IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation Tue-Mo-PL2-01 given at MT26, 22 – 27 September 2019, Vancouver, Canada.

Advances in Nb_3Sn Superconducting Accelerator Magnets

Helene Felice
CEA Paris-Saclay

International Conference on Magnet Technology,
September 22-27 2019, Vancouver

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
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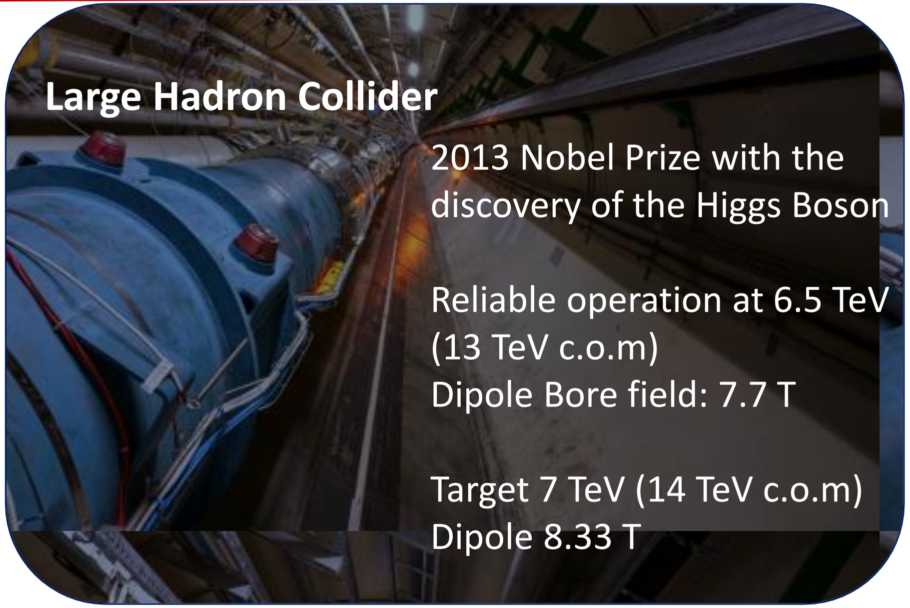
A word on Circular Colliders



E[GeV] ~ 0.3 B [T] R [m]

A word on Circular Colliders

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Large Hadron Collider

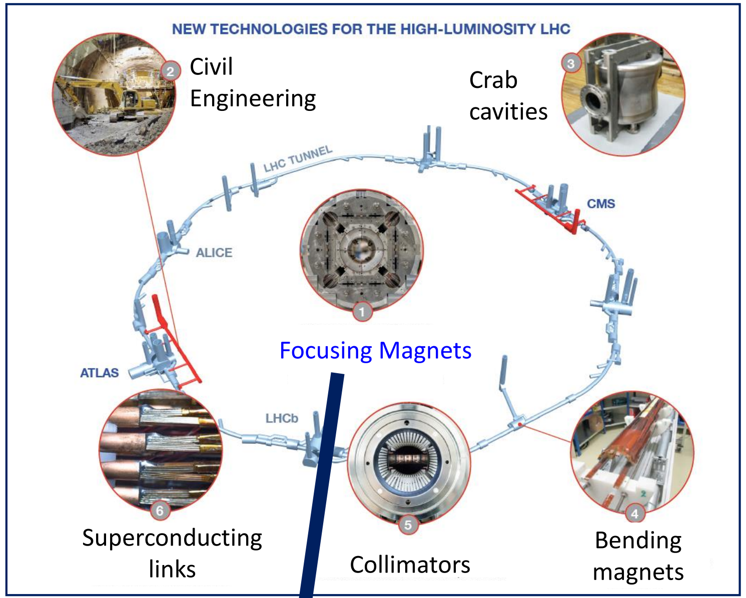
2013 Nobel Prize with the discovery of the Higgs Boson

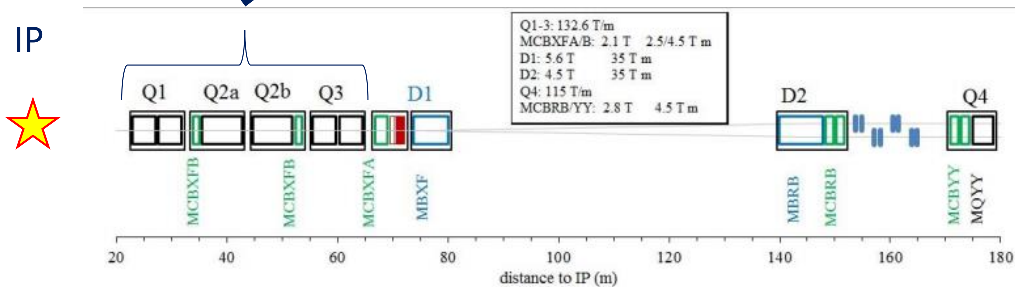
Reliable operation at 6.5 TeV (13 TeV c.o.m)
Dipole Bore field: 7.7 T

