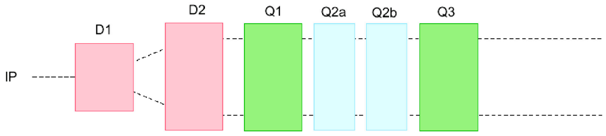

Figure 2: LHC-IR upgrade scenario where the beam-separation dipoles (D1 and D2) are located in front of the inner-triplet of final-focusing quadrupoles (Q1, Q2 and Q3) [7].

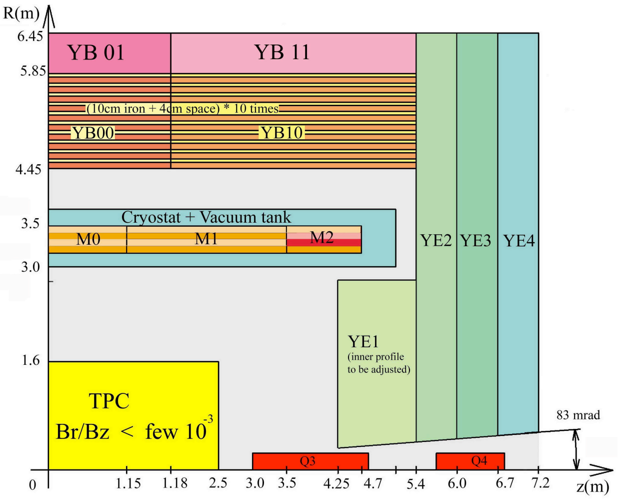

Figure 3: Layout of TESLA 1st IR where the final-focusing quadrupoles (Q3 & Q4) are located inside the detector solenoid (whose winding sections are labelled M0, M1 & M2) [9].

For the first IR of the Tera Electron volts Superconducting Linear Accelerator (TESLA), the layout proposed in the Technical Design Report (TDR) relies on final-focusing quadrupole magnets producing 250 T/m in a 56-mm-single-aperture. However, these magnets are positioned very close to the interaction point and must operate in the 4-T background field of the detector solenoid (see Figure 3) [9]. For the Next Linear Collider (NLC), or the second IR of TESLA, where it is foreseen that the two beams cross with a large angle, the final-focusing quadrupole magnets must be made very compact (*i.e.*, with a small overall outer radius) so as to clear the way for the crossing beam [10].

Roadmap for High-Field Accelerator R&D

Given the prospects outlined above, a reasonable roadmap for high-field accelerator magnet development is

- To get ready for LHC IR upgrade in 2015 (which calls for large-aperture, high-performance dipole or quadrupole magnets; note that here cost is not the primary issue),
- To develop final-focusing quadrupole magnets for implementation in a linear collider IR in the mid-2010's (which calls for LHC-type quadrupole magnets in a solenoidal background field or for compact quadrupole magnets; note that here also cost is not the primary issue),
- To promote generic magnet R&D aimed at LHC energy upgrade or a VLHC in the mid 2020's (which calls for high-performance, low-cost dipole and quadrupole magnets).

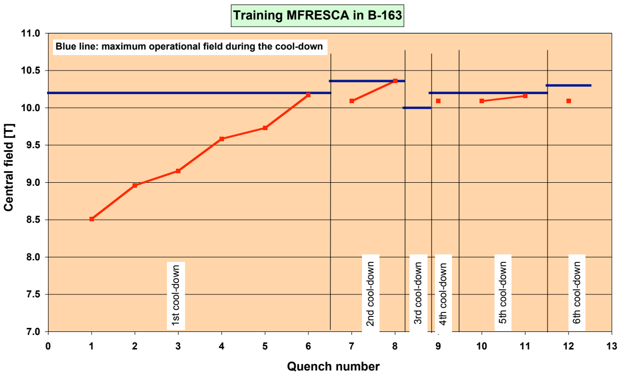

Figure 4: Quench performance of 88-mm-aperture (NbTi) MFRESCA dipole magnet model at CERN [13].

WHY IS IT SO HARD?

Ten to twelve years may seem like a comfortable time to develop a new dipole or quadrupole magnet design for LHC or linear collider IR applications. The issue, however, is that we cannot simply extrapolate existing designs and that we need to change of superconductor technology.

State of the Art in NbTi

Since the time of the Tevatron, the most widely used superconductor is a ductile alloy of niobium-titanium (NbTi) easy to co-process with copper by conventional extrusion and drawing techniques [11]. The world production of NbTi is estimated around 1500 metric tons per year, mainly under the form of multifilamentary composite wires for use in MRI magnets.

After several iterations, the CERN/LHC dipole magnet R&D program was successful in working out a design suitable for industrial production, but it demonstrated also that the limit of NbTi magnets (cooled down to superfluid helium at 1.8 K) lied in the 10-to-10.5-T range. This is illustrated in Figure 4, which shows the quench performance of the 88-mm-single-aperture MFRESCA dipole magnet, designed and built by a team led by D. Leroy and presently implemented in the superconducting cable test facility at CERN [12], [13]. Hence, to go beyond the present limitations and cross the 10-T threshold, it appears necessary to change of superconducting material.

Beyond NbTi: Nb_3Sn

High Temperature Superconductors (HTS) are not yet ready for large-scale applications requiring high current densities under high magnetic fields, and it is likely that it will take at least another decade before they become competitive (in terms of performances, production yield and cost). The present upper critical field of MgB_2 wires is two low. Nb_3Al exhibits promising properties, but there are serious manufacturing issues that have yet to be resolved. It follows that the only serious candidate to succeed NbTi is the intermetallic compound Nb_3Sn, whose world production is estimated around 15 metric tons per year (also under the form of multifilamentary composite wires) [14].

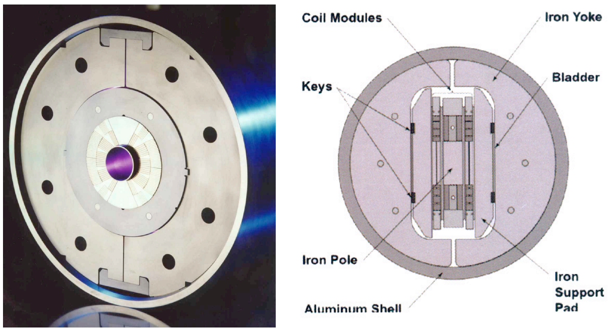

Figure 5: Record-breaking Nb_3Sn dipole magnet models; (a) 50-aperture, $\cos\theta$-type MSUT at Twente University (left) [19] and (b) 25-mm-gap, racetrack-type RD-3 at LBNL (right) [21].

Nb_3Sn has a critical temperature, T_C, and an upper critical field, B_{C2}, that are about twice those of NbTi. However, once formed, it becomes brittle and its critical parameters (T_C, B_{C2}, and the critical current density, J_C) are strain sensitive [15]. The brittleness and strain-sensitivity of Nb_3Sn require a different approach to all manufacturing processes and, so far, have limited its use to specific applications (such as insert coils for high-field Nuclear Magnetic Resonance or NMR spectrometers).

Progress on Nb_3Sn Technology

In spite of the aforementioned difficulties, significant progress has been made over the last decade thanks to

- The successful manufacturing and tests of the model coils for the International Thermonuclear Experimental Reactor (ITER) project, which, among other, have required the production of ~30 metric tons of Nb_3Sn wires [16], [17],
- A US National Program for the development of high-performance Nb_3Sn wires, supervised by R.M. Scanlan at Lawrence Berkeley National Laboratory (LBNL), which has led already to a three-to-four-fold increase in J_C with respect to ITER model coil specifications [18],
- A series of record-breaking dipole magnet models, opening the 10-to-15 T range, including the 50-mm-aperture, $\cos\theta$-type, MSUT model, built at Twente University and cold tested at CERN in 1995, which reached 11 T on its first quench at 4.4 K (Fig. 5(a)) [19], the 50-mm-aperture, $\cos\theta$-type, D20 model, built and cold tested at LBNL, which, after some training, reached 13.5 T at 1.8 K in 1997 [20], and the 25-mm-gap, racetrack-type, RD-3 model, also built and cold tested at LBNL, which, after some training reached 14.7 T at 4.2 K in 2001 (Fig. 5(b)) [21].

This progress shows that, although the Nb_3Sn technology is not yet mature, it could be at hand for the high-field and high-field-gradient accelerator magnets needed for LHC IR upgrade and for the IR's of future linear colliders. However, it is clear also that we need to keep working hard if we want to turn these few successful demonstrators into accelerator-class devices that can be implemented in a machine within 10 to 15 years.

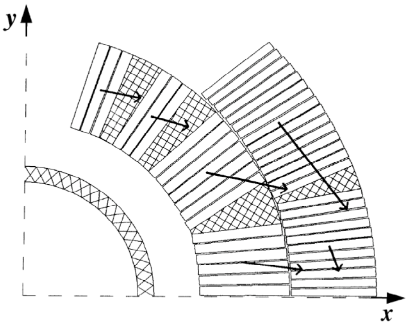

Figure 6: Lorentz force distribution in a quadrant of a $\cos\theta$ dipole magnet coil assembly (Courtesy R. Gupta).

WHAT DO WE HAVE TO DO?

Task List

Given the present state of the art on accelerator magnet technology and the requirements foreseen for LHC IR upgrade and for the IR's of future linear colliders, we need

- To revisit magnetic and mechanical designs to achieve enhanced performances with magnet coils made from brittle materials,
- To address coil cooling issued under high beam losses,
- To keep promoting high-performance Nb_3Sn wire development (and to ensure the survival of multiple suppliers around the world),
- To improve robustness and assess radiation hardness of Nb_3Sn conductor insulation (see, for instance, the innovative insulation scheme developed by Composite Technology Development, Inc., or CEA/Saclay [22]),
- To put into practice all of the above in magnet models and prototypes.

Of course, a number of laboratories around the world are already actively tackling these issues, including BNL, FNAL and LBNL in the USA, and CEA/Saclay and Twente University in Europe. A detailed review of the ongoing programs can be found elsewhere [23]. Given the limited space at our disposal, let us single out the problem of magnetic design.

Revisiting Magnetic Design

Most superconducting accelerator magnets rely on so-called saddle-shape coils, which, in their long straight sections approximate $\cos\theta$ or $\cos2\theta$ conductor distributions. Such designs were first optimized at BNL in the mid 1960's using R.A. Beth's complex formalism [24]. They are very efficient in terms of superconductor use and to control field quality, but, as illustrated in Figure 6, they result in a transverse stress accumulation towards the coil assembly midplane that could become detrimental when dealing with brittle conductors. Nevertheless, and in spite of the very high Lorentz forces developed in the MSUT and D20 models (which were both of $\cos\theta$-type), the performance of these magnets did not appear to be limited by stress-induced degradation.

