DE LA RECHERCHE À L'INDUSTRIE

Magnet R&D towards FCC-hh

Hélène Felice – CEA Paris Saclay

With contributions from many

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Andre Brem, Valerio Calvelli, Philip Mallon, Pierre Manil, Samuele Mariotto, Françoise Rondeaux

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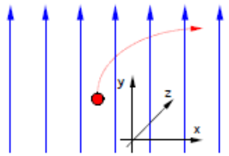
A brief reminder: why do we need strong B?

Increase BEAM ENERGY →

Dipoles to bend the trajectory of the beam



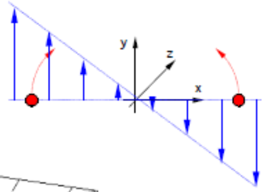
Beam energy — Bending radius

$$E[GeV] = 0.3\,B[T]\,\rho[m]$$

Dipole field

Increase collider LUMINOSITY (number of collisions) →

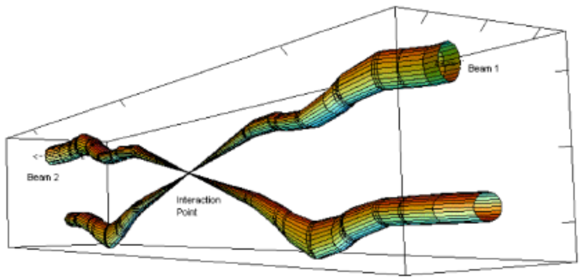
Final focus quadrupoles to reduce the beam dimension at the interaction point



Peak coil field

$$B\ell_q \approx \frac{1}{\sigma^*}$$

Quadrupole length — Beam size at the collision point

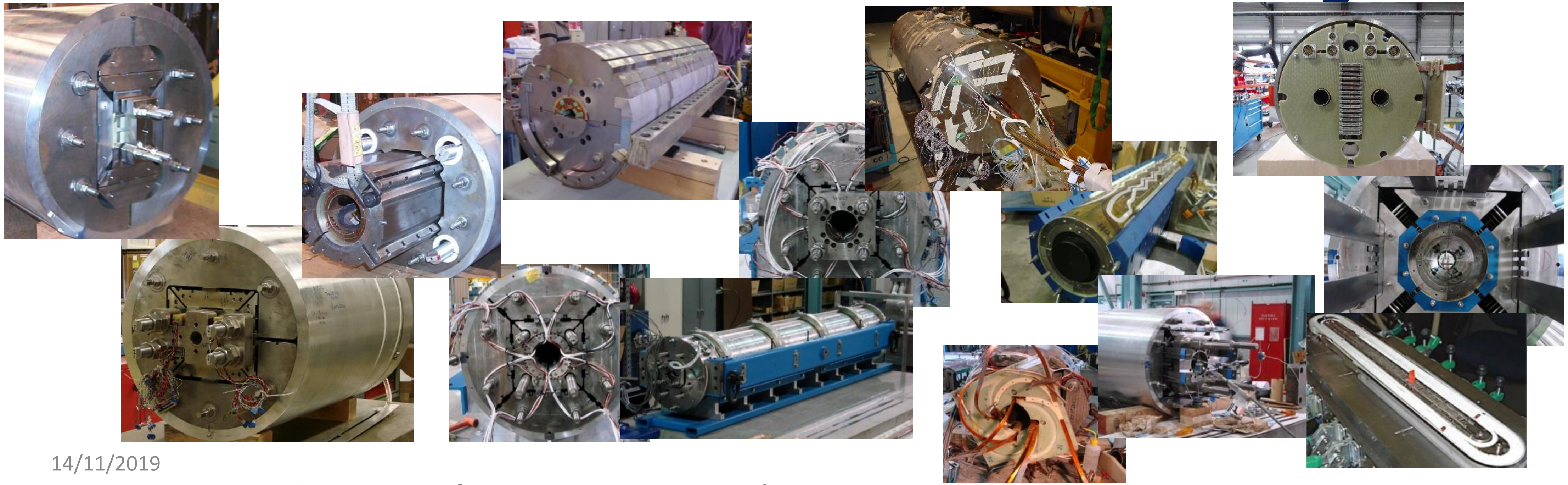


Relative beam sizes around IP1 (Atlas) in collision

Courtesy of B. Bordini

Background on magnet development

Where are we?

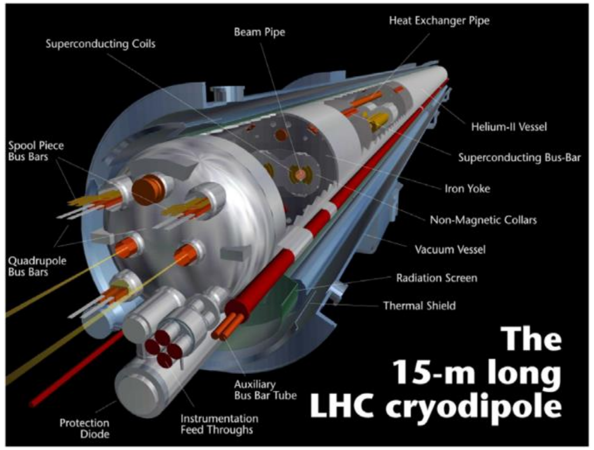


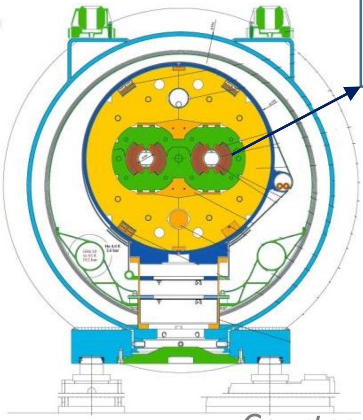
Pictures courtesy of FNAL, BNL, LBNL, CERN, Texas A&M

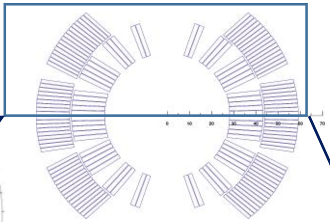
From NbTi to Nb_3Sn

LHC Technology

LHC NbTi dipoles







Courtesy of CERN

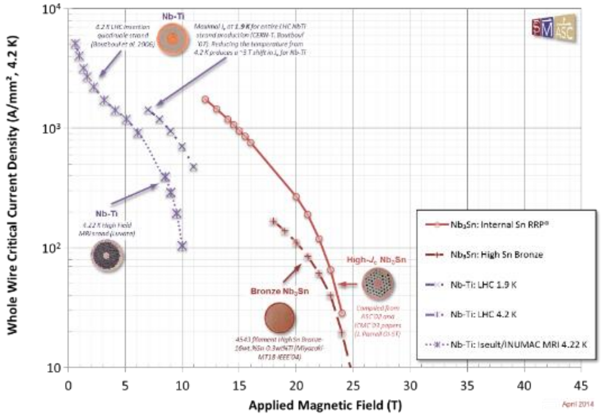
Reliable operation at 6.5 TeV (13 TeV c.o.m)

Dipole Bore field: 7.7 T

Target 7 TeV (14 TeV c.o.m)

Dipole 8.33 T

Beyond LHC

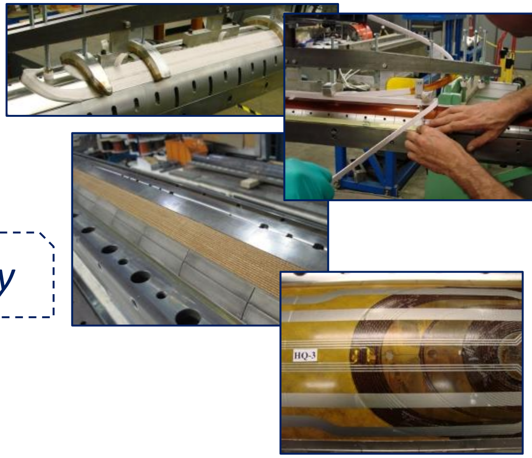


Courtesy of P. Lee

Nb_3Sn is the natural candidate

Coil technology

- *Heat treatment around 650°C*
- *Wind and react technology*
- *Vacuum impregnation with Epoxy*



Nb_3Sn strain sensitivity

- *I_c reduction (reversible)*
- *I_c degradation (permanent)*

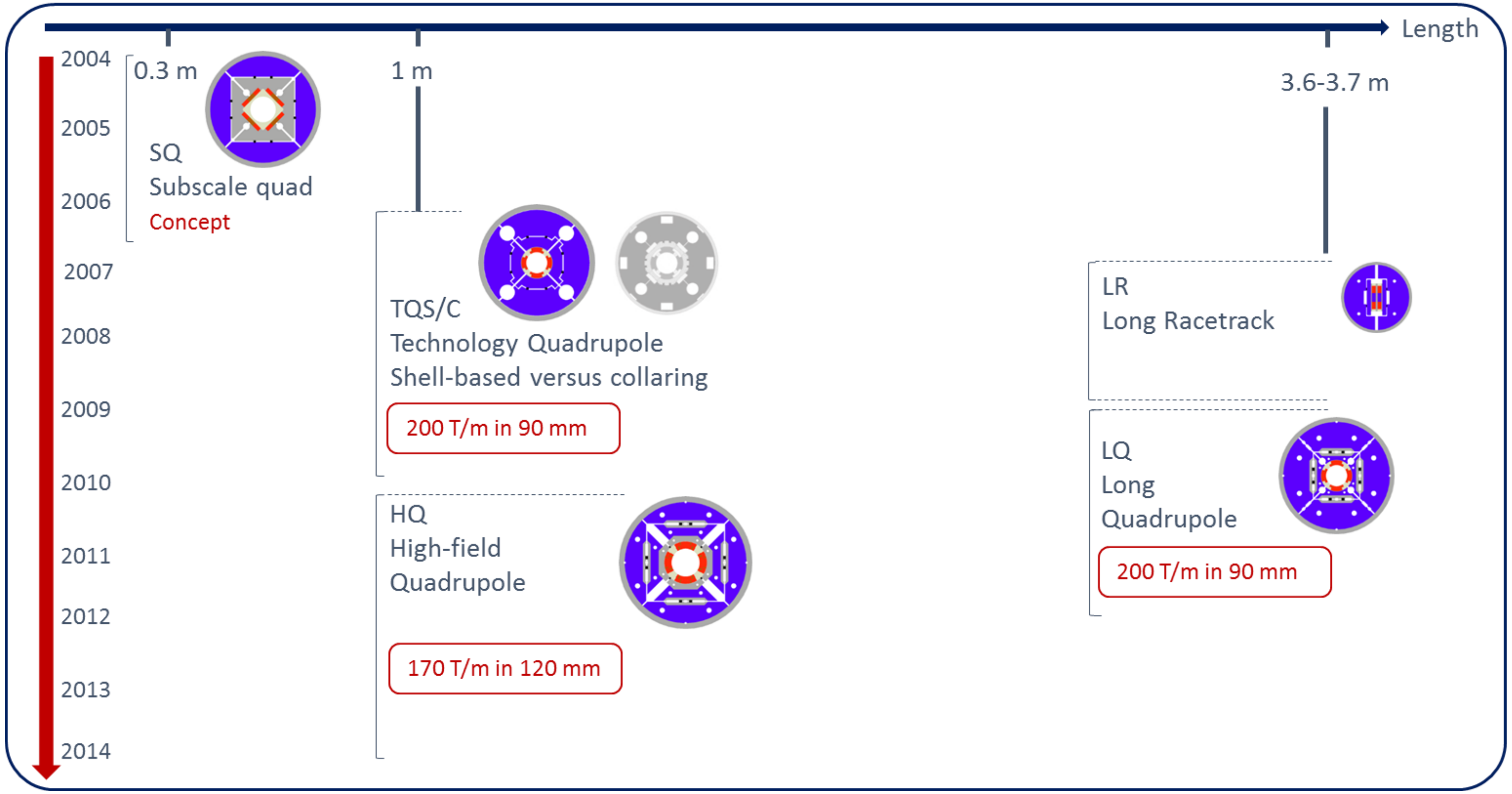
Strain sensitivity: a challenge impacting all the aspects of Nb_3Sn magnet design & fabrication