Target 7 TeV (14 TeV c.o.m)
Dipole 8.33 T

HL-LHC : High Luminosity LHC

- **Focusing triplet**: Gradient of 132.6 T/m in a 150 mm bore => 11.4 T peak field
- **11 T Bending dipoles** to allow space for new collimators





Courtesy of CERN

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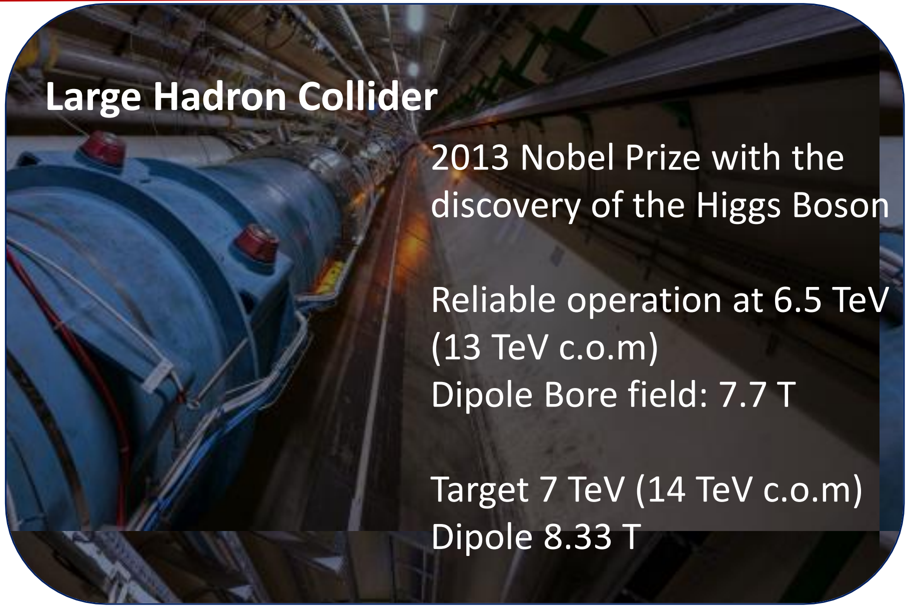

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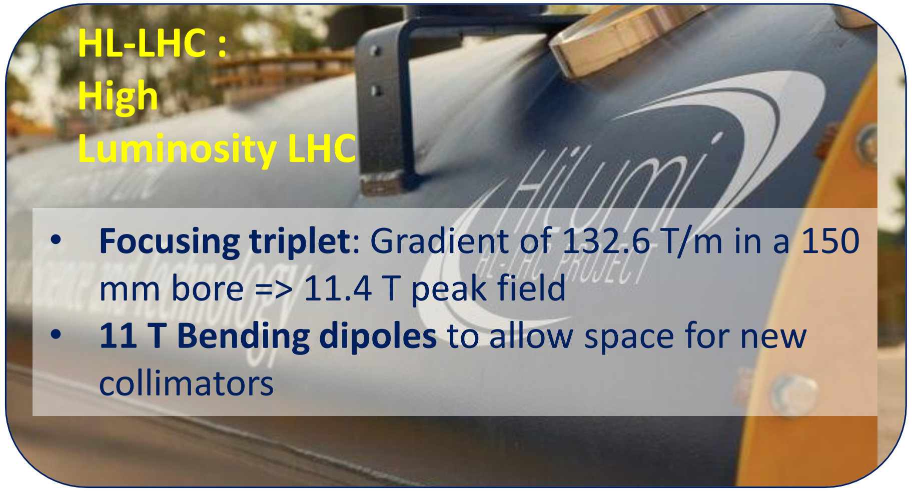

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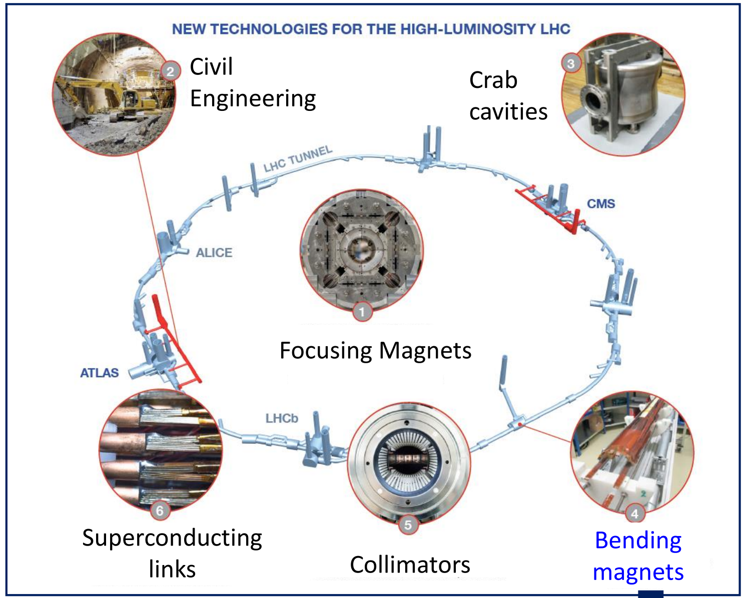