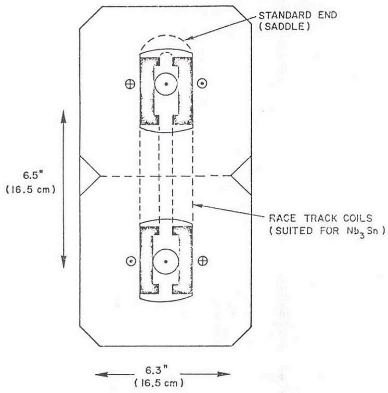

Figure 7: Original design of dual-bore dipole magnet relying on Racetrack-type coils first proposed by G.K. Danby (BNL) in 1983 [25].

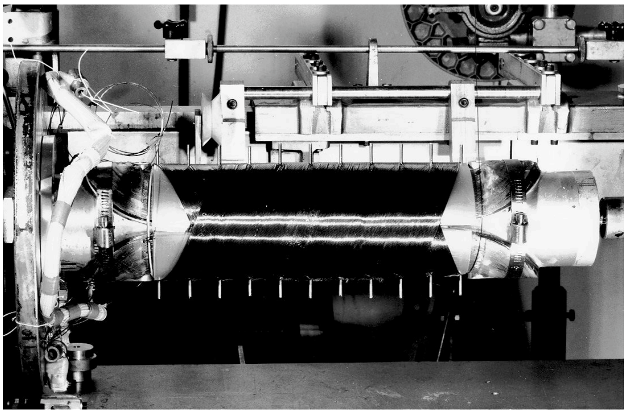

Figure 8: Dipole magnet model based on tilted solenoid coils under manufacturing at CEA/Saclay in 1974 [27].

The good results of the MSUT and D20 models indicate that we have not yet reached a hard limit on the mechanical point of view. This implies that, for LHC IR upgrade and for the first IR of TESLA, we can still safely rely on "conventional" $\cos\theta$ or $\cos 2\theta$ designs.

However, in the longer run, and given the very open time-scale for a LHC energy upgrade or a VLHC, it is, of course, worthwhile to investigate other designs. Among possible candidates, let us mention the racetrack-type coil design, illustrated in Figure 7, which was first proposed by G. Danby at BNL in 1983 [25] and was subsequently resuscitated by R. Gupta in 1996 [26]. This design has become the workhorse of the LBNL high-field magnet program and was used for the RD-3 model.

As a curiosity, let us also mention the tilted-solenoid design, illustrated in Figure 8 [27], which was investigated in the early 1970's and which is also being brought back into actuality by several authors.

HOW TO GET ORGANIZED?

At present, most of the worldwide resources are (for good reasons) used up by LHC and very little is left for accelerator magnet R&D. Given the little resources that are available

- We cannot afford to do everything at once, and we need to target our activities towards a limited number of clearly identified goals,
- We should avoid unnecessary work duplication and try to coordinate efforts among interested partners.

Some attempts at developing integrated programs are presently being made both in the USA and in the EU.

US LARP

BNL, FNAL and LBNL are presently collaborating to the US-LHC Accelerator Project, which, among others, include the in-kind contribution of a number of superconducting (NbTi) LHC IR magnets. In parallel, all 3 laboratories are also pursuing independent high-field magnet programs that are well described in the literature.

The US-LHC Accelerator Project team, led by J. Strait, FNAL, is now proposing to extend the present collaboration beyond LHC construction and is developing a US-LHC Accelerator Research Program (LARP) aimed at LHC IR upgrade. The Program scope and details are still under discussion. It will include Nb_3Sn magnet R&D work on both dipole and quadrupole magnets, but will focus mainly on large-aperture (up to 110 mm), high-field-gradient (> 200 T/m) quadrupole magnets [28].

EU CARE/NED Proposal

In October 2002, the European Committee for Future Accelerators (ECFA) has set up the European Steering Group for Accelerator R&D (ESGARD), chaired by R. Aleksan, CEA/Saclay, with the mandate of preparing a coherent set of bids to apply for EU funding [29]. The first outcome of ESGARD is the Coordinated Accelerator Research in Europe (CARE) proposal of Integrated Activities (IA), which was submitted to the EU on April 15, 2003.

The CARE proposal is a first attempt at integrating all HEP-related accelerator R&D in Europe and is supported by more than 100 institutes. It includes 3 Network Activities (linear colliders, neutrino beams and hadrom colliders) and 6 Joint Research Activies (JRA's), to develop specific hardware pieces or systems. One of the JRA's, nicknamed NED (for Next European Dipole) focuses on high field magnets.

The main objective of the NED JRA is to develop a large-aperture (up to 88 mm), high-field (up to 15 T) dipole magnet model, relying on high performance Nb_3Sn conductors (non-Cu J_C up to 1500 A/mm^2 at 4.2 K and 15 T). Such magnet is aimed at demonstrating the feasibility of the LHC IR upgrade scenario illustrated in Figure 2 where the beam-separation dipole magnets are located in front of the final-focusing quadrupole magnets, and it complements the US LARP. In addition, the NED magnet could be used to replace the MFRESCA magnet and upgrade the CERN cable test facility.

The NED JRA involves 7 collaborators (CEA/Saclay, CERN, INFN Milan and Genoa, RAL, Twente University and Wroclaw University) plus several industrial partners. The EU decision is expected before the end of the year. If approved, the program will start on January 1st, 2004, and the magnet should be cold tested in the Fall of 2008.

CONCLUSION

The US LARP and the EU NED proposal offer unique opportunities to develop the next generation of high-field magnets that will be needed for LHC-IR upgrade and for the IR's of future linear colliders.

Beyond HEP applications, such programs will help superconducting wire manufacturers to keep improving the performance and quality of their commercial Nb_3Sn products (such as high-field NMR wires).

Furthermore, lessons learned from Nb_3Sn should also help future HTS applications.

Let us hope that these two programs will be funded at a suitable level and that the accelerator magnet community will be given the means of maintaining its level of Excellency and of preparing its future…

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High-Field Accelerator Magnets Beyond LHC

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- Why do we need higher-field accelerator magnets?
- Why is it so hard?
- What do we have to do?
- How can we get organized to do it?
- Conclusion

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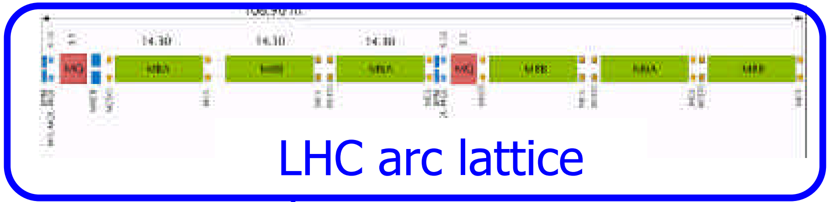
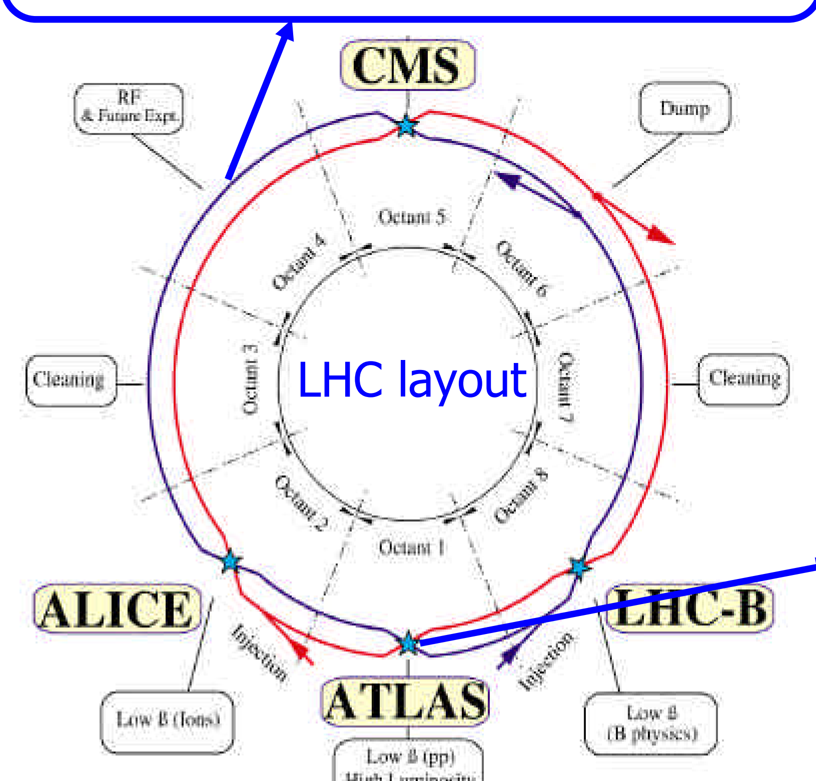
Accelerator Limitations

- For a given tunnel size, the energy of a circular machine is limited by the strength of bending magnets.

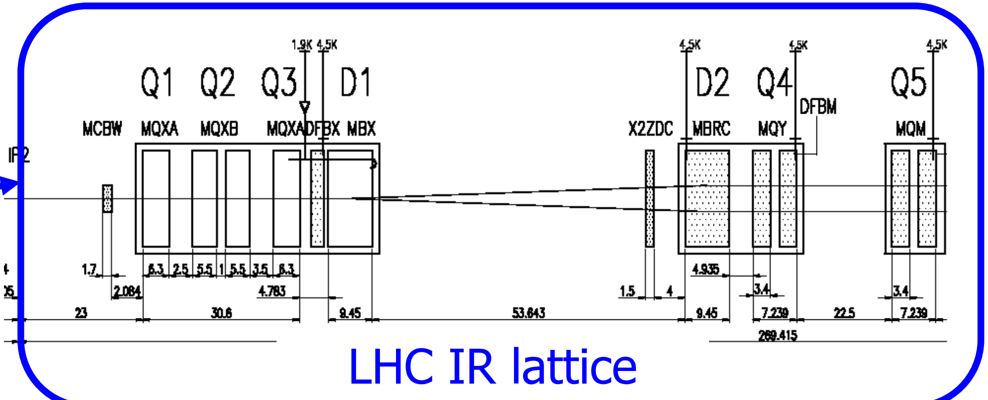


LHC arc lattice



LHC layout

- For both linear and circular colliders, the luminosity is determined (mainly) by the optics of Interaction Regions (IR's), which is itself limited by the strength and quality of final-focusing quadrupole magnets.