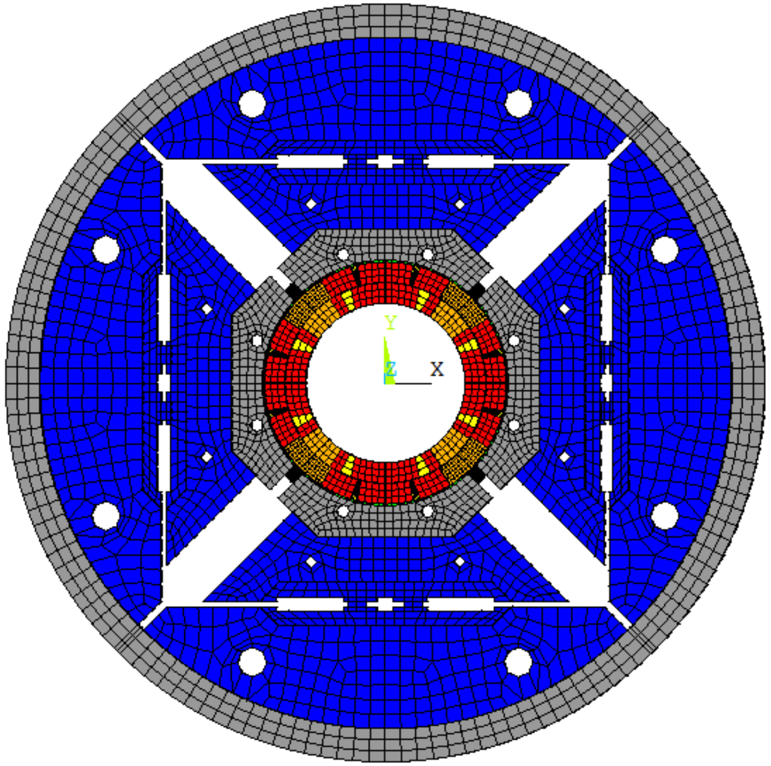
The LHC Accelerator Research Program

GOAL

Demonstrate Nb_3Sn technology viability for the interaction region upgrade

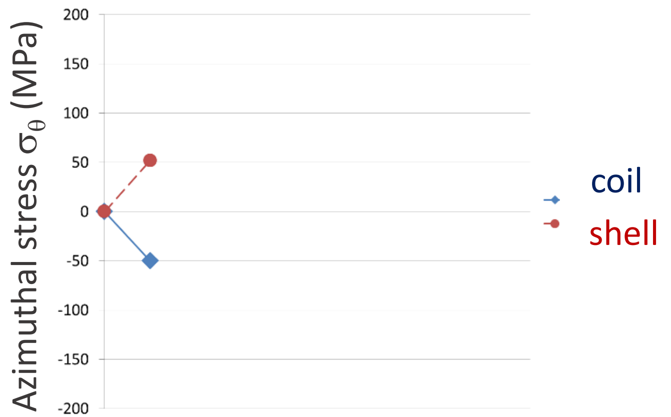
- Develop reliable coil technology
- Develop reliable magnet assembly process
- Demonstrate long magnets feasibility
- Demonstrate accelerator integration readiness