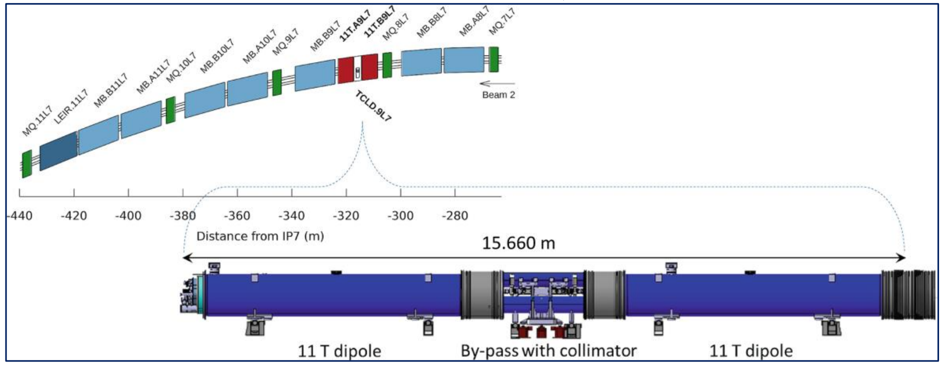

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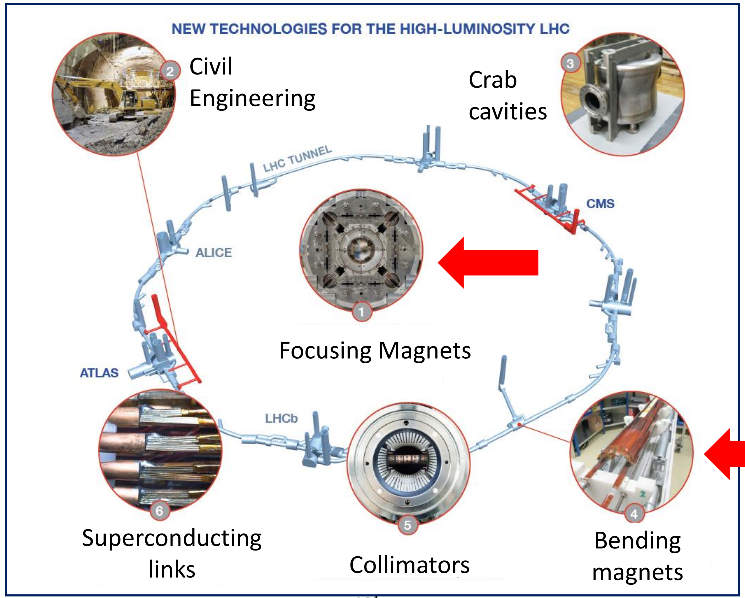

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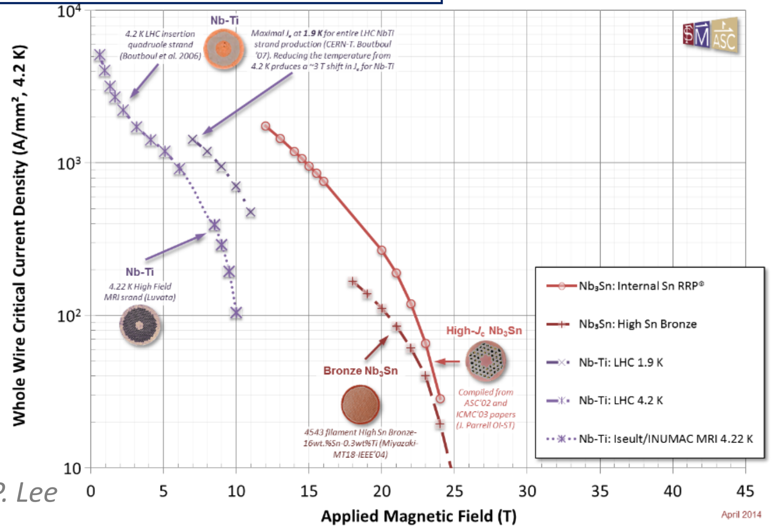

Courtesy of P. Lee

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FCC-hh
Future Circular Collider

100 km - **16 T**: 100 TeV (c.o.m)

Courtesy of CERN

HL-LHC : High Luminosity LHC

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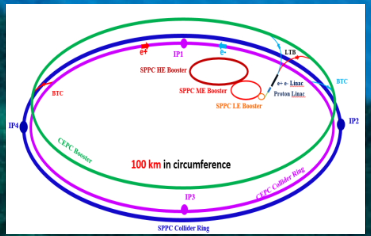
SPPC
Super Proton Proton Collider