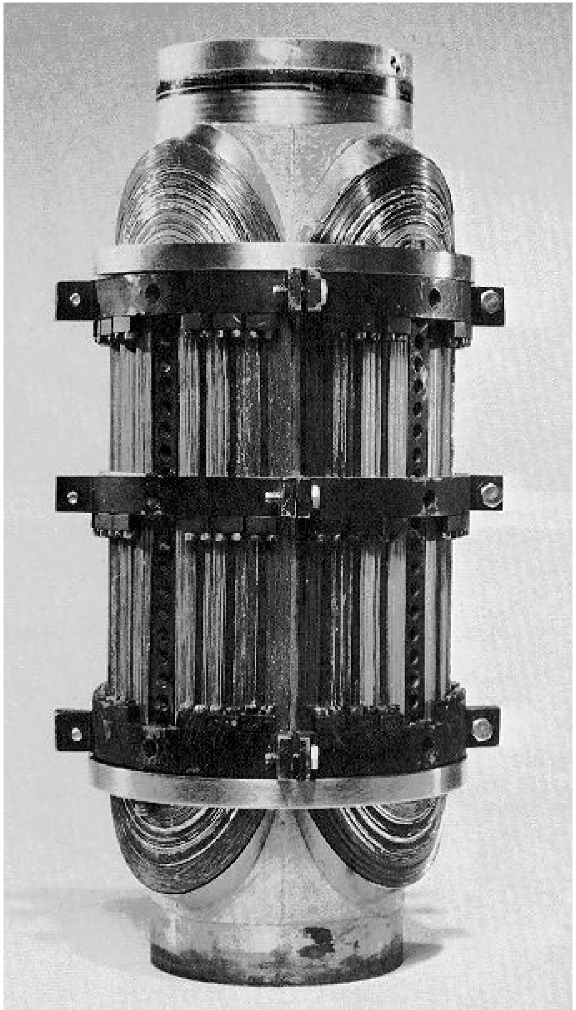


LHC IR lattice

The Push Towards Higher Fields

- Over the years, there has been a constant push from the High-Energy Physics (HEP) community to keep developing higher-field and higher-field-gradient accelerator magnets, so as to
  - achieve higher energies (circular machines),
  - achieve higher luminosities (all machine types).

Superconducting Accelerator Magnets



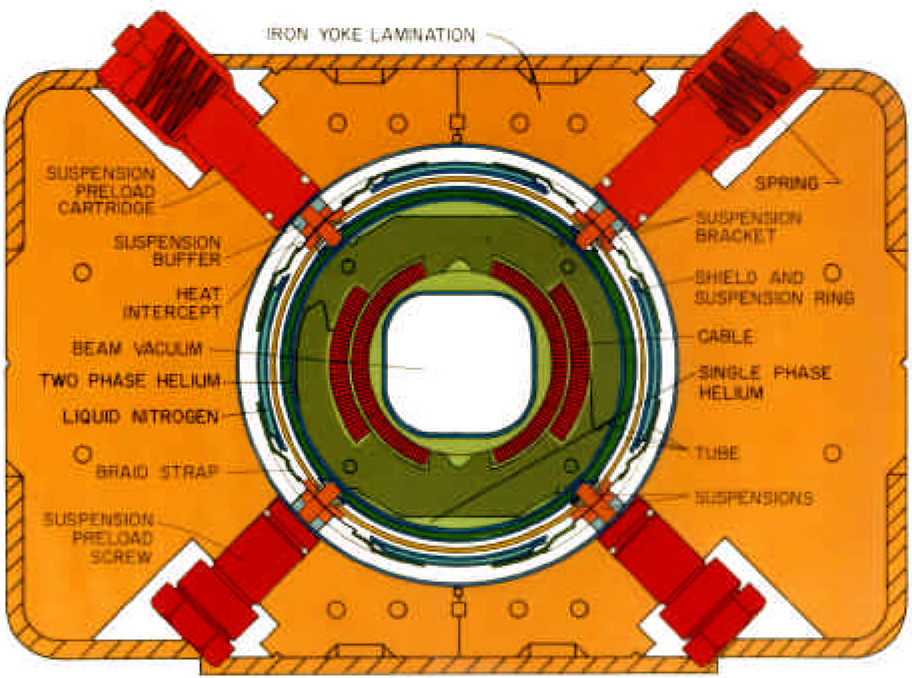
- The push towards higher fields led naturally to the use of superconductors.
- Let us for instance recall the pioneer work carried out by W.B. Sampson at BNL in the 1960’s.

76-mm-aperture, 85-T/m quadrupole magnet model wound from Nb_3Sn ribbons and cold tested at BNL in January 1966 (Courtesy W.B. Sampson)

PS: What else is new?

The Tevatron

- The first successful use of sc magnets in a machine took place at the Tevatron at Fermilab, which was commissioned in 1983 and which has been running very reliably since then.

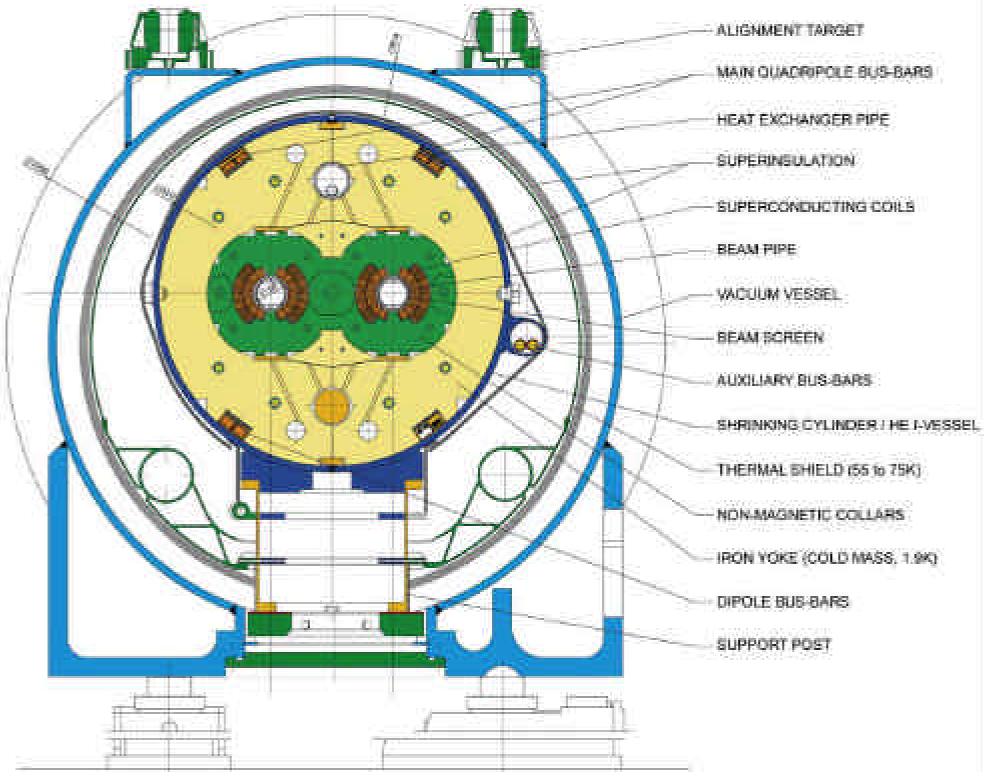


76.2-mm-aperture, 4-T Tevatron dipole magnet

- Note that the Tevatron was instrumental in demonstrating the feasibility and reliability of superconducting magnet systems and has paved the way to their commercial applications (such as MRI systems).

The LHC

- Since the time of the Tevatron, significant progress has been made in the design and production of superconductors and magnets, enabling a gain of a factor ~2 in field.



56-mm-twin-aperture, 8.33-T
LHC arc dipole magnet

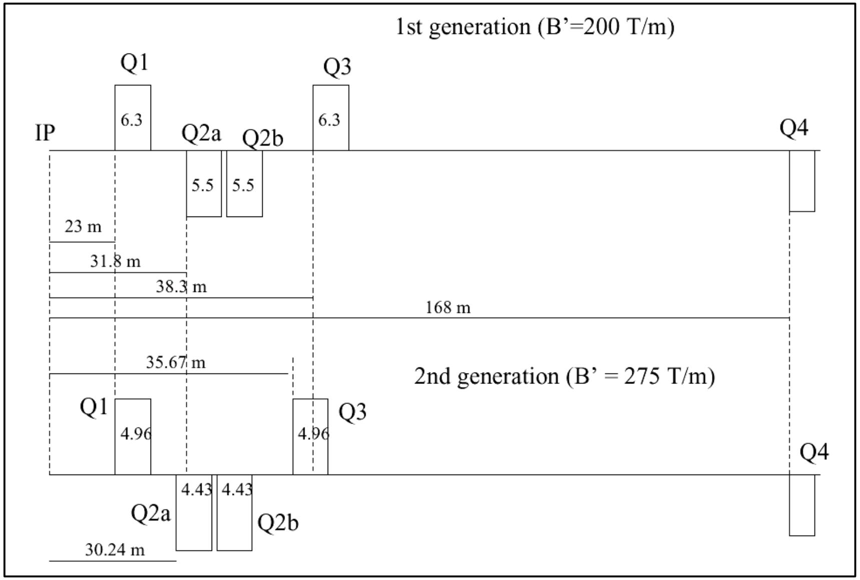
- The ongoing dipole and quadrupole magnet productions for LHC at CERN is the culmination of 20 years of worldwide sc accelerator magnet development.

What's Next?

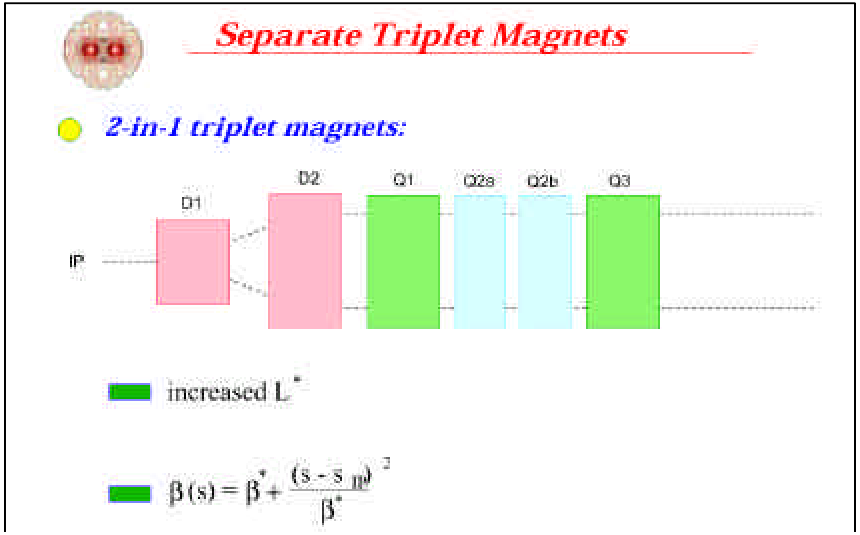
- Due to the high radiation doses to which they will be submitted, the life expectancy of LHC IR quadrupole magnets is estimated ~7 years.
- Hence, it is likely that these magnets will have to be replaced around 2015, thereby offering an opportunity of upgrading LHC IR optics to improve luminosity.
- Mid-2010's is also the earliest time frame when one can expect to need final-focusing quadrupole magnets for any of the proposed projects of linear colliders.