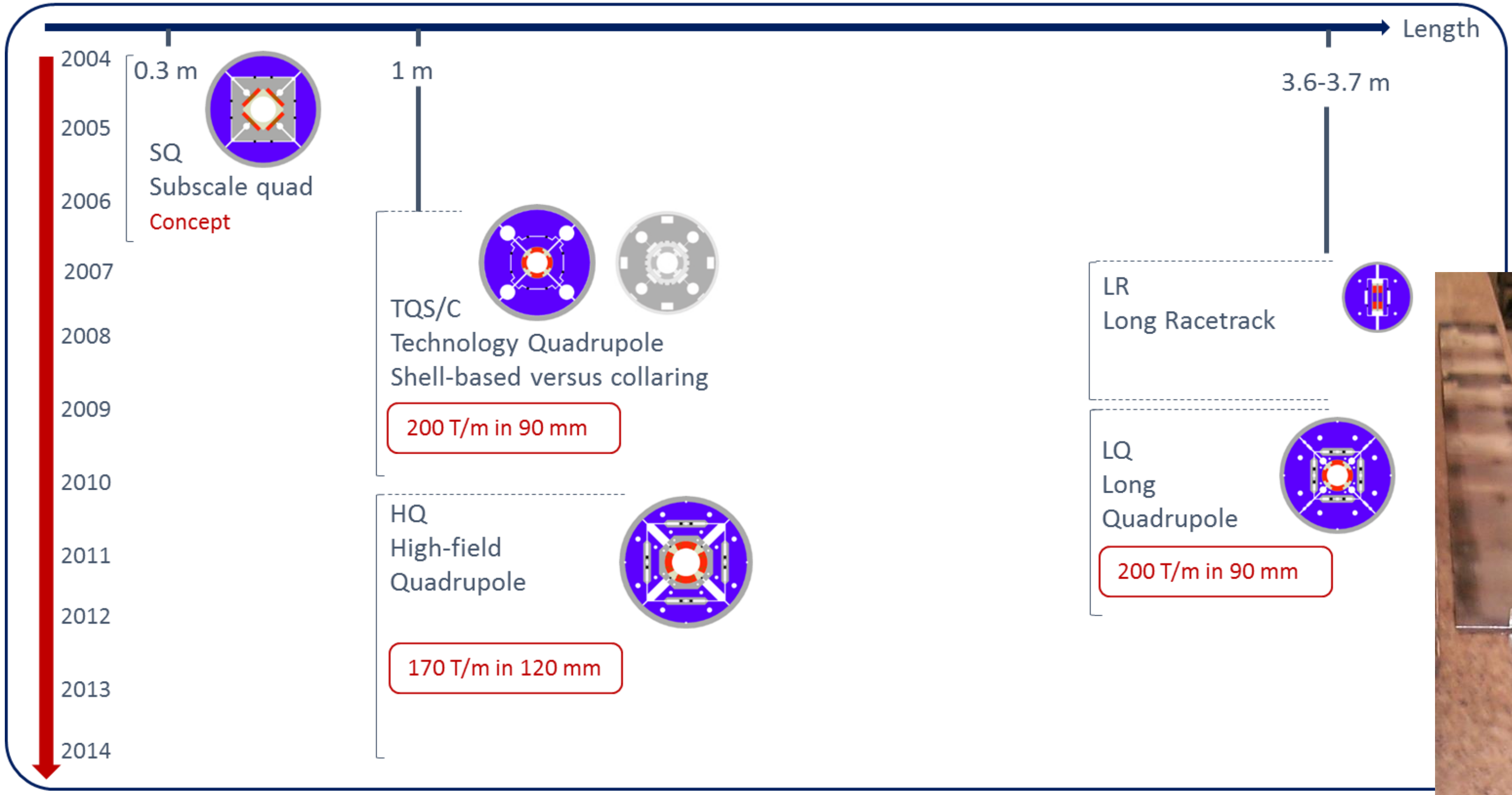


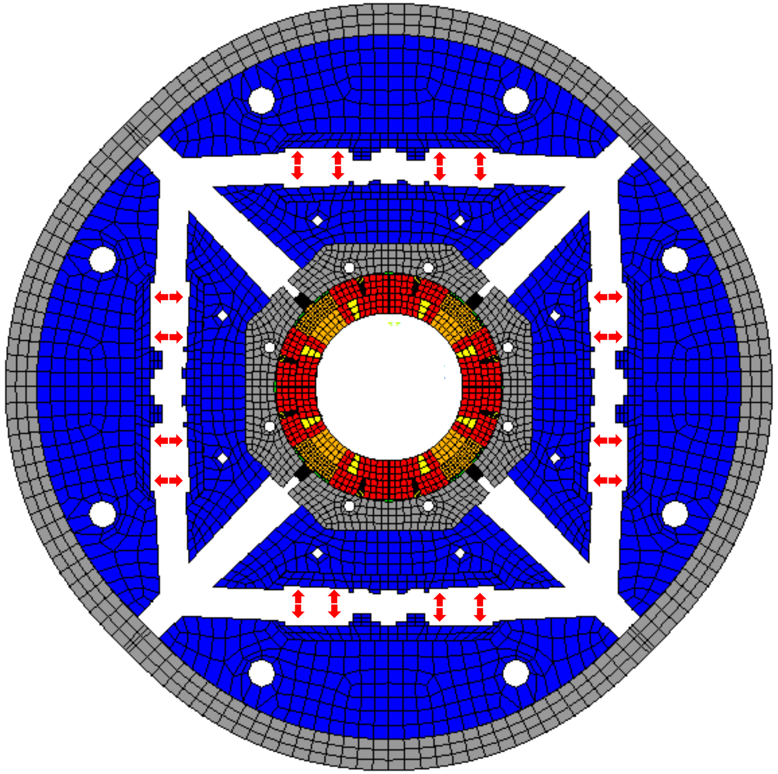


Bladder and key structure

The LHC Accelerator Research Program
an example of contribution

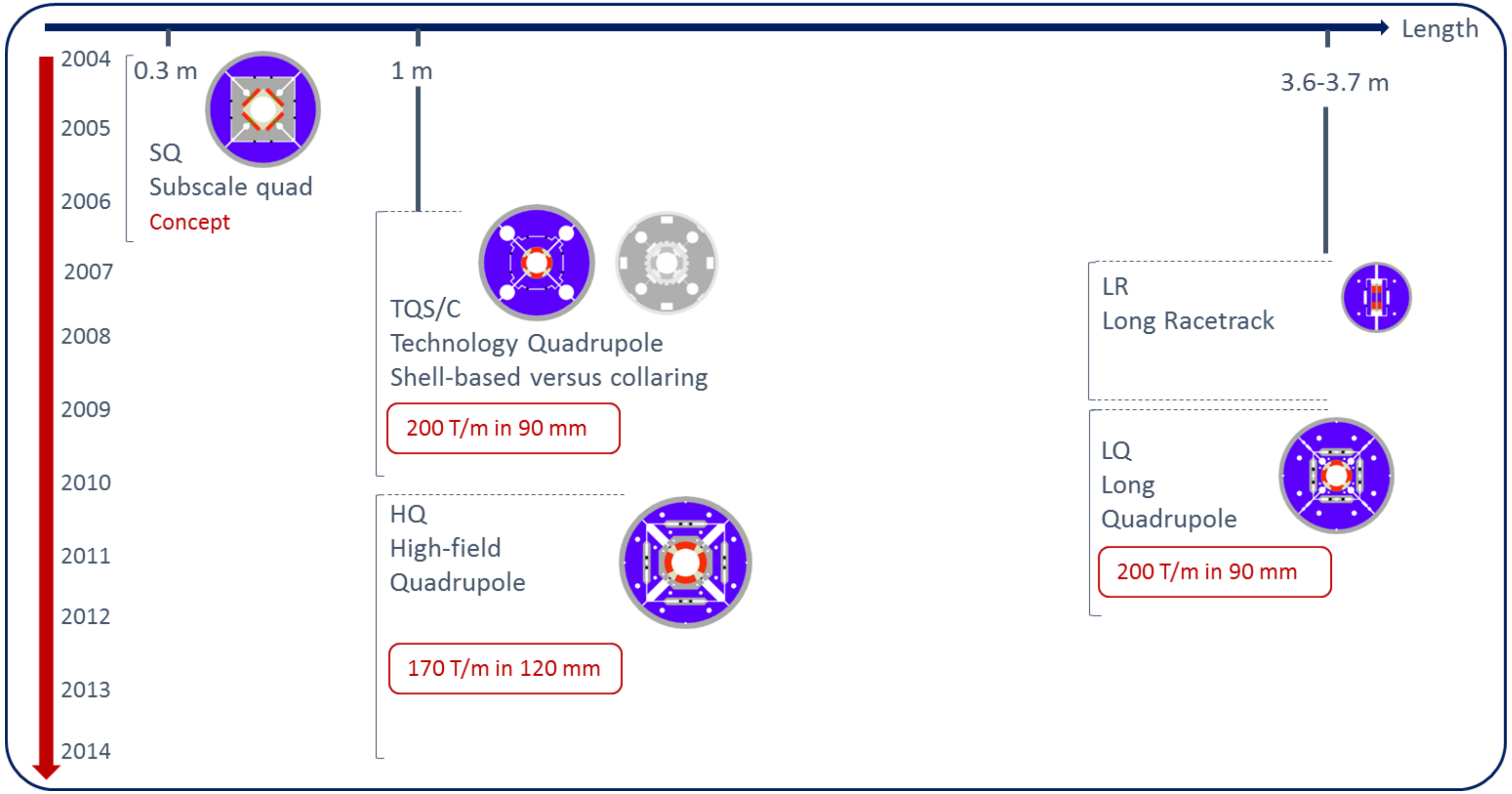


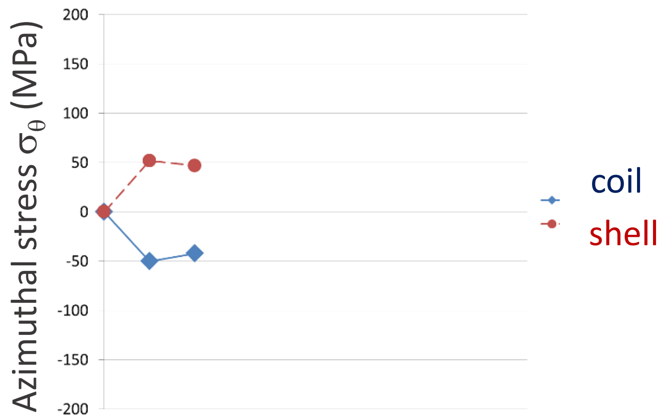


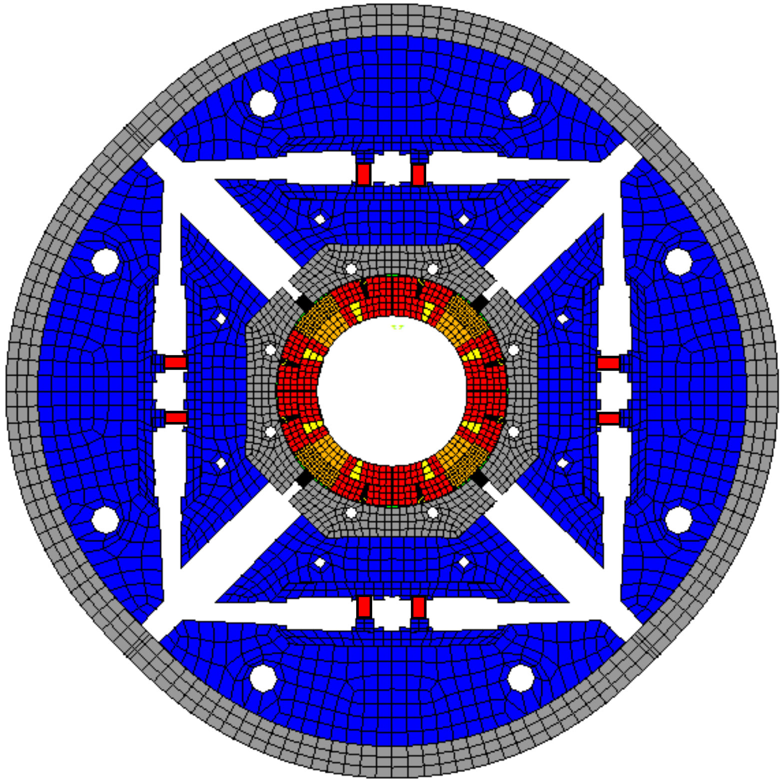


Inflated bladders

The LHC Accelerator Research Program
an example of contribution





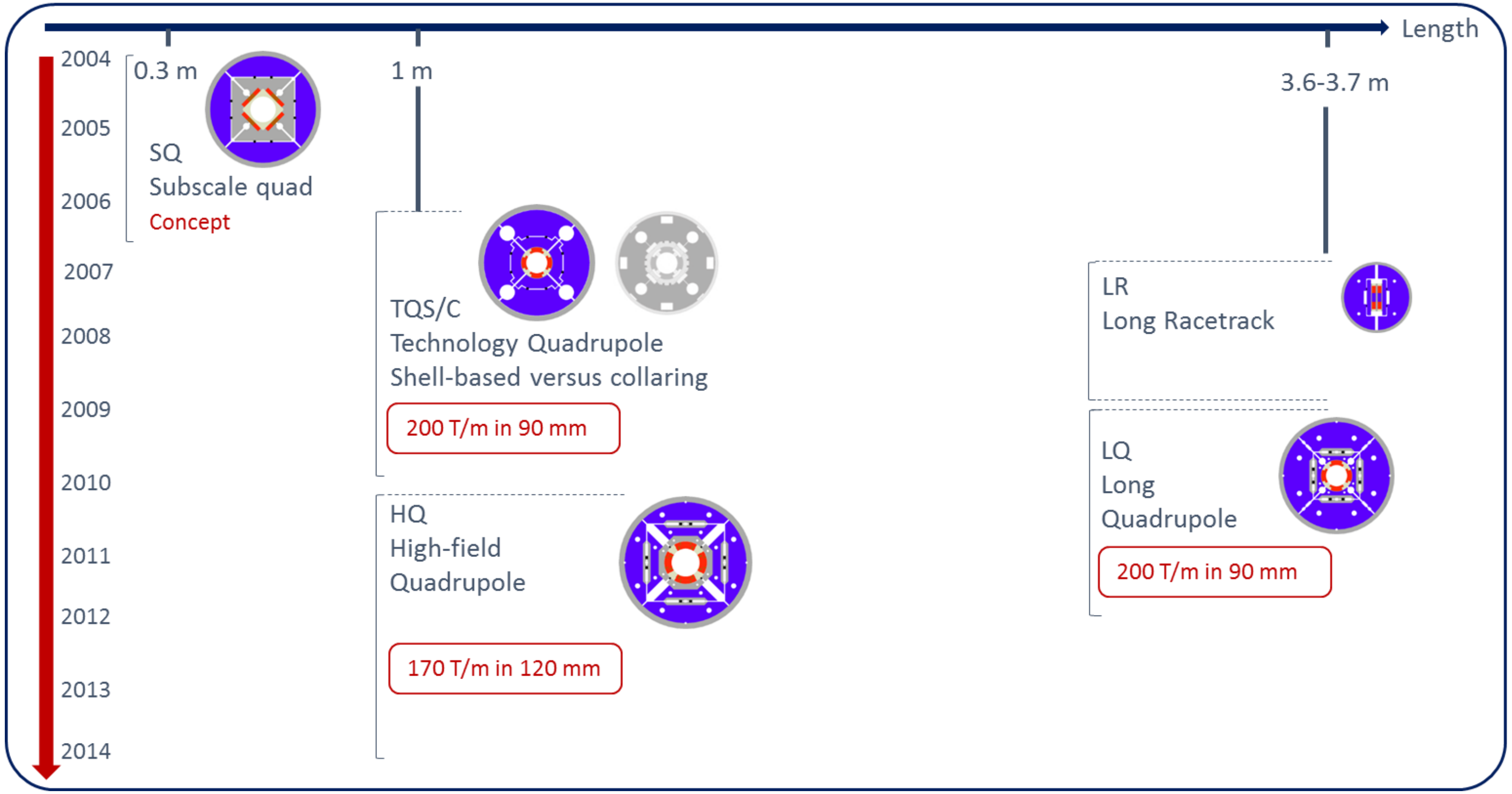


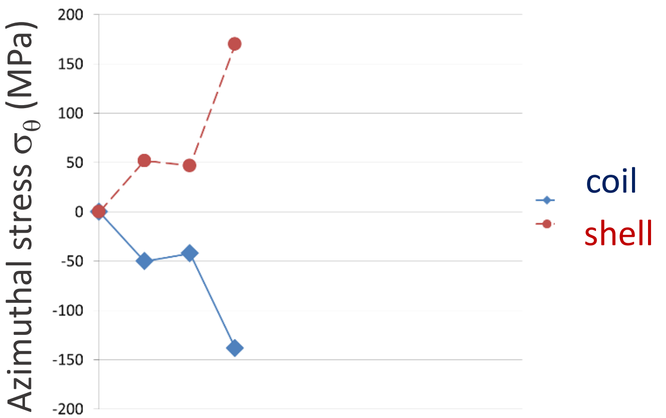
shimming

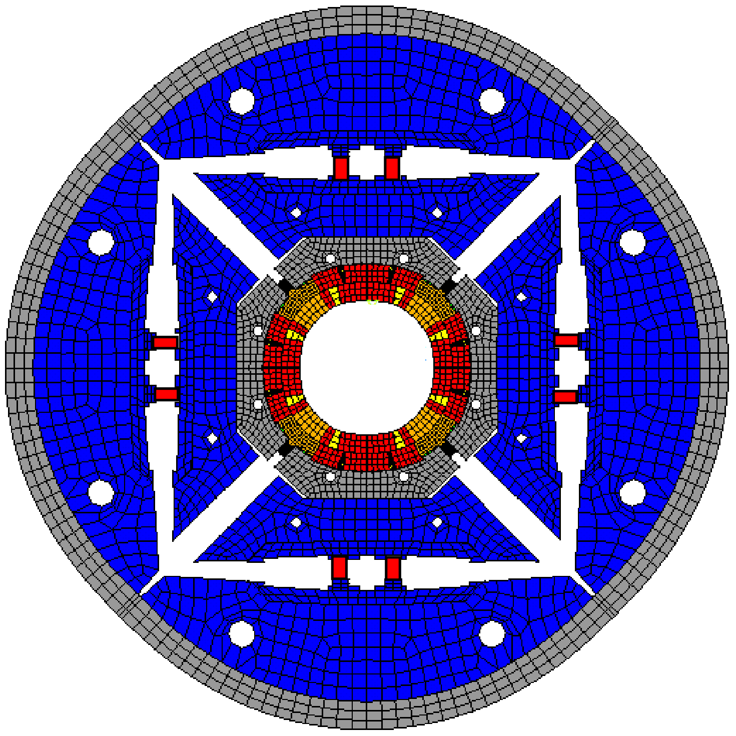
Gradual application of the preload

The LHC Accelerator Research Program
an example of contribution

Fermilab
BROOKHAVEN NATIONAL LABORATORY
BERKELEY LAB
U.S. DEPARTMENT OF ENERGY







Cool-down

Gain of preload during cool-down
No stress overshoot after cooldown

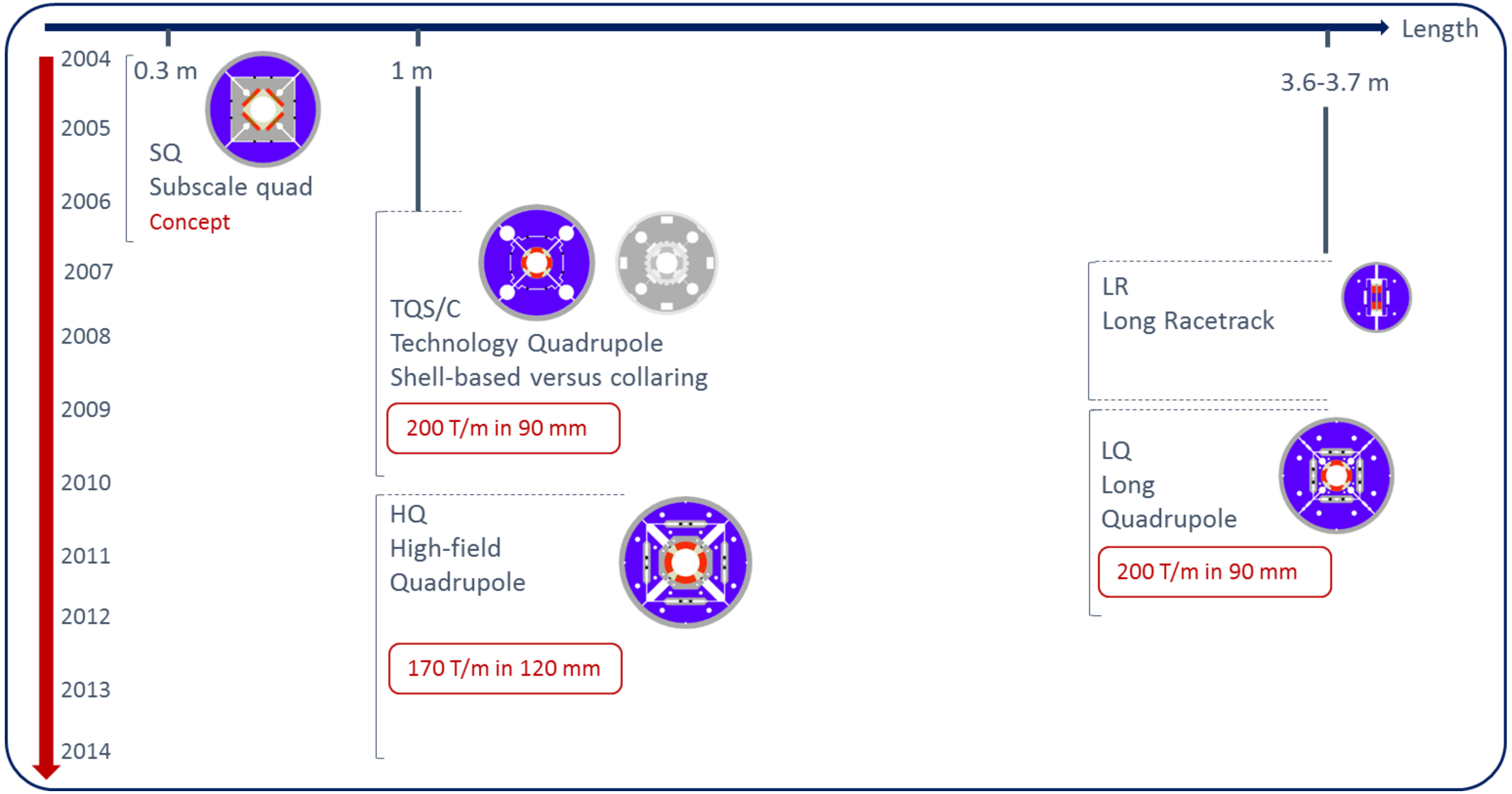
The LHC Accelerator Research Program
an example of contribution