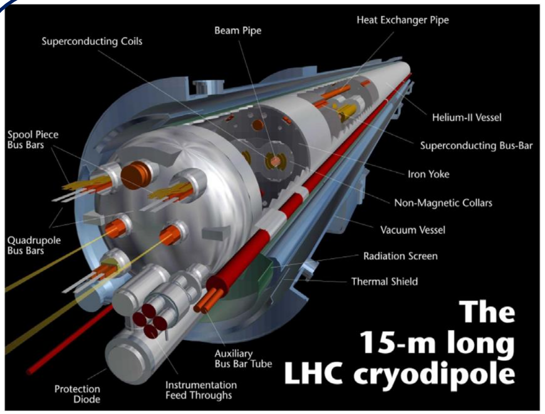


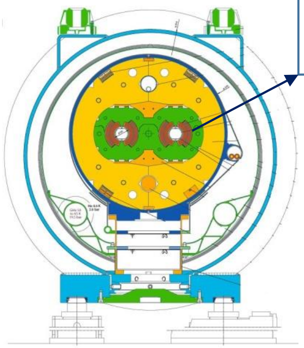
100 km - **12-24 T**:
=> 75 to 150 TeV (c.o.m)

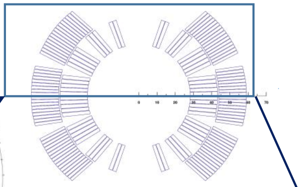
Courtesy of Q. Xu, IHEP

From NbTi to Nb_3Sn

LHC Technology



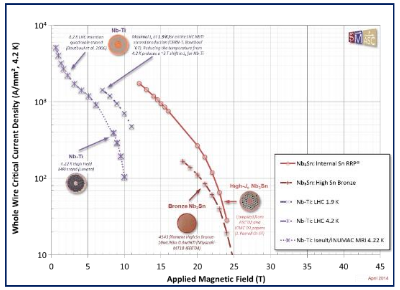




LHC NbTi dipoles

Courtesy of CERN

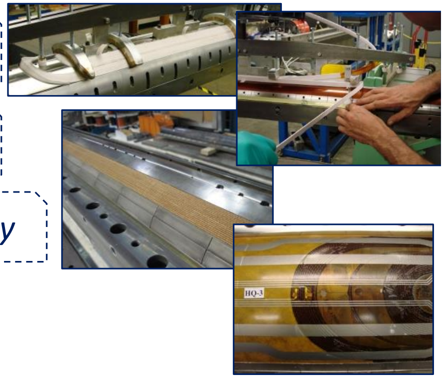
Beyond LHC



Courtesy of P. Lee

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)*

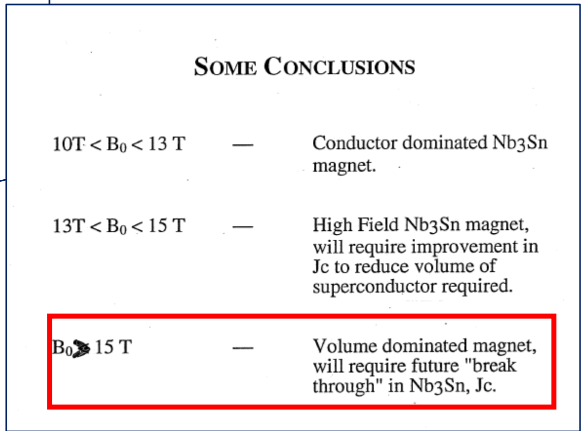
Strain sensitivity: a challenge impacting all the aspects of Nb_3Sn magnet design & fabrication

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

Operation close to critical surface => Ensuring Nb_3Sn integrity during its life cycle