Magnets for LHC IR Upgrade

- Several scenarios of LHC IR upgrade are presently being considered, e.g.



Same layout as presently, but with larger-aperture and stronger final-focusing quadrupoles (Courtesy T. Sen)



Separate Triplet Magnets

- *2-in-1 triplet magnets:*

🟩 increased L^*

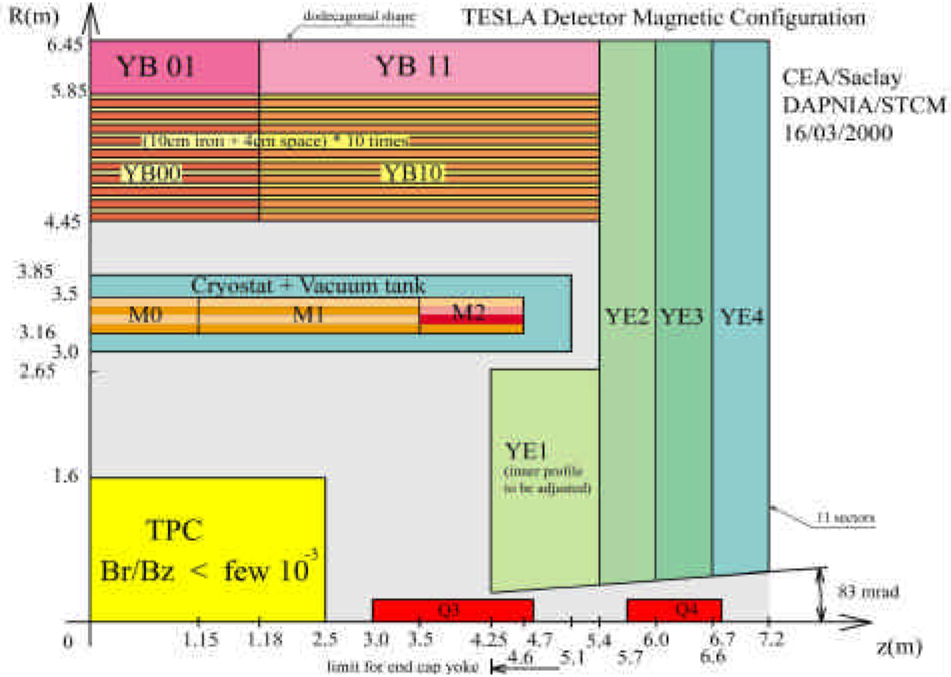
🟩 $\beta(s) = \beta^* + \frac{(s - s_{IP})^2}{\beta^*}$

New layout where beam-separation dipoles are positioned in front of final focusing quadrupoles (Courtesy O. Brüning)

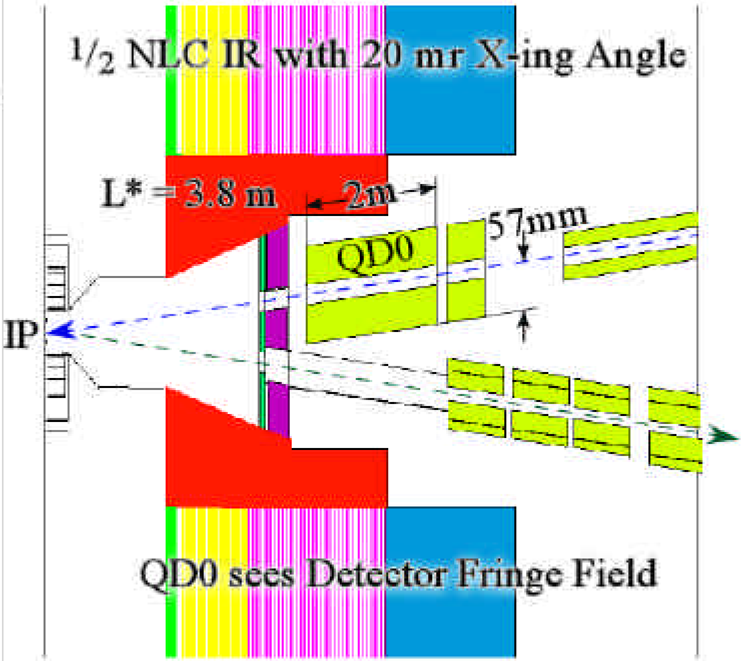
- The various scenarios call for the development of large-aperture, high-field or high-field gradient magnets.

Magnets for Linear Collider IR's

- Magnet requirements are IR-design dependent, e.g.



TESLA first IR requires LHC-type quadrupole magnets to be operated in a 4-T solenoidal background field (Courtesy F. Kircher)



NLC IR with large crossing angle requires strong but very compact quadrupole magnets to clear the way for crossing beam (Courtesy B. Parker)

Roadmap for High-Field Accelerator Magnet R&D

- A reasonable roadmap for high-field accelerator magnet development appears to be
  - get ready for LHC-IR upgrade in 2015 (large-aperture, high-performance dipole and/or quadrupole magnets; cost is not the primary issue),
  - develop final-focusing quadrupole magnets for implementation in a linear collider IR in the mid-2010’s (LHC-type quadrupole magnets in a solenoidal background field, or compact quadrupole magnets; cost is not the primary issue),
  - promote generic magnet R&D aimed at LHC energy upgrade or a VLHC in the 2020’s

    (high-performance, low-cost dipole and quadrupole magnets).

Contents

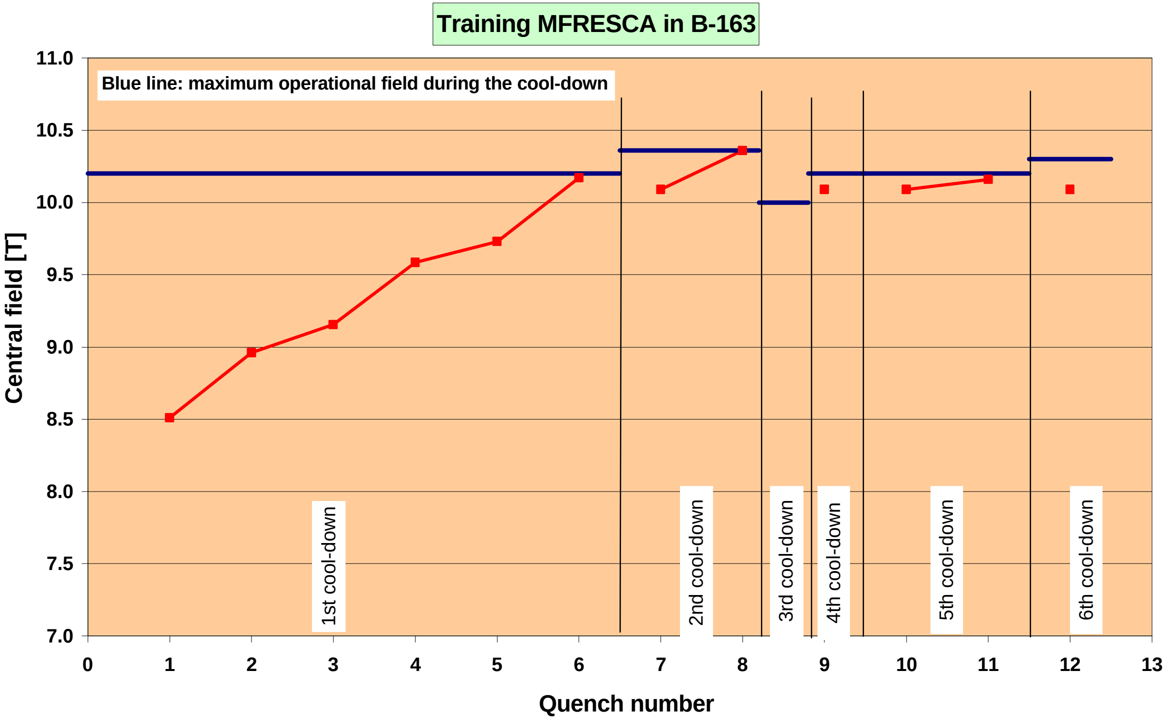
- Why do we need higher-field accelerator magnets?
- **Why is it so hard?**
- What do we have to do?
- How can we get organized to do it?
- Conclusion

Main Challenge of High-Field Accelerator Magnet

- 10 to 12 years may seem like a comfortable time to develop new dipole and quadrupole magnet designs for LHC or linear collider IR applications.
- The issue, however, is that we cannot simply extrapolate existing designs and that we have to change of superconductor technology.

State of the Art in NbTi

- Since the Tevatron, the most widely used superconductor is NbTi (world production: ~1500 t/year).
- The LHC magnet R&D programs have shown that the limit of NbTi at 1.8 K was around 10 to 10.5 T.



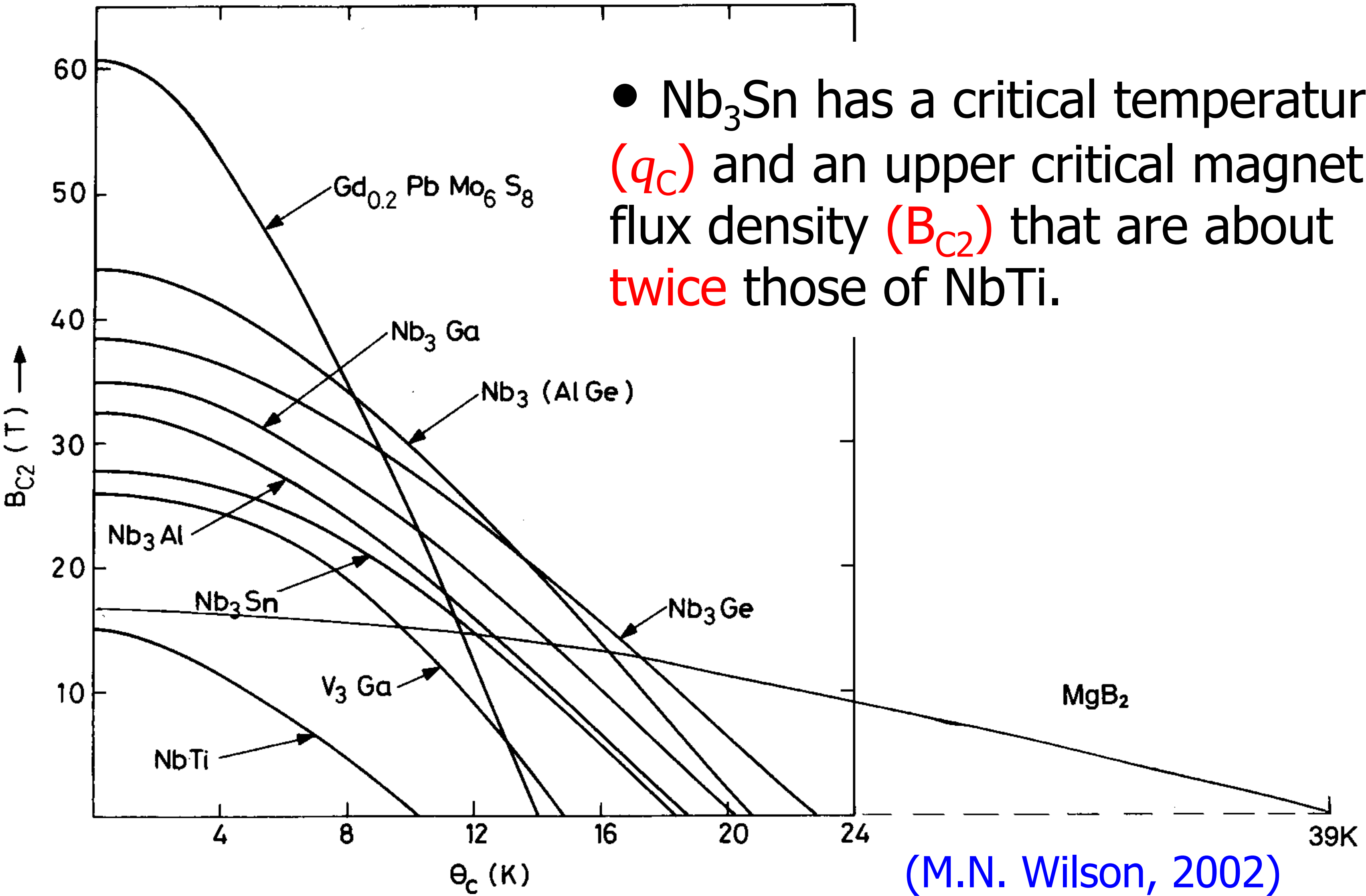
- Hence, to go beyond the 10-T threshold, it is necessary to change the material.