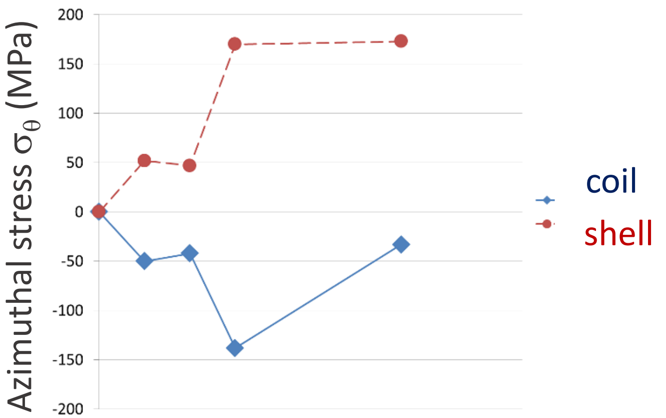
Fermilab

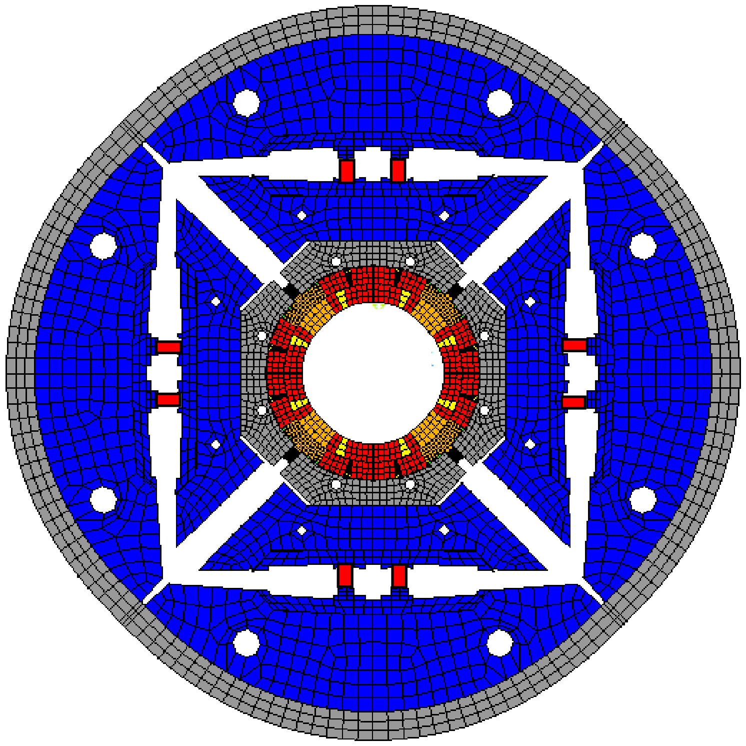
BROOKHAVEN NATIONAL LABORATORY

BERKELEY LAB

U.S. DEPARTMENT OF ENERGY





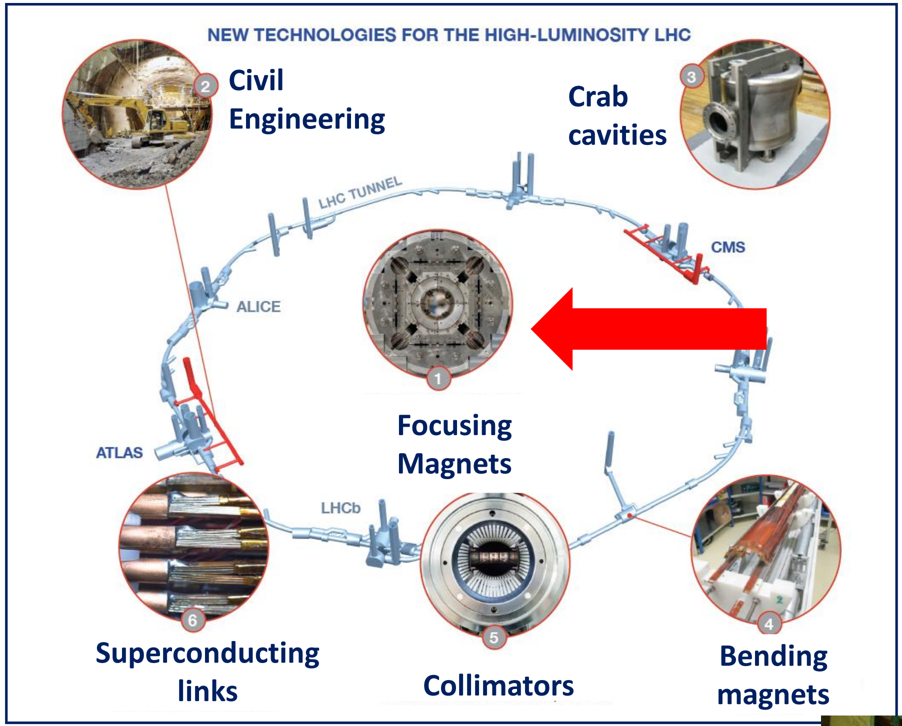


Energization

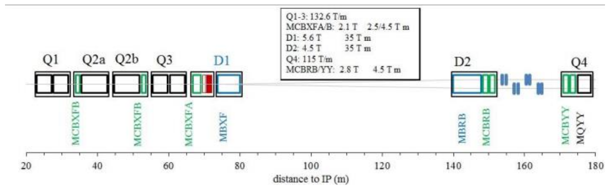
Development of the B&K support structure toward integration in an accelerator

Nb_3Sn magnets in HL-LHC: MQXF an outcome of LARP

Focusing triplet



Courtesy of CERN

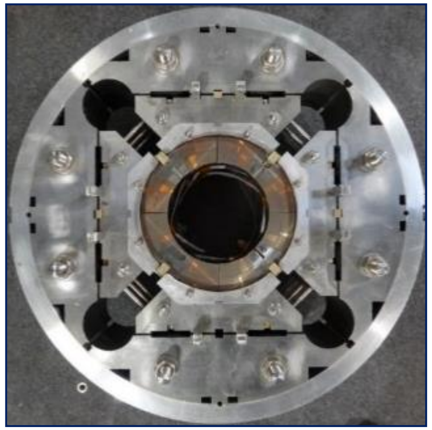


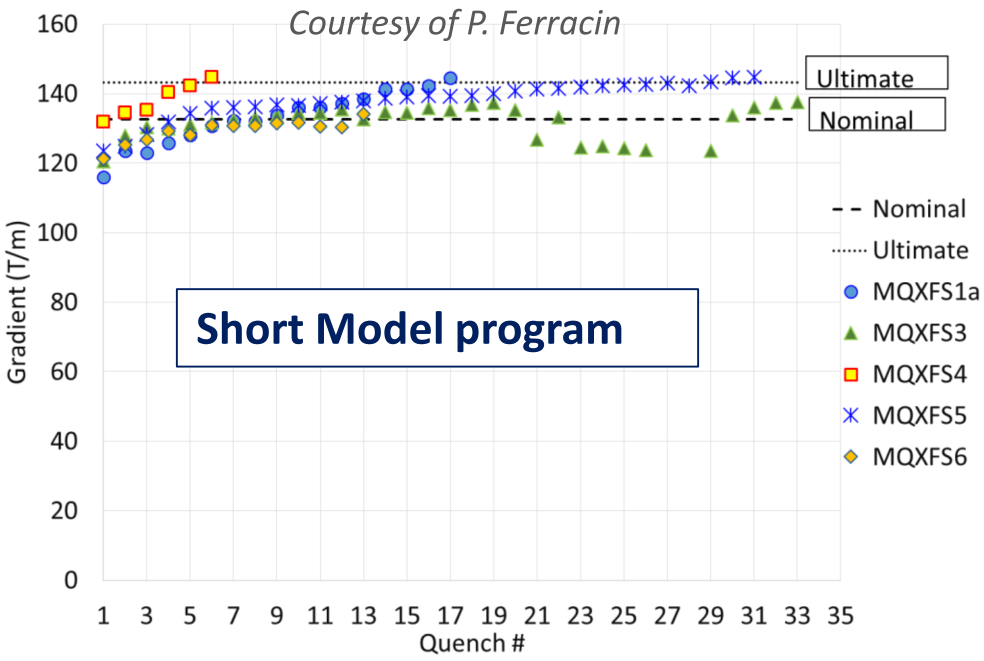
150 mm aperture

G_{op} 132 T/m @1.9K

B_{peak} 11.4 T

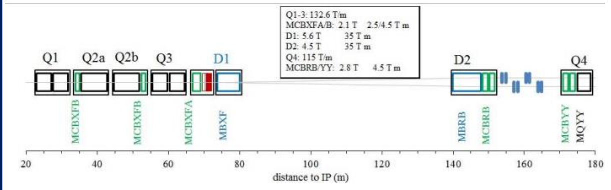
77 % on the LL





Courtesy of D. Cheng, LBNL

Nb_3Sn magnets in HL-LHC: MQXF an outcome of LARP



150 mm aperture
G_{op} 132 T/m @1.9K
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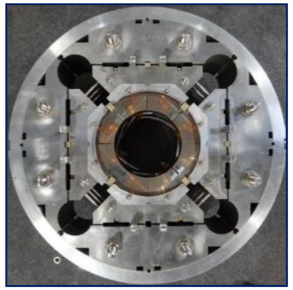
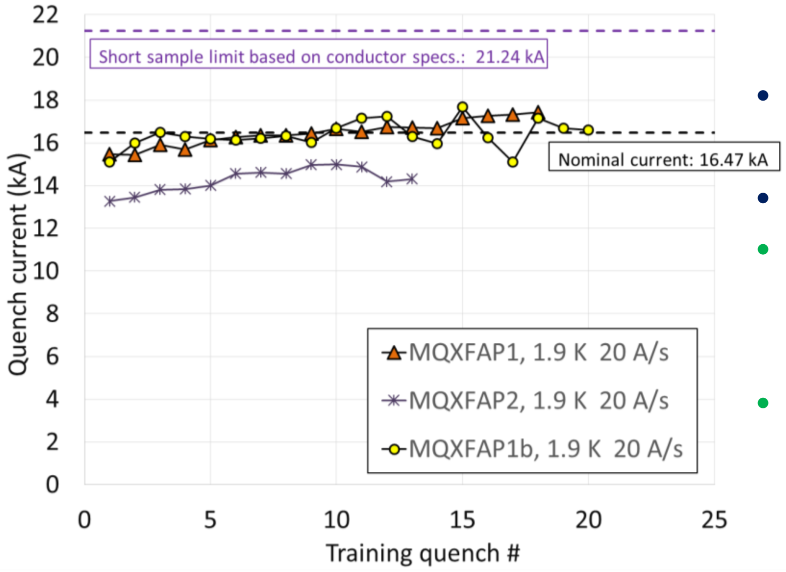


Prototypes

4.2 m MQXFA



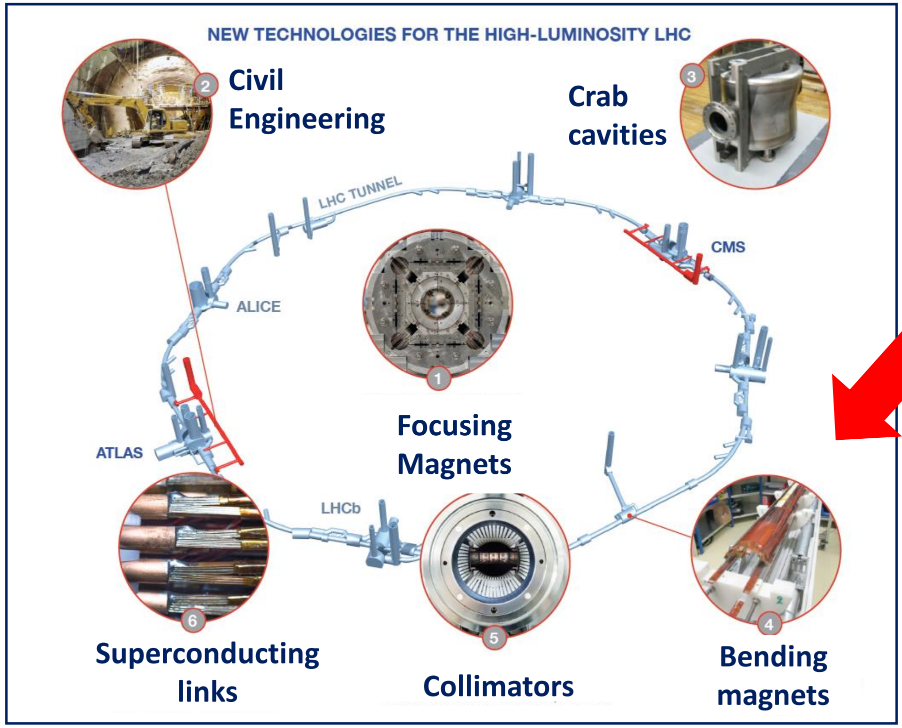
- 2 MQXFA prototypes tested
- Pre-series on its way
- MQXFA3 to be tested by the end of 2019