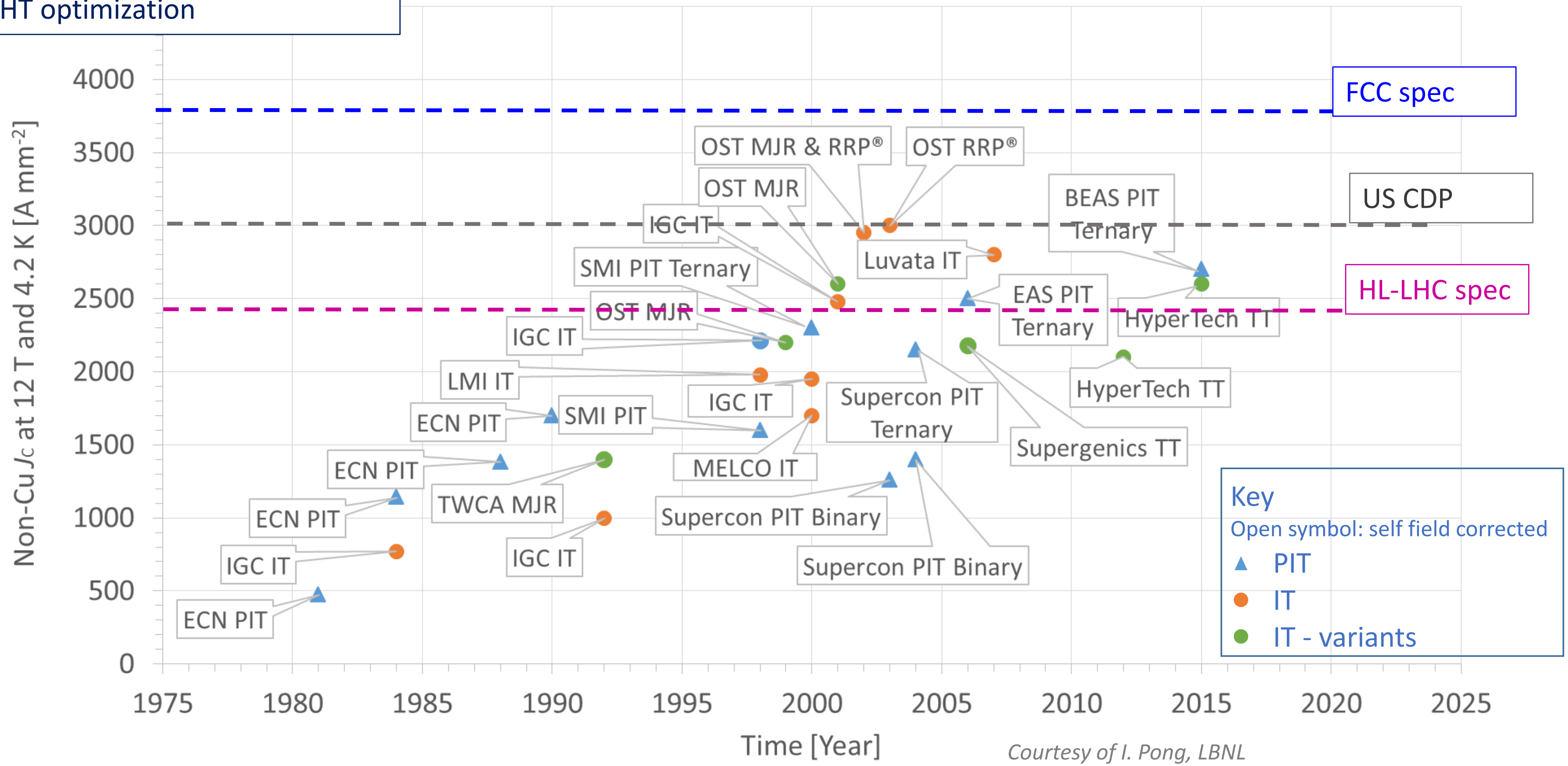
SOME CONCLUSIONS

10T < B_0 < 13 T	—	Conductor dominated Nb3Sn magnet.
13T < B_0 < 15 T	—	High Field Nb3Sn magnet, will require improvement in Jc to reduce volume of superconductor required.
B_0 > 15 T	—	Volume dominated magnet, will require future "break through" in Nb3Sn, Jc.

From LBNL internal report
By Shlomo Caspi, 1990s

Non Cu Jc improvement through
- Strand architecture
- Strand fabrication process
- HT optimization

A constant Non-Cu J_c improvement



Courtesy of I. Pong, LBNL

J_c development toward FCC target

CERN FCC Conductor Development Program

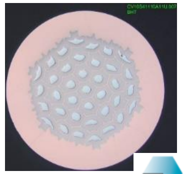
Courtesy of A. Ballarino

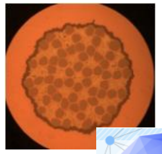
Many institutes and industry in Japan, Korea, Russia and Europe