Quench performance of 88-mm-aperture MFRESCA dipole magnet at CERN (Courtesy D. Leroy)

Beyond NbTi

- The limited gain that can be expected from ternary NbTiTa alloys does not seem worth the investment.
- High Temperature Superconductors (HTS) are not yet ready for large-scale applications requiring high current densities under high magnetic fields, and it is likely that it will take at least another decade before they become competitive (in terms of performances, yield and cost).
- The upper critical field of MgB_2 wire is presently too low.
- Nb_3Al exhibits promising properties but there are serious manufacturing issues that have yet to be resolved.
- At present, the only serious candidate to succeed NbTi, that is suitable for industrial production, is the intermetallic compound Nb_3Sn (world production: ~15 t/year).

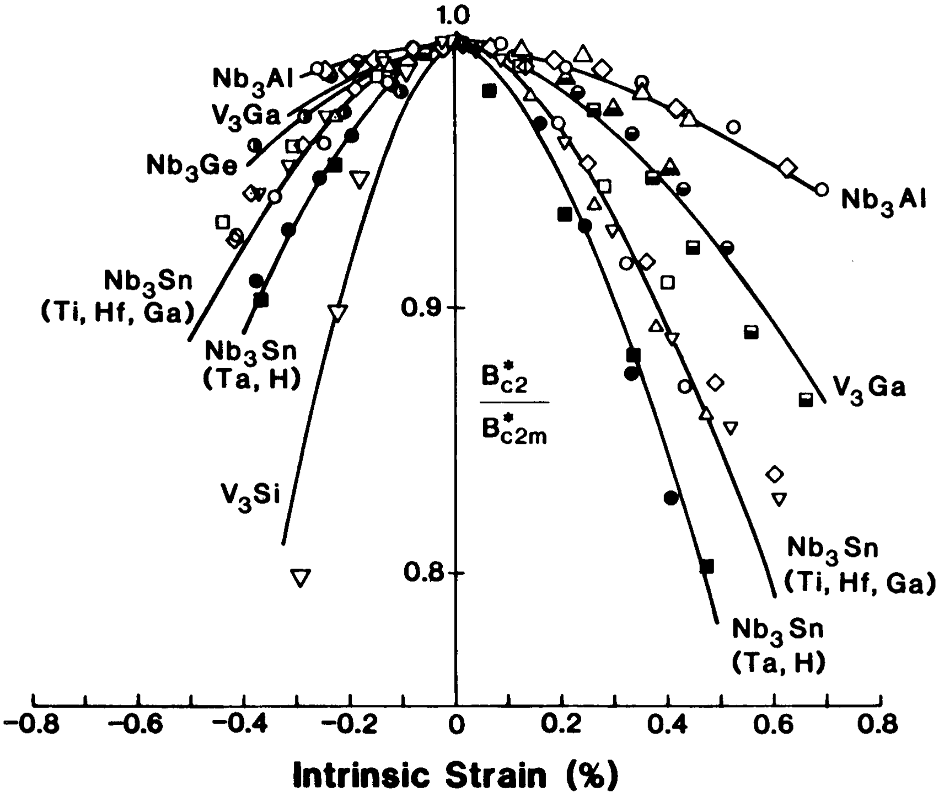
Pros of Nb_3Sn



- Nb_3Sn has a critical temperature (q_C) and an upper critical magnetic flux density (B_{C2}) that are about twice those of NbTi.

(M.N. Wilson, 2002)

Cons of Nb_3Sn



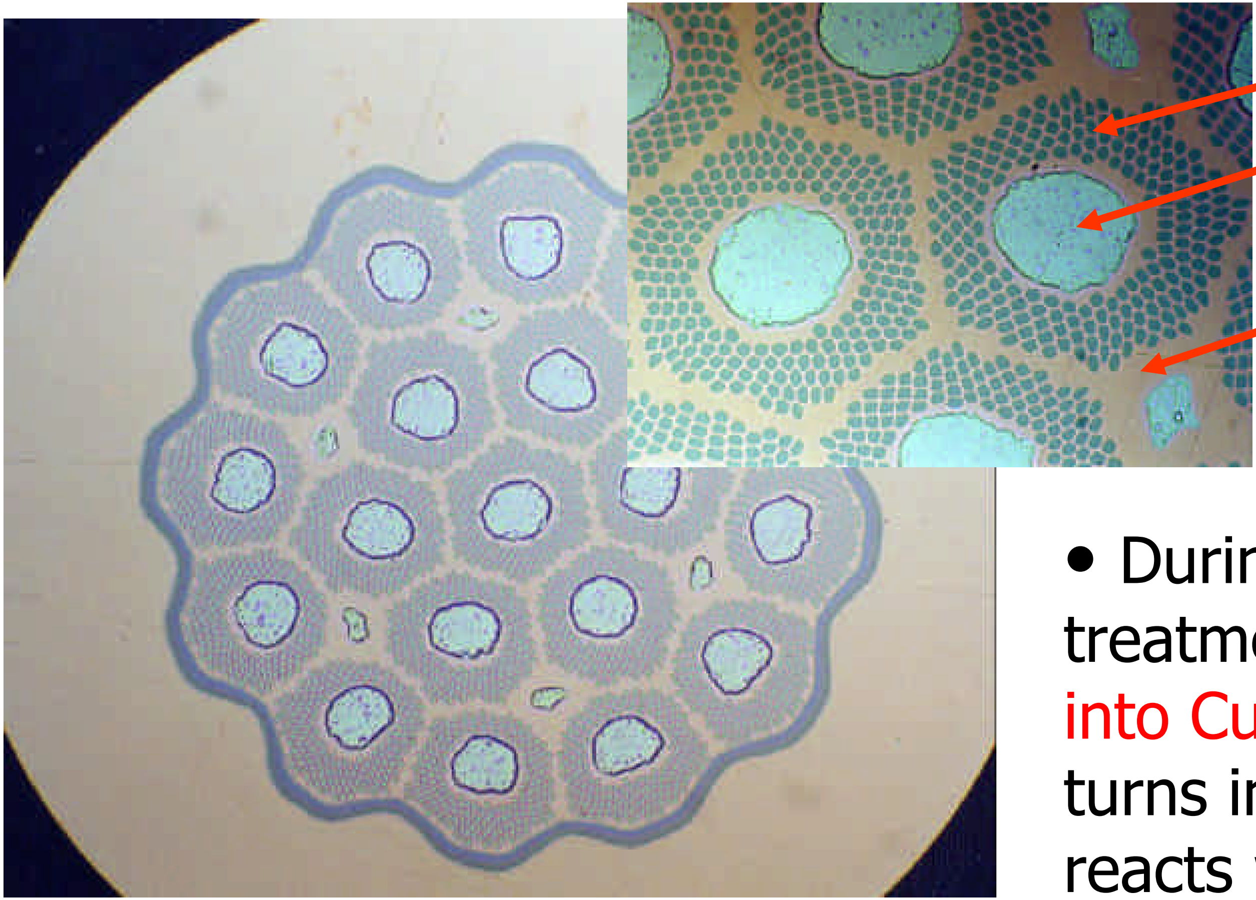
Degradation of upper critical magnetic flux density of A15 compounds as a function of strain (J.W. Ekin, 1984)

- Once formed, Nb_3Sn becomes brittle and its critical parameters (q_C, B_{C2} et J_C) are strain-sensitive.
- The brittleness and strain sensitivity require a different approach to all manufacturing processes.
- So far, Nb_3Sn has been dedicated only to specific applications (such as insert coils for high-field NMR magnet systems).

Dealing with Nb_3Sn (1/3)

- In practice, the brittleness problem is circumvented by
  - elaborating the conductor from ductile precursors that can be co-processed and formatted using conventional extrusion and drawing techniques,
  - submitting the finished product to a heat treatment that precipitates Nb_3Sn A15 phase.

Dealing with Nb_3Sn (2/3)



Exemple of un-reacted “Internal Tin” multifilamentary composite wire (Courtesy Alstom/MSA)

- During heat treatment, Sn diffuses into Cu matrix, which turns into bronze, and reacts with Nb filaments to precipitate Nb_3Sn.

Dealing with Nb_3Sn (3/3)

- The aforementioned elaboration technique presents at least two main challenges
  - the co-processed materials have very different crystallographic structures and mechanical properties (such as flow stress and shear modulus), eventually leading to breakages and limiting production yield,
  - the upper critical field and critical current density of Nb_3Sn depend strongly on the homogeneity and grain size of the A15 precipitates, which need to be controlled and optimized.

React & Wind vs. Wind & React

- The heat treatment parameters are typically: 700 °C for 150 to 250 hours.
- Depending on coil geometry, the heat treatment can be performed
  - either on the conductor prior to winding ("react & wind" process; suited to coils with large radii of curvature),
  - or on the whole coil after winding completion, –("wind & react" process; suited to coils with small radii of curvature).
- The wind & react process minimizes handling of reacted conductor, but it requires a heat-treatment furnace of the size of the finished coil, and a conductor insulation system able to sustain high temperature cycle.