- MQXFBP1 to be tested early 2020

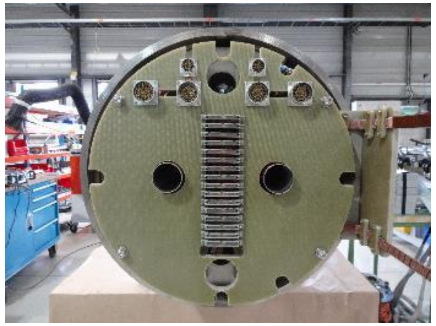
7.15 m MQXFB

Courtesy of G. Ambrosio, FNAL and P. Ferracin, CERN

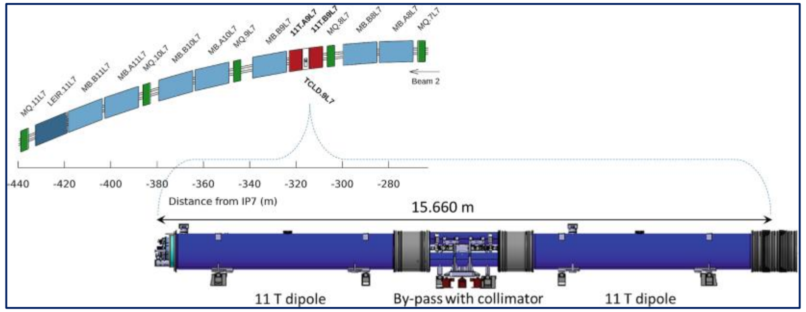
Nb_3Sn magnets in HL-LHC

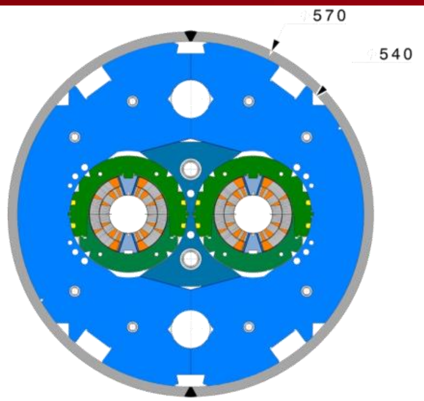


Courtesy of CERN



11 T Bending dipoles to allow space for new collimators



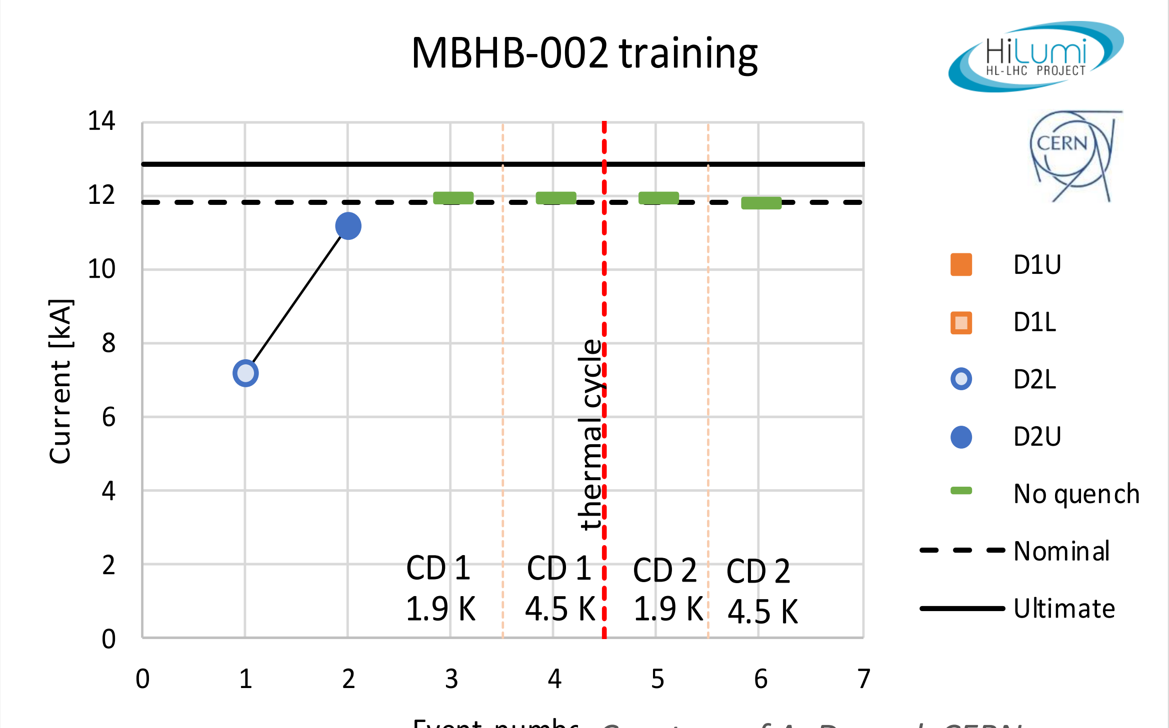


Double aperture magnets (5.5 m)

60 mm aperture
B_{nom} 11.2 T @ 1.9 K
80 % on the LL

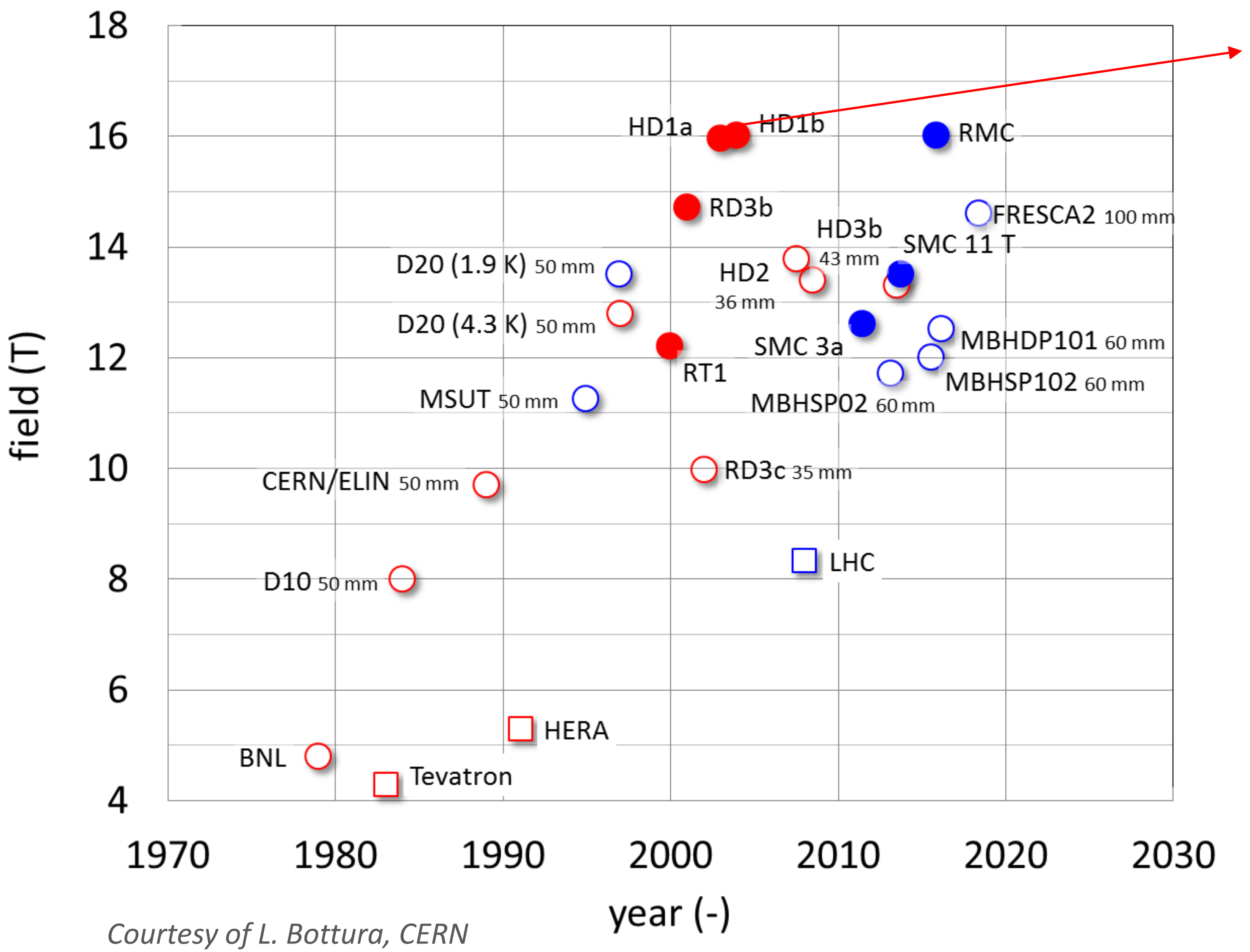
1st dipole tested => ready for tunnel since 10/2019

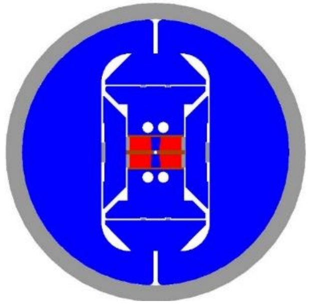
All four dipoles should be ready in April 2020