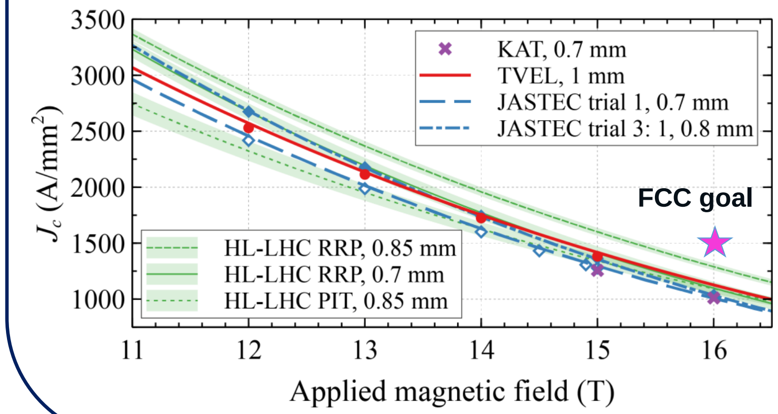
TVEL, Φ = 1mm

KAT, Φ = 1 mm

Jastec, Φ = 0.8 mm







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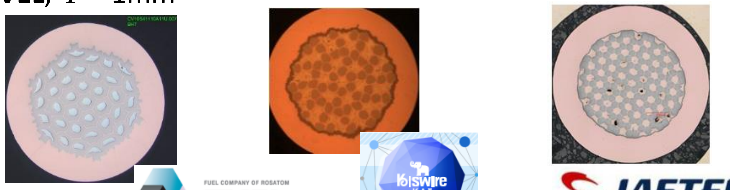
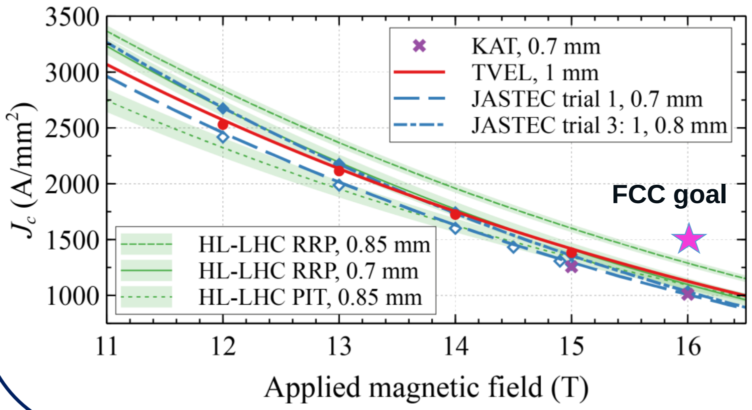


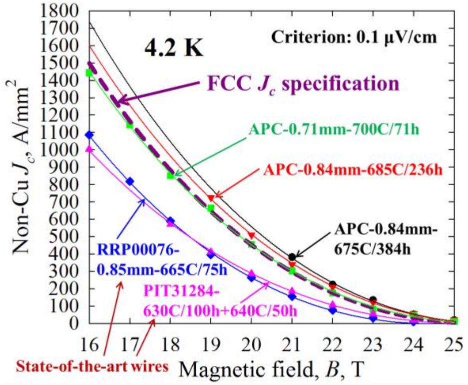


Artificial Pinning Center

Courtesy of X. Xu

Internal oxidation of Nb-1%Zr

- Pinning point: ZrO_2 particles
- enhance J_c
- High J_c but stability < 16 T compromised
- Stability but J_c compromised



Collaboration between FNAL [LDRD], Hypertech and OSU

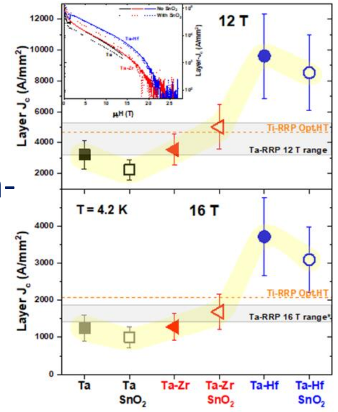
U.S. MAGNET DEVELOPMENT PROGRAM

Hf alloying of Nb-Ta

Courtesy of S. Balachandran

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

Alloy	SnO_2	J_{clayer} (A/mm²)		Eq. RRP non-Cu J_c
		12 T	16 T (A/mm²)	
Nb-Ta-Hf	No	9609 ±2744	3714 ±1061	2229 ± 636
Nb-Ta-Hf	Yes	8523 ±2434	3093 ± 883	1856 ± 530



Jan Evetts SUST Award 2019

ASC/NHMFL, FSU

Shows untapped potential of Nb_3Sn
Optimization in progress

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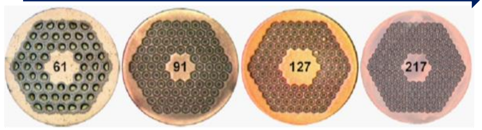
Strand to Rutherford cable