Vacuum Impregnation

- Upon winding completion (react & wind process) or heat treatment completion (wind & react process), the coil is usually transferred to a specific mold to be vacuum-impregnated with epoxy-type resin.
- The vacuum impregnation reinforces conductor insulation, provides a rigid shape to the coil, and protects reacted conductor during subsequent operations.
- However, it further complicates magnet assembly and limits helium cooling.

Progress on Nb_3Sn (1/2)

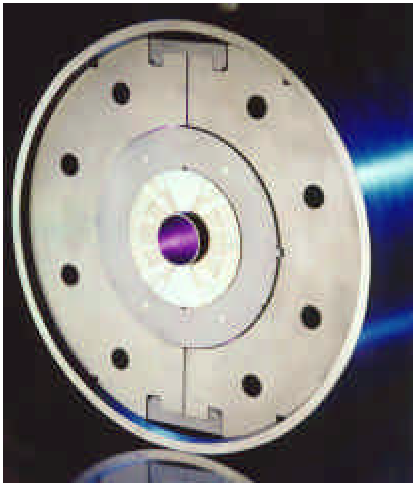
- In spite of all the difficulties, significant progress has been made on Nb_3Sn over the last decade, thanks to
  - the successful manufacturing and test of ITER model coils (which have required the production of ~30 t of Nb_3Sn wires),
  - a US National Program for the development of high-current density Nb_3Sn wires (having led to a three-to-four-fold increase in non-Cu-J_C with respect to ITER model coil specifications),

(After R.M. Scanlan)

Progress on Nb$_3$Sn (2/2)

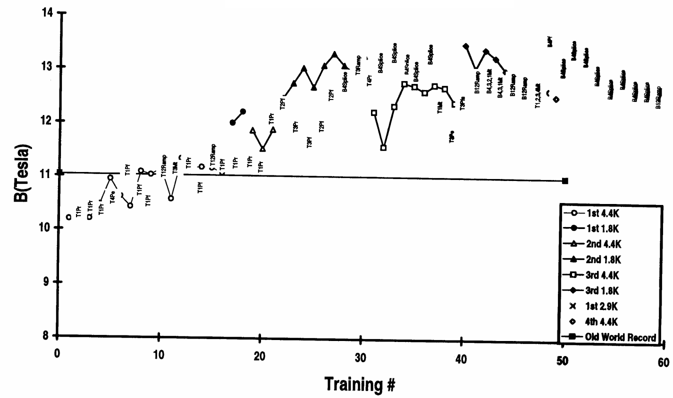
– a series of record-breaking dipole magnet models, opening the 10-to-15 T field range.

MSUT (cos*q*)

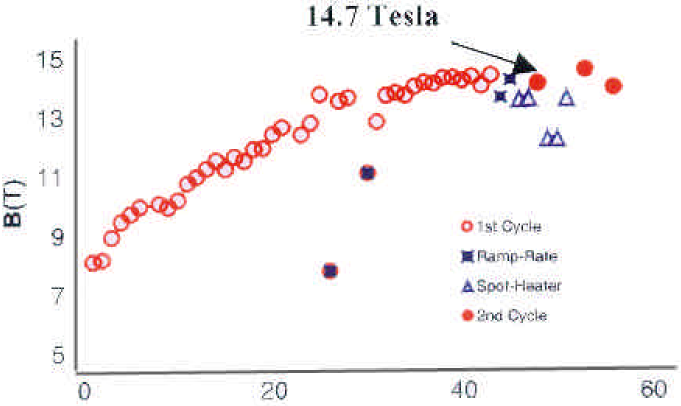


11 T on first quench at 4.4 K
in a 50-mm-bore
(Twente University, 1995)

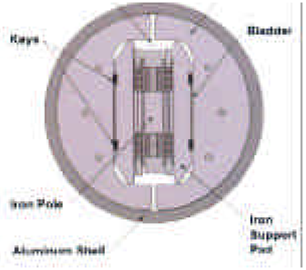
D20 (cos*q*)



13.5 T at 1.8 K
in a 50-mm bore
(LBNL, 1997)



RD-3
(Racetrack)



14.7 T at 4.2 K
in a 25-mm gap
(LBNL, 2001)

Main Challenge of High-Field Accelerator Magnet (Cont.)

- Although the Nb_3Sn technology is far from being mature, it seems at hand for the high-field and high-field-gradient accelerator magnets needed for LHC IR upgrade and for future linear collider IR's.
- However, we do need to keep working hard if we want to turn these few successful demonstrator magnets into accelerator-class devices that can be implemented in a machine in a 10-year time frame.

Contents

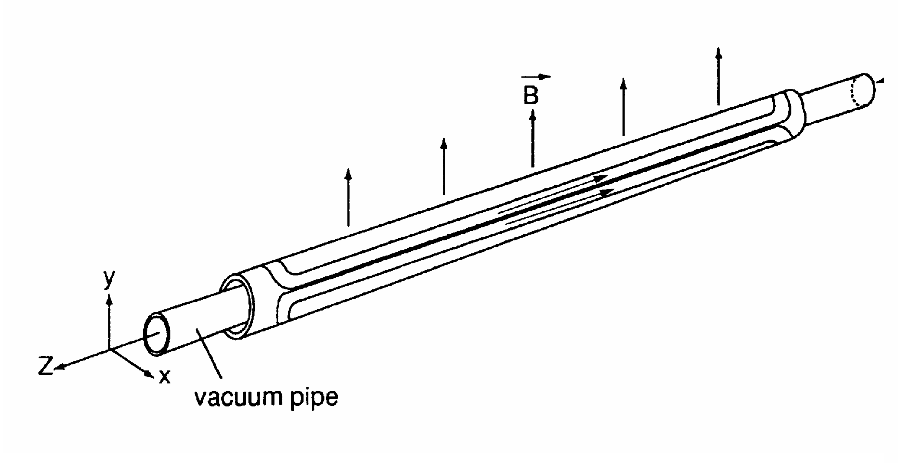
- Why do we need higher-field accelerator magnets?
- Why is it so hard?
- **What do we have to do?**
- How can we get organized to do it?
- Conclusion

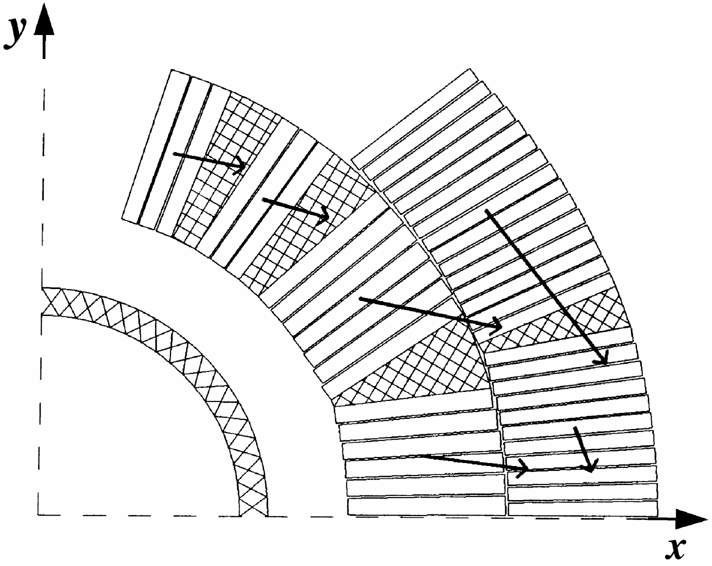
What do we have to do?

- Given the present State of the Art and the magnet requirements foreseen for LHC IR upgrade and for IR's of future linear colliders, we need
  - to revisit magnetic and mechanical designs to achieve enhanced performances with coils made from brittle conductors,
  - to address coil cooling issue under high beam losses,
  - to keep promoting high-performance Nb_3Sn wire development (and to ensure the survival of multiple suppliers around the world),
  - to improve mechanical robustness and assess radiation hardness of Nb_3Sn conductor insulation,
  - to put into practice all of the above in magnet models and prototypes.

Revisiting Magnetic Design (1/6)

- Most superconducting accelerator magnets rely on saddle-shaped coils, which, in their long straight sections, approximate cos$q$ or cos2q conductor distributions.

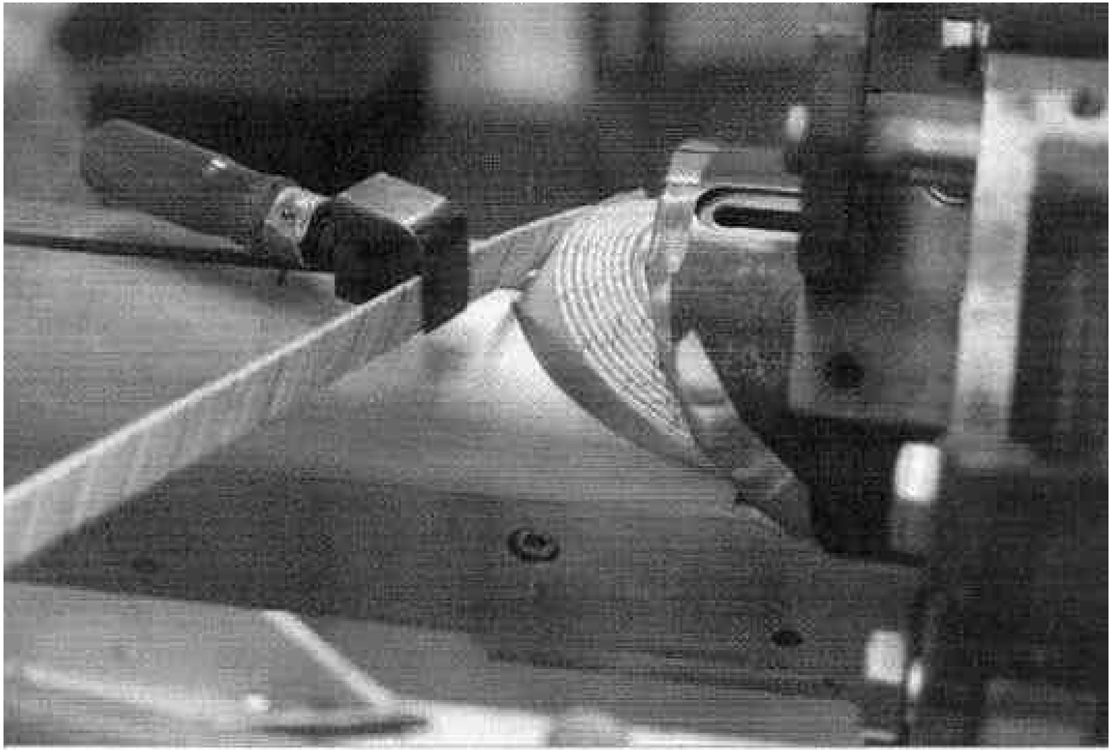




- Such design (first optimized at BNL in the mid-1960’s) is very efficient, but results in a transverse Lorentz stress accumulation towards the coil assembly midplane that could become detrimental when dealing with brittle conductors.