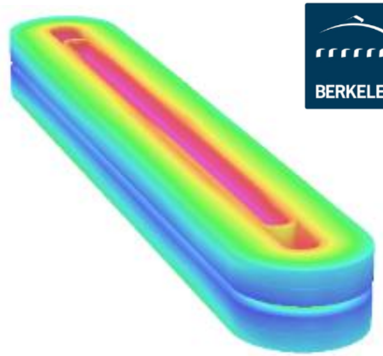


Courtesy of A. Devred, CERN

Quest towards high field





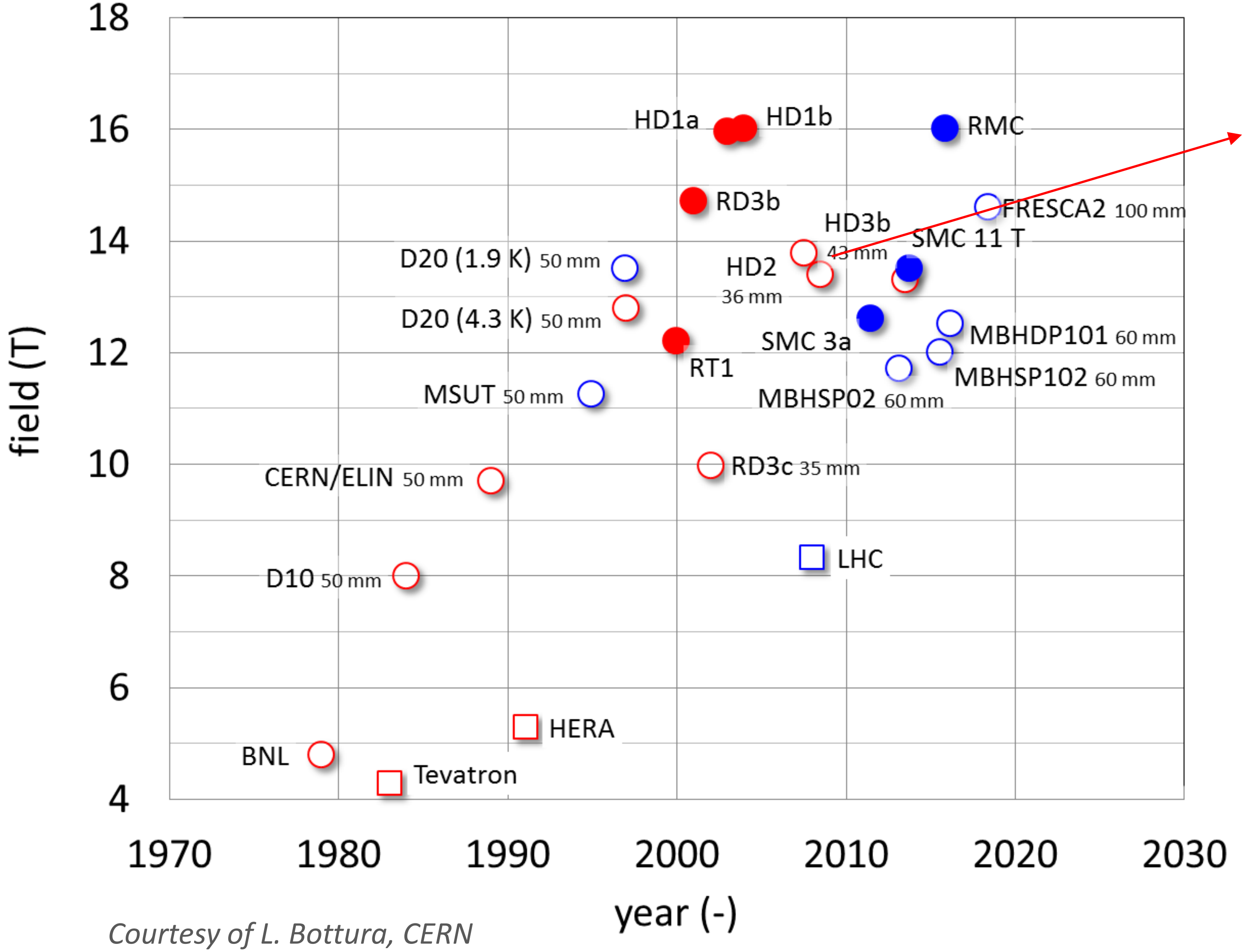


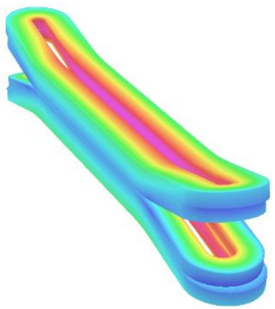
HD1
16 T bore field @ 4.3 K in 2003

- 8 mm aperture
- Racetrack, 1-m
- 155-185 MPa

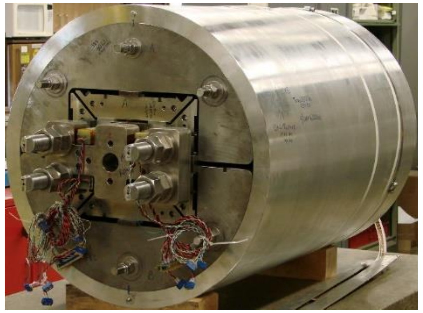
Courtesy of L. Bottura, CERN

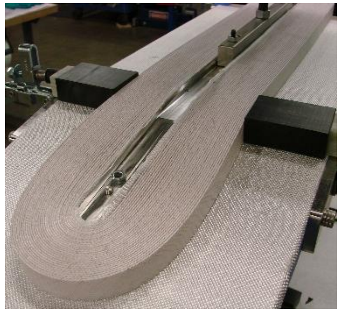
Quest towards high field





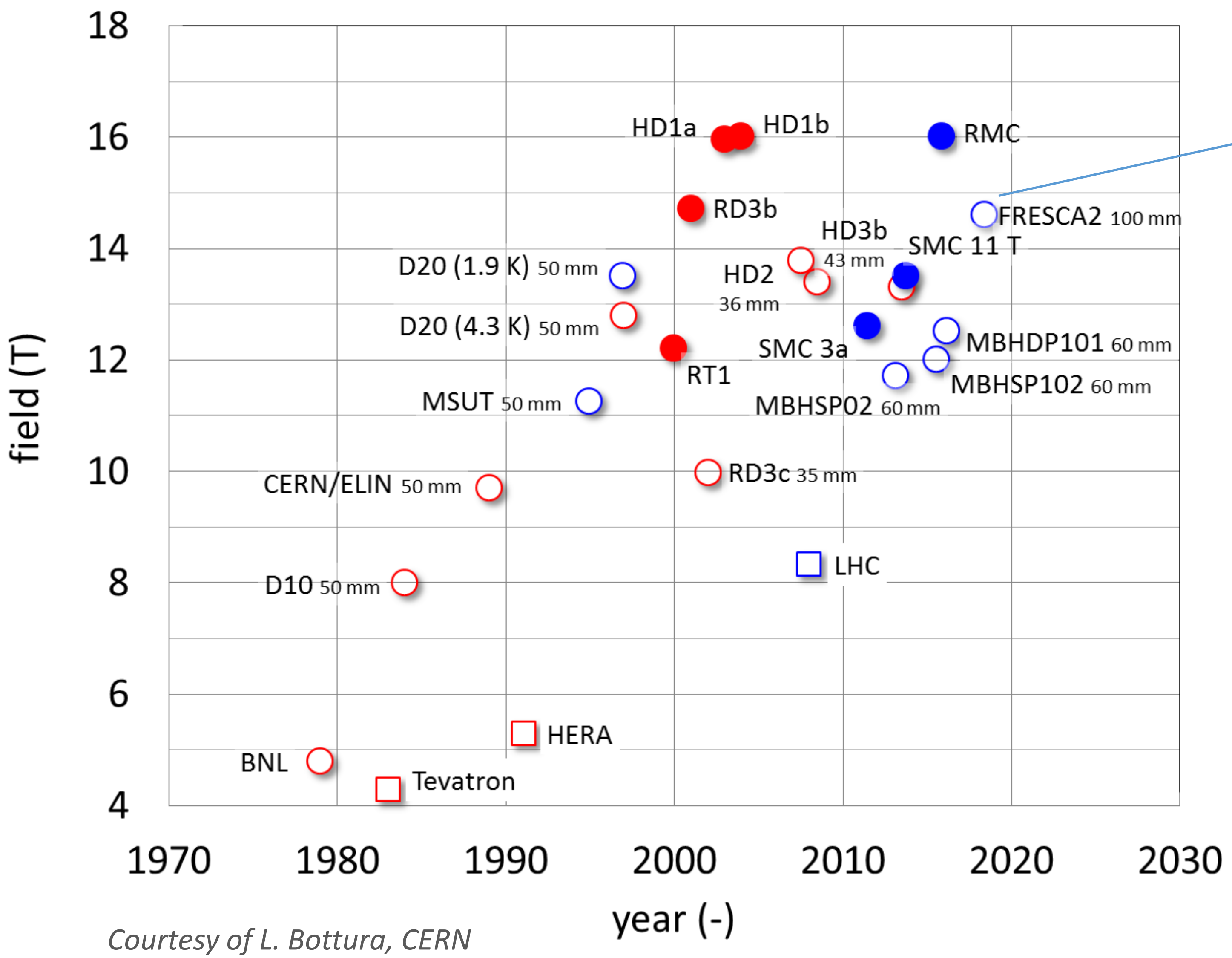
HD2: 13.8 T @ 4.3 K in 2008
HD3: 13.4 T @ 4.3 K in 2013



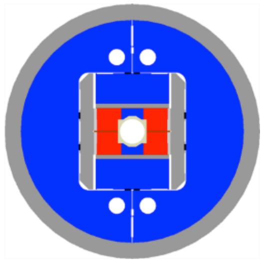


Courtesy of L. Bottura, CERN

Quest towards high field

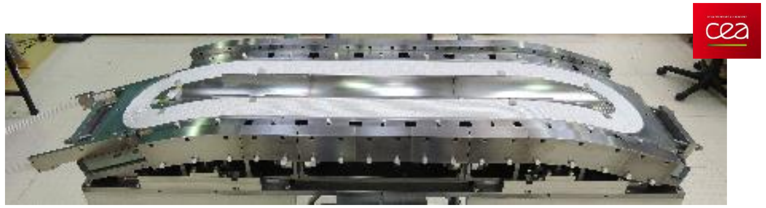


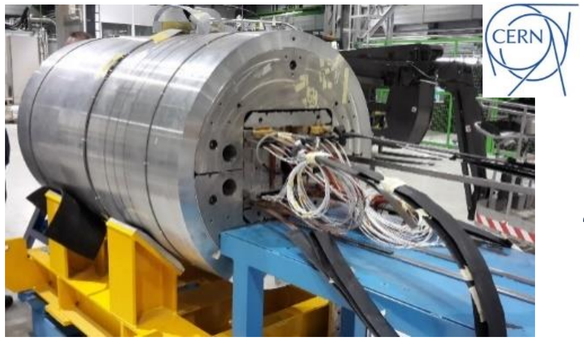
Courtesy of L. Bottura, CERN



FRESCA2
14.6 T at 1.9 K
in 2018

Test facility (13 T) and
Technology carrier for HFM





100mm bore
2.2-m long
~120 MPa

Courtesy of F. Rondeaux and JC Perez

ACCELERATOR MAGNET TECHNOLOGY OVERVIEW

Background on magnet development

Where are we?

What do we need for FCC-hh?

Strong R&D programs in 2000s

- Successful 16 T Nb_3Sn magnets without bore
- Encouraging 13-14$^+$ T Nb_3Sn short models
- Successful 11$^+$ T Nb_3Sn **long** dipoles and quadrupoles **to be installed in HL-LHC**

Toward 16 T magnets

- Compact cost effective magnets
- Reliable series production
- Field quality
- Fast training magnets

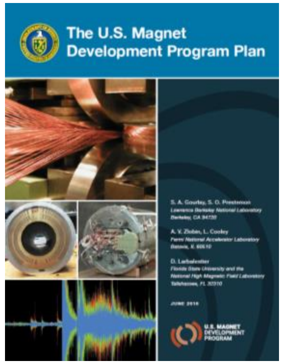
- High Je > 600 A/mm2
- Large Cu fraction Cu/NonCu > 1.2
- Jc (@4.2 K , 16 T) > 1500 A/mm^2
- RRR > 100
- Φ_{eff} < 20 µm

Understand the « effective critical surface » of Nb_3Sn Magnets

Programs and collaborations aiming at tackling these topics

U.S. MAGNET DEVELOPMENT PROGRAM *ASC/NHMFL, BNL, FNAL, LBNL*

Leveraging past experience



Item 2.2 : High Field Dipole Development to Explore the Limits of Nb_3Sn

Item 2.4 : Magnet Science: Developing Underpinning Technologies

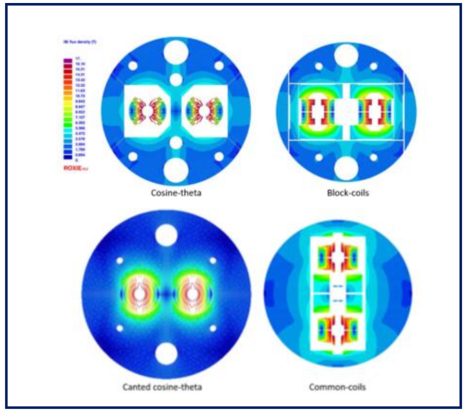
Item 2.5: Superconducting Materials -Conductor Procurement and R&D (CPRD)

FCC hh ee he

EuroCirCol A key to New Physics

CEA, CERN, CIEMAT, UNIGEneva, KEK, INFN, TampereU, UTwente

- Design study for FCC CDR
- **Conductor development & procurement**
- R&D magnets and associated development
- Model magnets



Series of Worskhops on Nb_3Sn technology for accelerator magnets

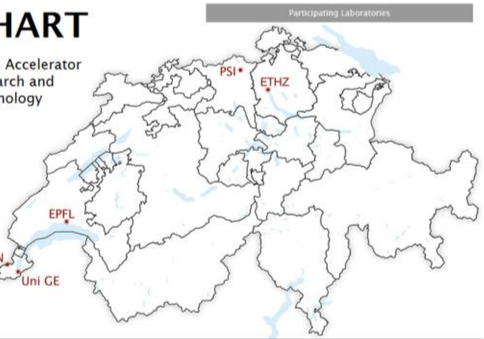
- **2017:** https://indico.cern.ch/event/665458/
- **2018 :** https://indico.cern.ch/event/743626/
- **2020 in preparation**