US conductor development program

CERN conductor development program

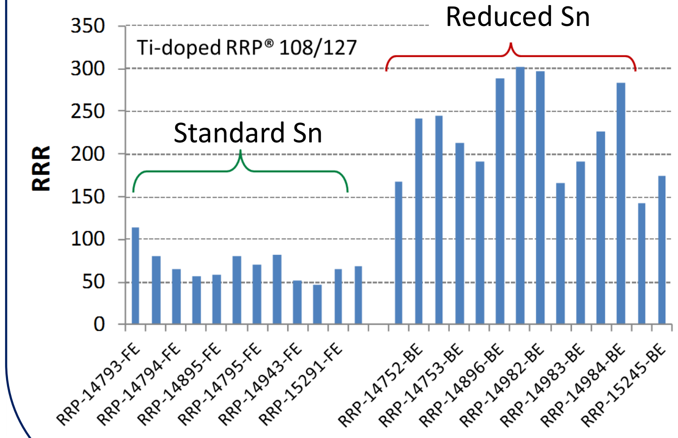
Magnetization reduction

Smaller filament size

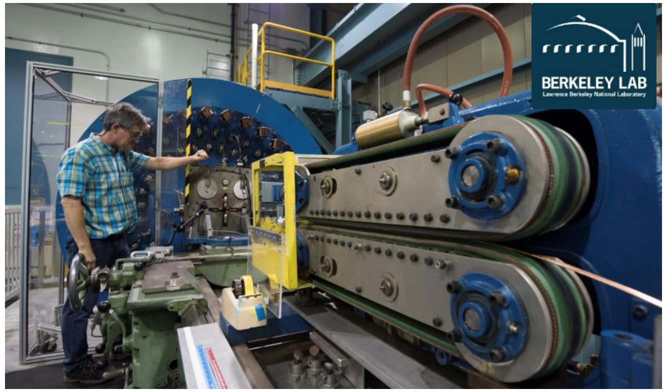


RRP® 54/61 RRP® 192/217

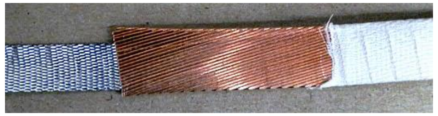
Strand RRR improvement



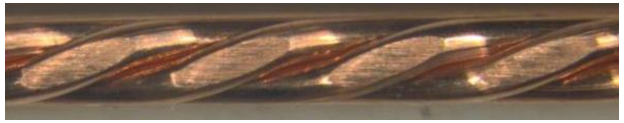
Courtesy of A. Ghosh, BNL



Courtesy of J. Fleiter, CERN



Courtesy of E. Barzi, FNAL

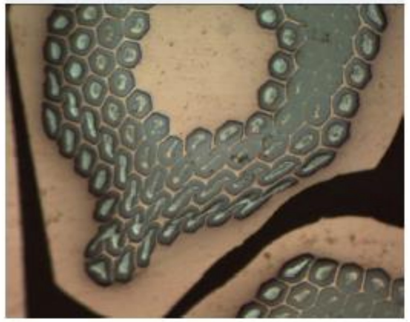


Courtesy of J. Fleiter, CERN

Cabling optimization required to:

- limit J_c and RRR degradation due to subelement damage
- While ensuring Rutherford cable mechanical stability

1044Z-6 – B position

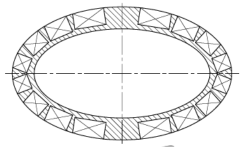


Courtesy of D. Dietderich, LBNL

Assessement through:

- Extracted strand I_c measurement
- Facet size inspection
- metallography

Snapshot on Nb_3Sn acceleror magnet history



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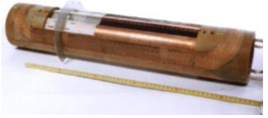
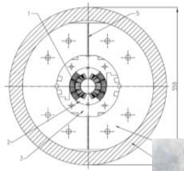
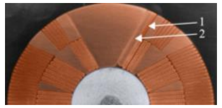


J. Perot, CEA, 1983

BERKELEY LAB KEK cea CERN

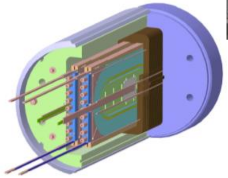


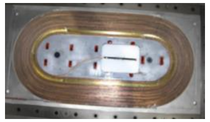
Courtesy of ELIN, Austria



UNIVERSITY OF TWENTE.

Courtesy of H. Ten Kate





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Fermilab

1954 DISCOVERY — 1960s — 1990s — 2000s

D20

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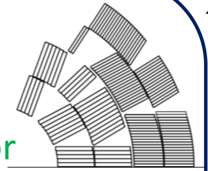
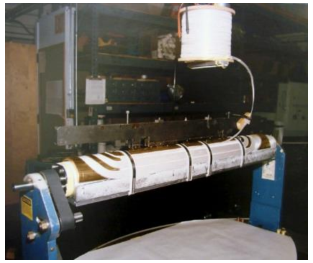
Grading / double layers
MJR and other IT conductor
50 mm aperture
1m long