Revisiting Magnetic Design (4/6)

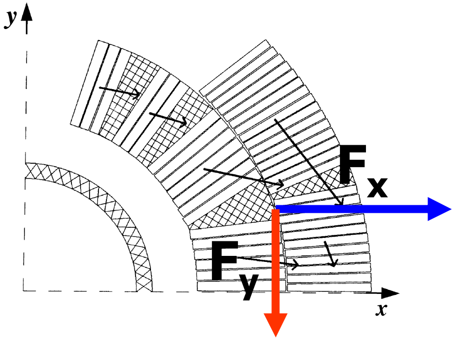
- Furthermore, given the small radii of curvature of their ends, saddle-shaped coils must be produced by the wind & react process.

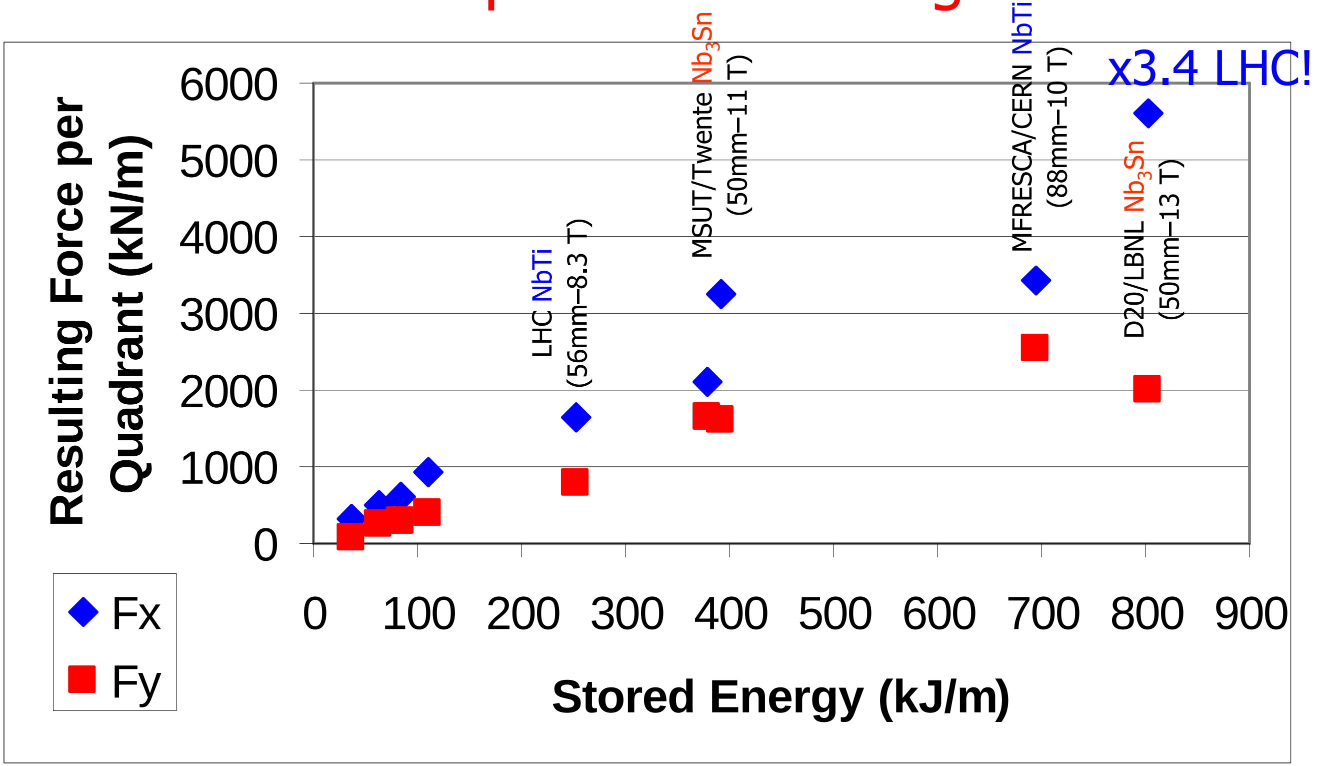


Winding of a saddle-shaped Nb_3Sn coil
at Twente University
(Courtesy A. den Ouden)

Revisiting Magnetic Design (2/6)

- In spite of these difficulties, and even with the very high lorentz forces developed in the MSUT (Twente University) and D20 (LBNL) models, these two magnets did not appear to exhibit any severe stress-induced performance degradation.





Revisiting Magnetic Design (3/6)

- The good results obtained with the MSUT and D20 models indicate that we have not yet reached a hard limit on the mechanical point of view.
- This implies that for LHC IR upgrade and for the first IR of TESLA, we can probably still safely rely on "conventional" cos*q* or cos2*q*-type designs manufactured by the wind & react process.

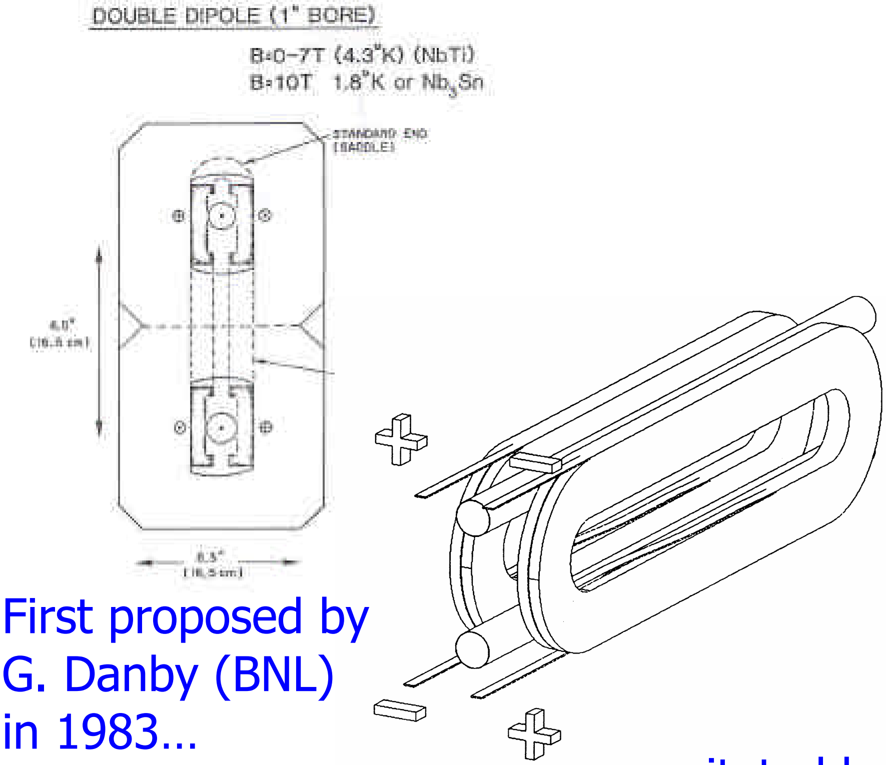
Revisiting Magnetic Design (5/6)

- In the longer run, and given the very open time scale for an LHC energy upgrade or for a VLHC, it is of course worthwhile to investigate other designs, with two goals
  - to enable better stress management,
  - and/or to allow reliance on the react & wind process.

Revisiting Magnetic Design (6/6)

- Among possible design candidates, let us mention

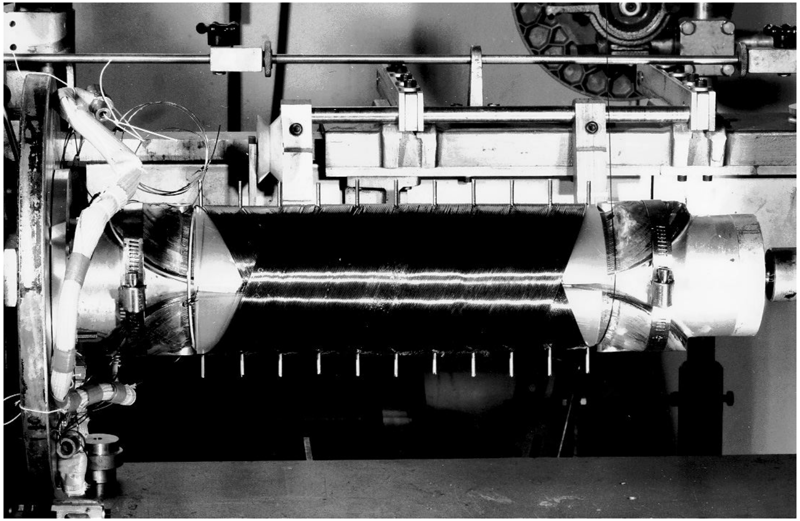
Racetrack type



First proposed by G. Danby (BNL) in 1983…

…resuscitated by R. Gupta (BNL) in 1996.

Double-Helix solenoid type



(Courtesy, J. LeBars, 1974)

What do we have to do?

- Given the present State of the Art and the magnet requirements foreseen for LHC IR upgrade and for IR's of future linear colliders, we need
  - to revisit magnetic and mechanical designs to achieve enhanced performances with coils made from brittle conductors,
  - to address coil cooling issue under high beam losses,
  - to keep promoting high-performance Nb_3Sn wire development (and to ensure the survival of multiple suppliers around the world),
  - to improve mechanical robustness and assess radiation hardness of Nb_3Sn conductor insulation,
  - to put into practice all of the above in magnet models and prototypes.

Insulation R&D (1/7)

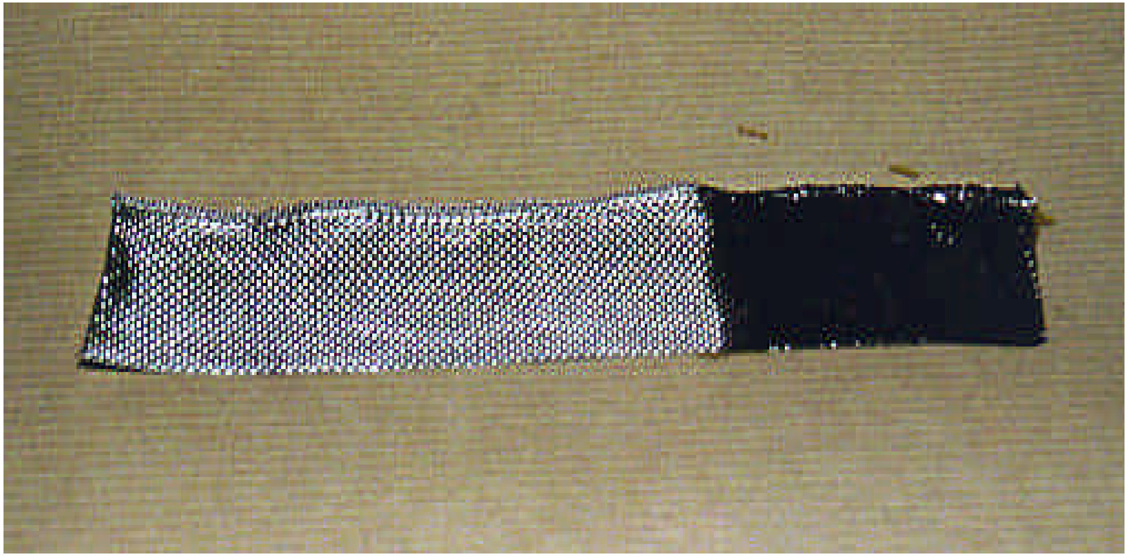
- As already mentioned, the small radii of curvature of present saddle-shaped coils impose to rely on the wind & react process.
- The insulation of wind & react Nb_3Sn coils is usually performed in two steps
  - wrapping of (un-reacted) conductor with a mineral fiber cloth prior to winding,
  - vacuum-impregnation of coil with epoxy-type resin after heat-treatment completion.