Budker INP Novosibirsk

Ongoing discussion on high field dipole program definition

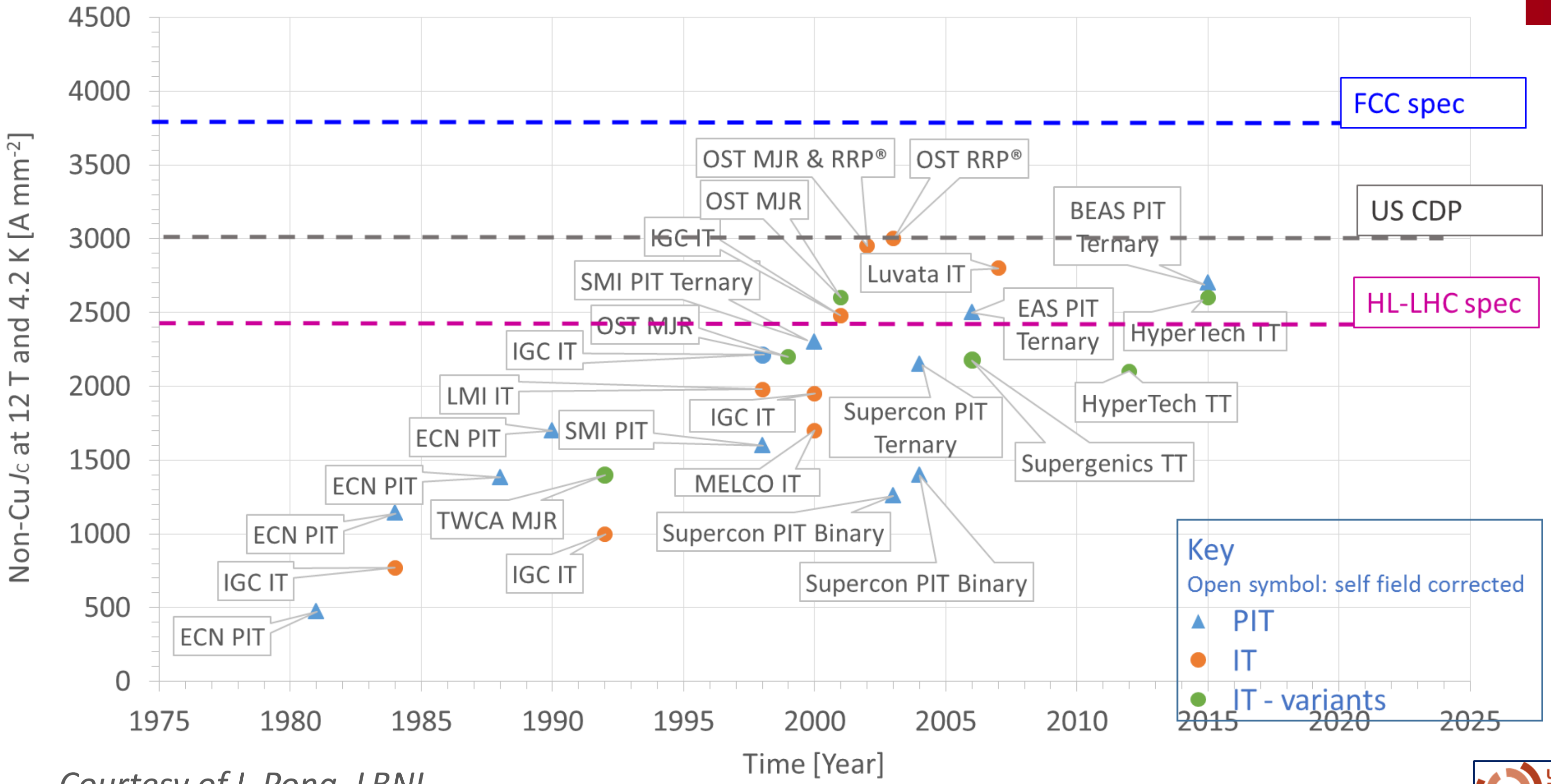
CHART

Swiss Accelerator Research and Technology



High field magnets development
Focus on innovative concept

Worldwide conductor development toward FCC-hh target

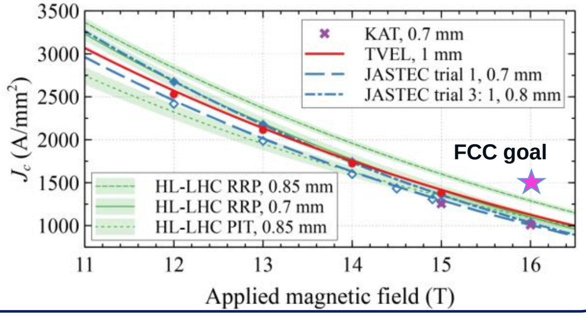


Courtesy of I. Pong, LBNL

CERN FCC Conductor Development Program

Many institutes and industry in Japan, Korea, Russia and Europe

Courtesy of A. Ballarino



Hf alloying of Nb-Ta

Courtesy of S. Balachandran *ASC/NHMFL, FSU*

- Improved pinning through Hf dopping
- Nb or NbTa rods can be replaced by Nb-Ta-Hf alloy without change of architecture
- Prototype wire

U.S. MAGNET DEVELOPMENT PROGRAM

Artificial Pinning Center

Courtesy of X. Xu

Internal oxidation of Nb-1%Zr

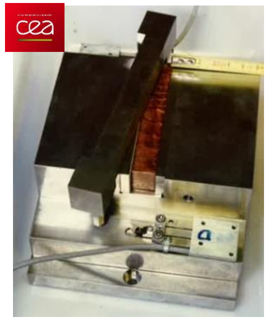
- Pinning point: ZrO_2 particles
- enhance J_c

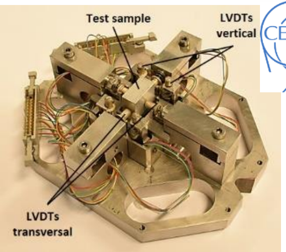
Ongoing work to get both Jc and stability

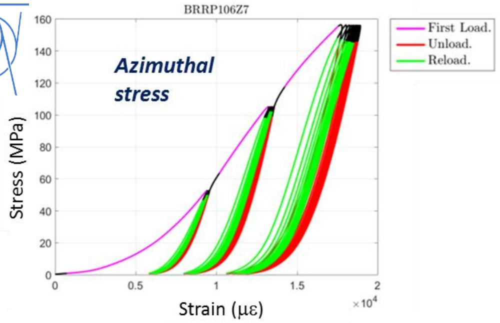
Collaboration between FNAL [LDRD], Hypertech and OSU

Shows untapped potential of Nb_3Sn
Optimization in progress

Magnet Technology Development: a non exhaustive list

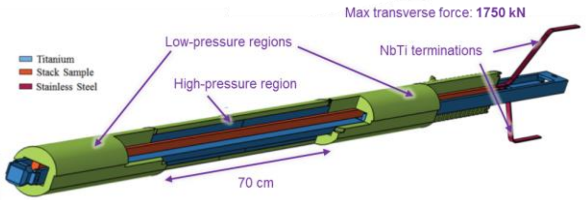






Mechanical behavior characterization of Epoxy impregnated Nb_3Sn => complex non linear orthotropic behavior

Conductor electromechanical characterization => Ic versus stress



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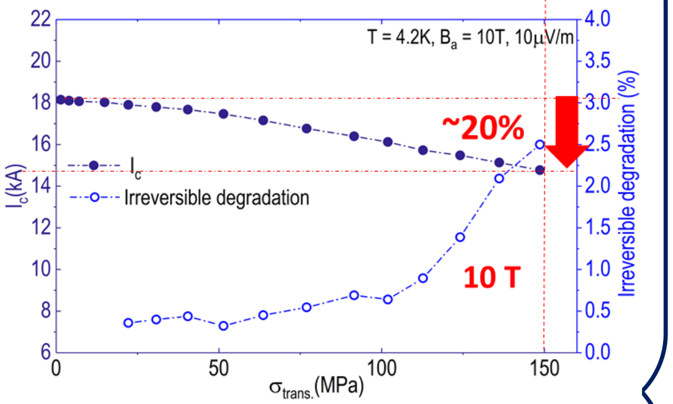
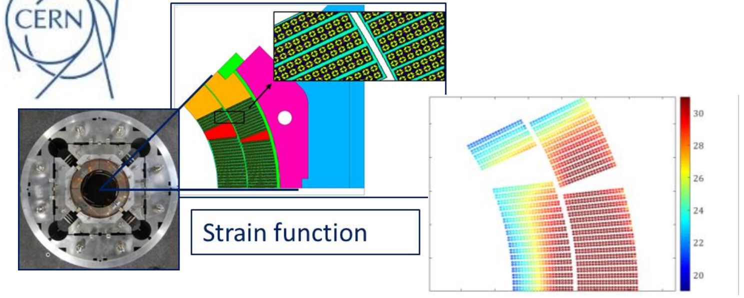
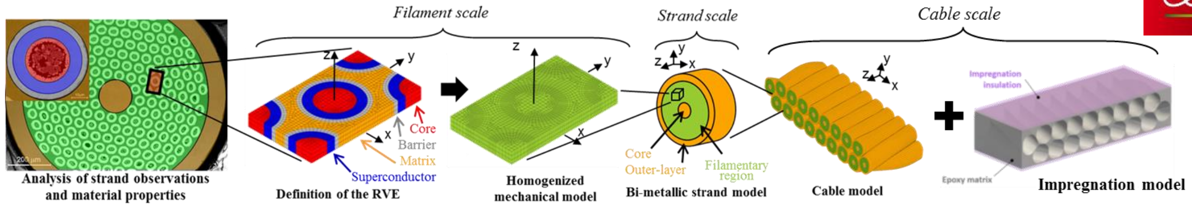
FACULTÉ DES SCIENCES
UNIVERSITY OF TWENTE.



Modeling => accounting for Ic reduction in magnet design



- Ic reduction map trough strain function
- Multiscale approach



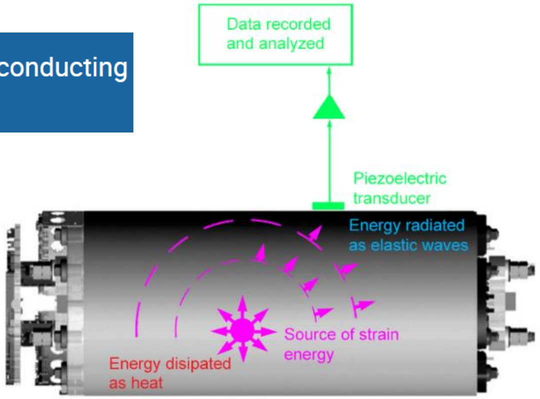
Understanding magnet performance using diagnostics

IDSM01 First Workshop on Instrumentation and Diagnostics for Superconducting Magnets
Berkeley, California, USA 24-26 April 2019

BERKELEY LAB

3rd International Workshop of the Superconducting Magnets Test Stands

Accoustic sensors



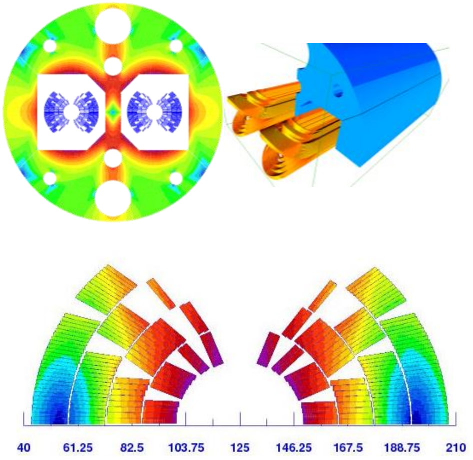
Courtesy of B. Bordini (CERN), M. Durante (CEA),C. Fichera (CERN), G. Vallone (LBNL), M. Marchevsky (LBNL)

Magnet Concepts for 16 T magnets

- Compact cost effective magnets
- Reliable series production
- Field quality
- Fast training magnets

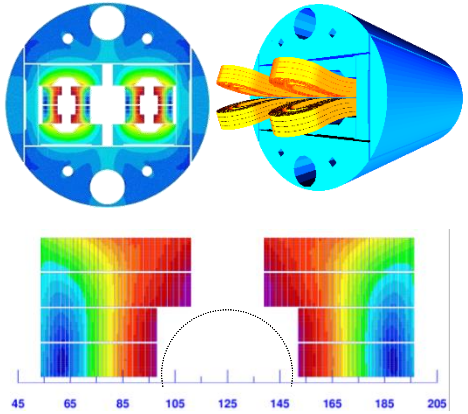
Exploration of different magnetic designs

INFN
Istituto Nazionale di Fisica Nucleare



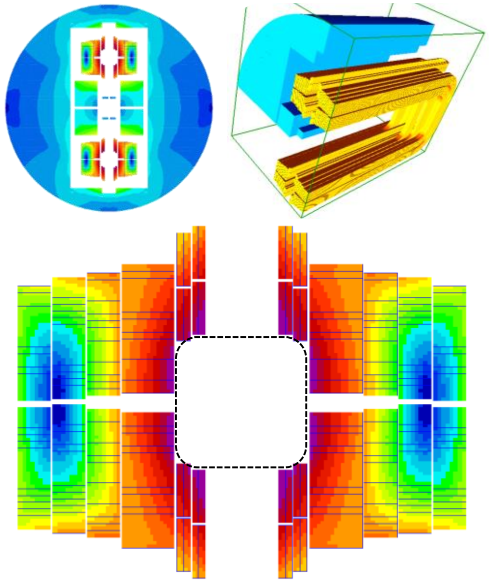
-Conductor amount
- Simple *Grading*
-Mechanical stress distribution

CEA



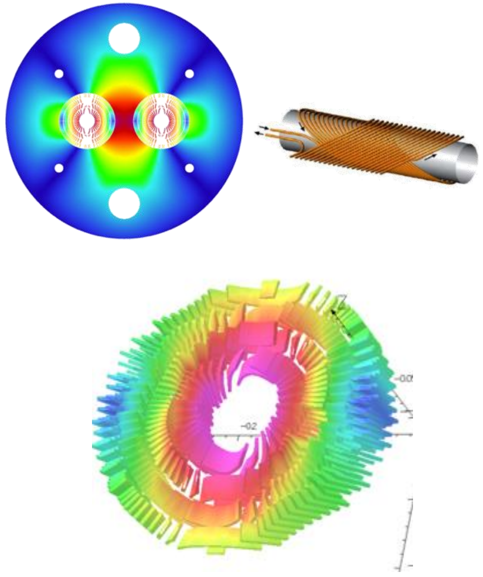
-Conductor amount
-Mechanical stress distribution
-Complex *Grading*

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas



- Simple *racetrack coils*
-Amount of conductor
-Mechanical stress

PAUL SCHERRER INSTITUT
PSI



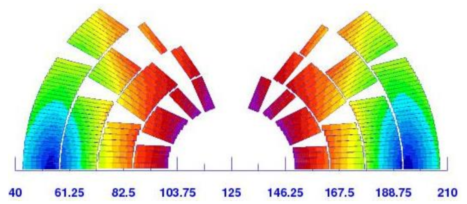
-Number of components
-Amount of conductor
- Number of interfaces

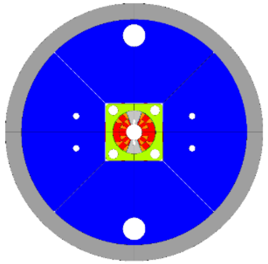
Courtesy of C. Lorin, CEA

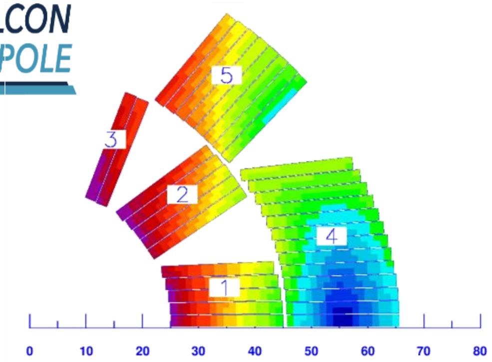
Through agreements between CERN and EU institutes

INFN

FALCON DIPOLE





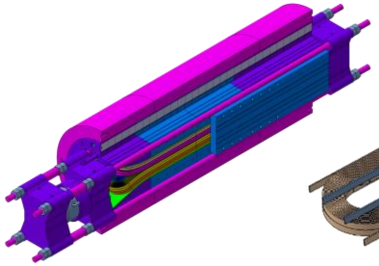


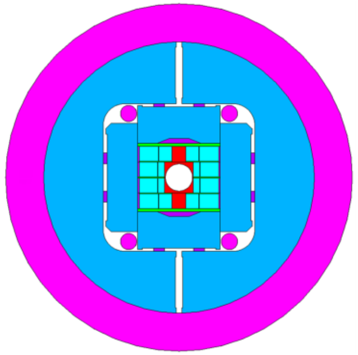
- 50 mm aperture
- 13.5 T bore field at 1.9 K

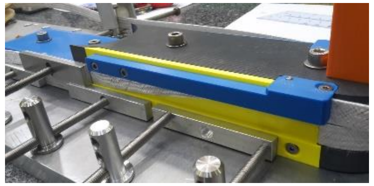
Courtesy of R. Valente, INFN

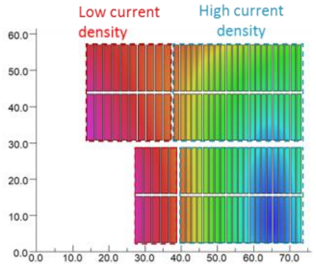
F2D2: FCC Flared ends Dipole Demonstrator

- 50 mm aperture
- 15.5 T bore field at 1.9 K and 14% margin





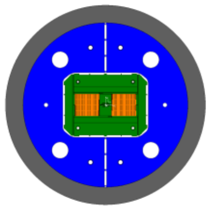




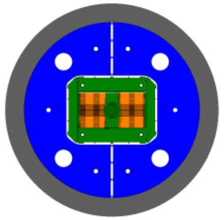
Development plan in progress to demonstrate GRADING in block configuration

FCC hh ee he

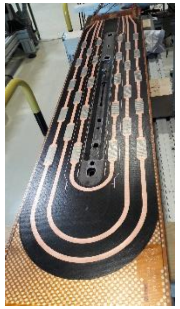
CERN



eRMC
No bore
16 T target



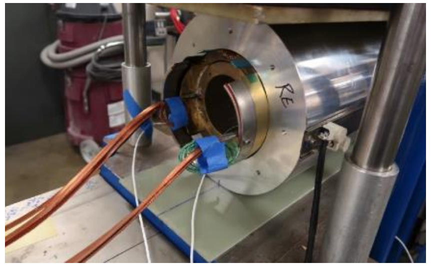
Racetrack Model Magnet = RMM
50 mm bore
16 T target

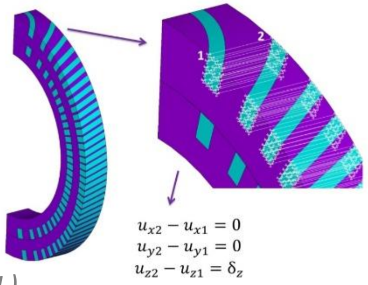


Courtesy of S. Izquierdo Bermudez, CERN

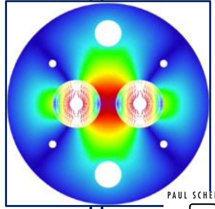
Models and demonstrators are on their way

- 10 T technology toward high field
- Analysis tools



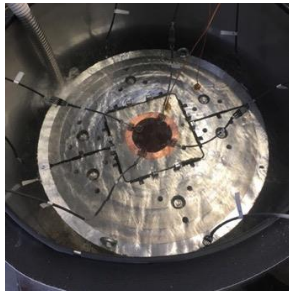


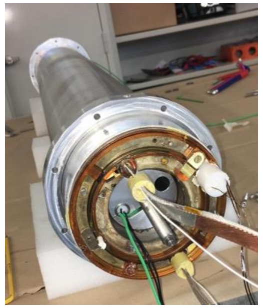
Courtesy of D. Arbelaez (LBNL)



CD1 under construction

11 T in 65.6 mm bore

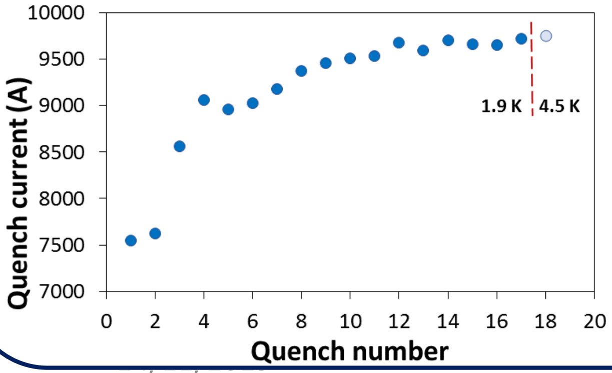


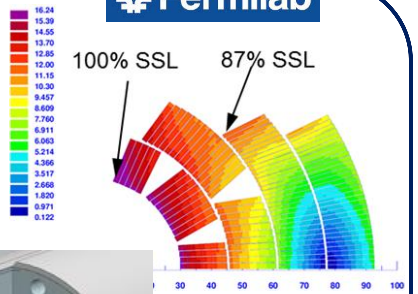


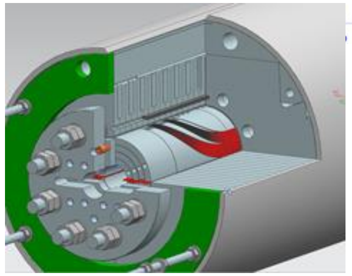
Courtesy of B. Auchmann

Key milestone: 15 T dipole

- 4 layer graded magnet, 1-m long
- 1st step: **14.1 T performance**



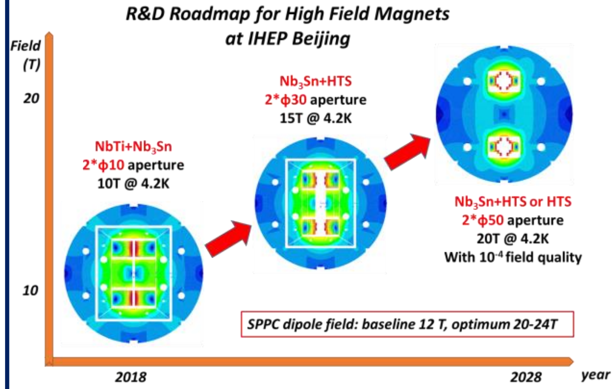


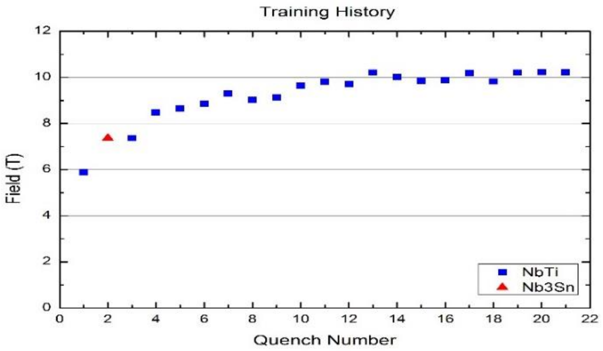


Courtesy of A. Zlobin, FNAL

Institute of High Energy Physics

Chinese Academy of Sciences

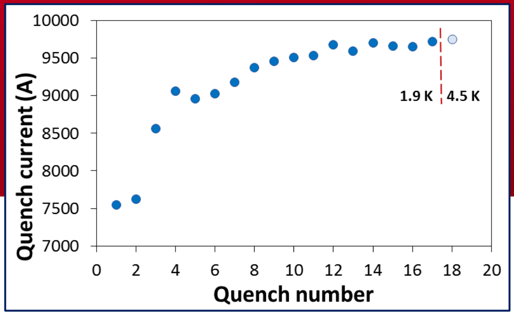


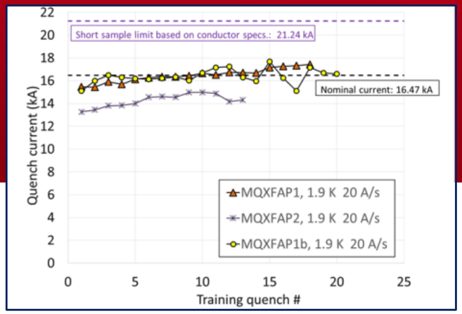


Courtesy of Q. Xu, IHEP

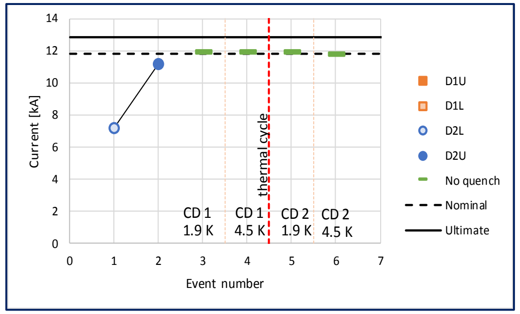
10.2 T at 4.2 K in 2 apertures

TAKE AWAY MESSAGES





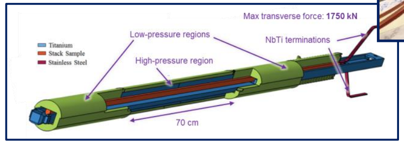
- Successful 16 T Nb_3Sn magnets without bore
- Encouraging 13-14$^+$ T Nb_3Sn short models
- Successful 11$^+$ T Nb_3Sn **long** dipoles and quadrupoles **to be installed in HL-LHC**

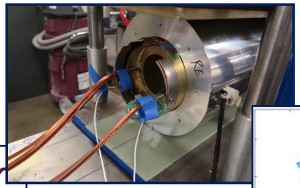


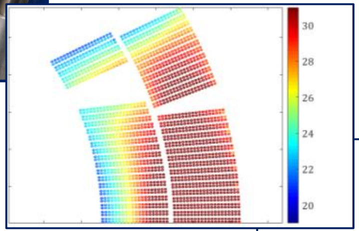
The community is working

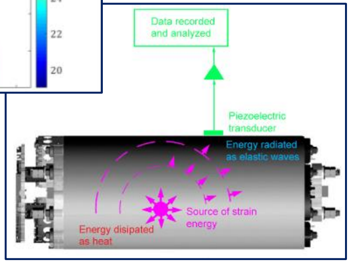
- as an international team
- with a consistent development program

to tackle the remaining Nb_3Sn challenges









We are on a consistent path toward the 16 T frontier