Insulation R&D (2/7)

- A first issue with such insulation scheme is the choice of fiber wrap, which must be able to sustain the high-temperature cycle without significant degradation.
- This eliminates E glass, whose recrystallization temperature is two low (~660 °C), and imposes the use of purer glasses (such as R, S2 or quartz…) or of ceramics.

Insulation R&D (3/7)

- Another issue with such insulation scheme is the fact that the fibers of commercially available tapes or sleeves are sized with organic compounds.
- During the high-temperature heat treatment, the organic compounds undergo a graphitization-like decomposition which leaves electrically-conducting carbon residues.



- Example of R glass fiber tape that was heat-treated without removing sizing.
- The carbon residues were revealed by dipping the tape into resin.

Insulation R&D (4/7)

- It follows that all organic compounds must be eliminated from fibers prior to heat treatment.
- The most commonly used de-sizing procedure is by carbonization in air at 300-350 °C for a few hours.

- Then, the problem is that de-sized tapes or sleeves become fragile and very easy to tear off by friction.

Bending test on a Nb_3Sn cable wrapped with a de-sized quartz fiber tape (Courtesy M. Durante).

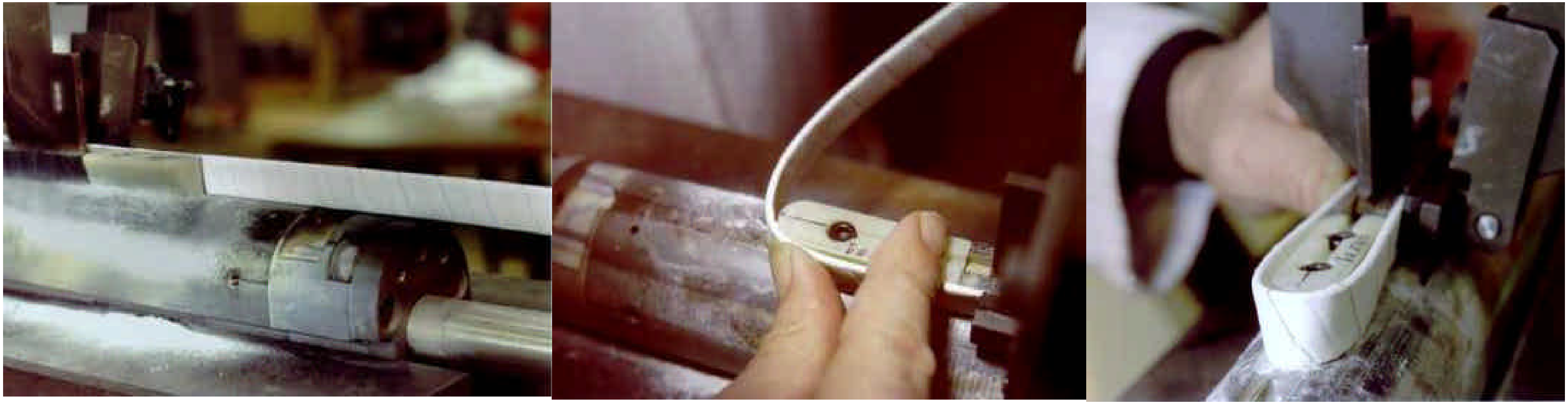
Insulation R&D (5/7)

- The weakness of de-sized tapes or sleeves complicates most manufacturing operations (from conductor wrapping, to coil winding and coil handling in and out of heat treatment retort), and renders the whole manufacturing process ill-suited to industrial production.
- More R&D on innovative insulation schemes is needed to suitably address this issue.

Insulation R&D (6/7)

- CTD, Inc., in the USA and CEA/Saclay are presently working on parallel (and competing) programs aimed at developing an inorganic binder for mineral or ceramic fiber tapes, that
  - enhances mechanical strength, while keeping enough flexibility to allow conductor wrapping and winding on small radii of curvature,
  - transforms into a rigid bonding agent during the high-temperature heat treatment, thereby eliminating the need for subsequent vacuum impregnation.

Insulation R&D (7/7)



Bending test on un-reacted Nb_3Sn cable wrapped with CEA/Saclay innovative pre-impregnated fiber tape (Courtesy S. Marchant).

Stack of Nb_3Sn cables insulated with CEA/Saclay innovative pre-impregnated fiber tape after heat treatment (Courtesy L. Girard).

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How Can We Get Organized?

- At present, most of the worldwide resources are (for good reasons) used up by LHC and very little is left for high-field accelerator magnet R&D.
- Given the little resources that are available
  - we cannot afford to do everything at once, and we need to target our activities towards a limited number of clearly identified goals,
  - we should avoid unnecessary work duplication and try to coordinate efforts among interested partners.
- Some attempts at developing integrated programs are being made both in the USA and in the EU.

US-LARP (1/2)

- Fermilab, BNL and LBNL are presently collaborating to the US-LHC Accelerator Project, which among others, include the in-kind contribution of a number of superconducting (NbTi) LHC-IR magnets.
- In parallel, all three laboratories are also pursuing independent high-field magnet programs (see the wealth of papers presented in all major conferences).

US-LARP (2/2)

- The US-LHC Accelerator Project team, led by J. Strait (Fermilab) is now proposing to extend the existing collaboration beyond LHC construction and is developing a US-LHC Accelerator Research Program (US-LARP) aimed at LHC-IR upgrade.
- The Program scope and details are still under discussion, but it will include Nb_3Sn magnet R&D work, with a main focus on large-aperture (up to 110 mm), high-field gradient (> 200 T/m) quadrupole magnets.

EU CARE/NED Proposal (1/5)

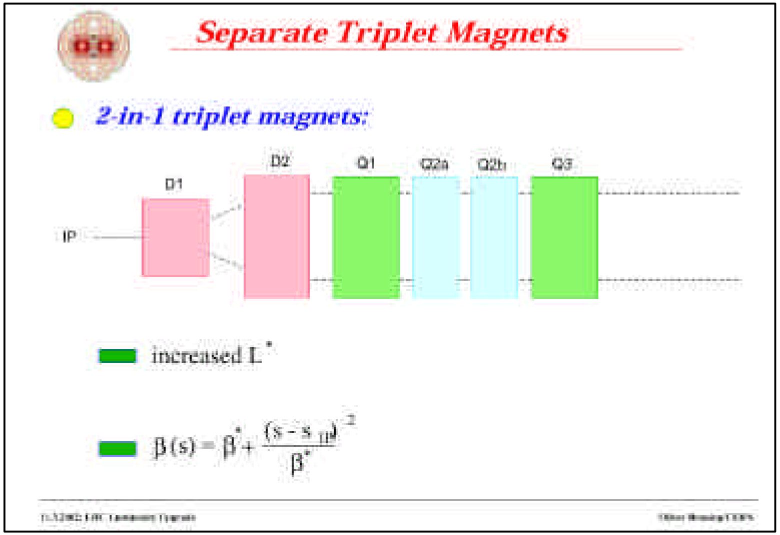
- In october 2002, ECFA has set-up the European Steering Group for Accelerator R&D (ESGARD), chaired by R. Aleksan (CEA/Saclay), with the mandate of preparing a coherent set of bids to apply for EU funding (http://esgard.lal.in2p3.fr).
- ESGARD first outcome is the Coordinated Accelerator Research in Europe (CARE) Proposal of Integrated Acitivies (IA), that was submitted to the EU on April 15, 2003.

EU CARE/NED Proposal (2/5)

- The CARE proposal is a first attempt at integrating all HEP-related accelerator R&D in Europe and is supported by more than 100 Institutes.
- It includes 3 Network Activities (linear colliders, neutrino beams, and hadron colliders) and 6 Joint Research Activities (JRA) to develop specific hardware pieces or systems.
- One of the JRA's, nicknamed NED (for Next European Dipole), focuses on high-field magnets.

EU CARE/NED Proposal (3/5)

- The main objective of the NED JRA is to develop a large-aperture (up to 88 mm), high-field (up to 15 T) dipole magnet model relying on high-performance Nb_3Sn conductors (non-Cu J_C up to 1500 A/mm^2 @15 T and 4.2 K).



Separate Triplet Magnets

- 2-in-1 triplet magnets:

🟩 increased L^*

🟩 $\beta(s) = \beta^* + \frac{(s - s_{IP})^2}{\beta^*}$

- Such magnet is aimed at demonstrating the feasibility of the LHC-IR upgrade scenario where the beam-separation dipole magnets are positioned in front of the final-focusing quadrupole magnets and is meant to complement the US-LARP.

EU CARE/NED Proposal (4/5)

- In addition, the NED model could be used to upgrade the CERN superconducting cable test facility (presently limited to 10-10.5 T by the NbTi MFRESCA magnet).

(Courtesy A. Verweij, CERN)

- Such facility could provide services to the entire applied superconductivity community

EU CARE/NED Proposal (5/5)

- The NED JRA proposal involves 7 collaborators (CEA/Saclay, CERN, INFN-Milan and Genoa, RAL, Twente University and Wroclaw University), plus several industrial sub-contractors.
- EU decision is expected at the end of July 2003.
- If approved, the program will start on January 1st, 2004, and the magnet model should be cold tested in the Fall of 2008.

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Conclusion

- The US-LARP and the EU NED proposal offer unique opportunities to develop the next generation of high-field accelerator magnets that will be needed for LHC-IR upgrade and for the IRS's of future linear colliders.
- Beyond HEP applications, such programs will help wire manufacturers to keep improving the performance and quality of their commercial Nb_3Sn products (such as high field NMR wires).
- Furthermore, lessons learned from Nb_3Sn should help also future HTS applications.
- Let us hope that both programs will be funded at a suitable level…