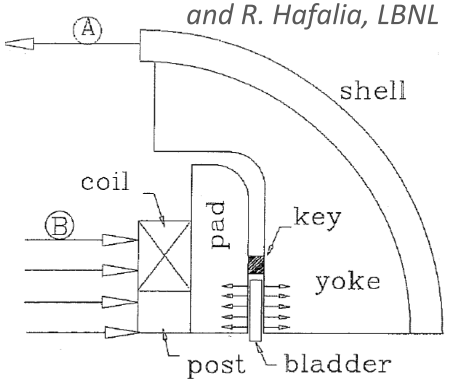
12.8 T at 4.4 K
13.5 T at 1.8 K
in 1996



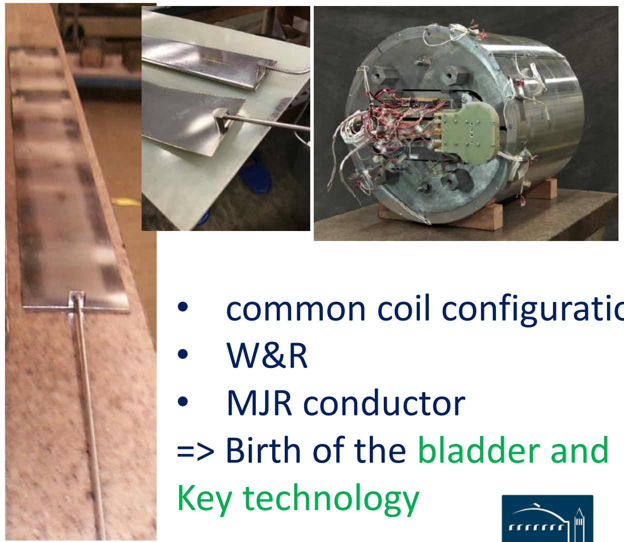
Courtesy of S. Caspi

RD3b

Courtesy of S. Caspi and R. Hafalia, LBNL



14.7 T bore at 4.5 K
in 2001



- common coil configuration
- W&R
- MJR conductor

=> Birth of the bladder and Key technology

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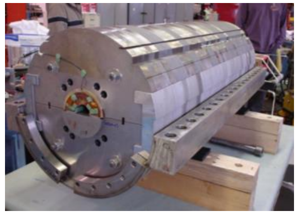
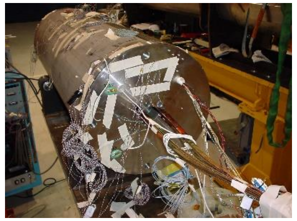
Bladder and keys: one Stepping stone for today's technology

2000s: progress on dipoles and quadrupoles

DIPOLES

Fermilab

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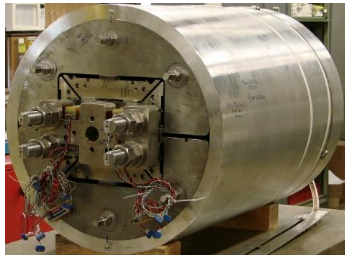
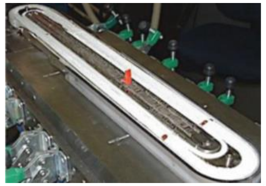
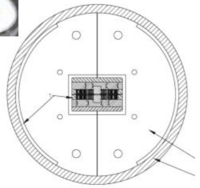




ATM

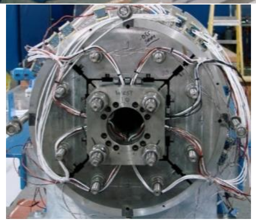


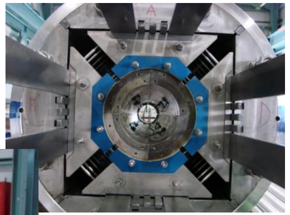
2000s

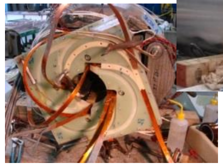
QUADRUPOLES

LARP







The LHC Accelerator Research Program (LARP)

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

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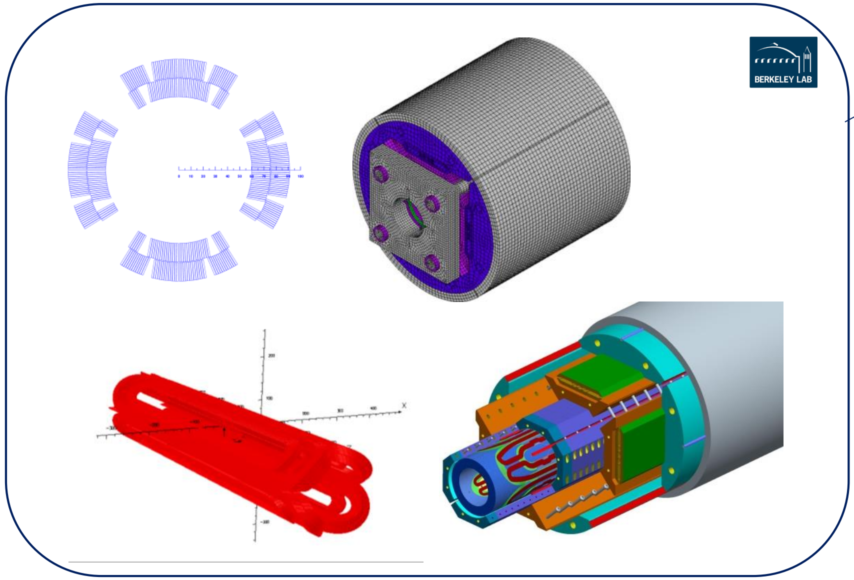
U.S. DEPARTMENT OF ENERGY

Supporting tools:

- **Integrated** magnetic, mechanical **analysis** and CAD
- **Mechanical instrumentation** on magnets



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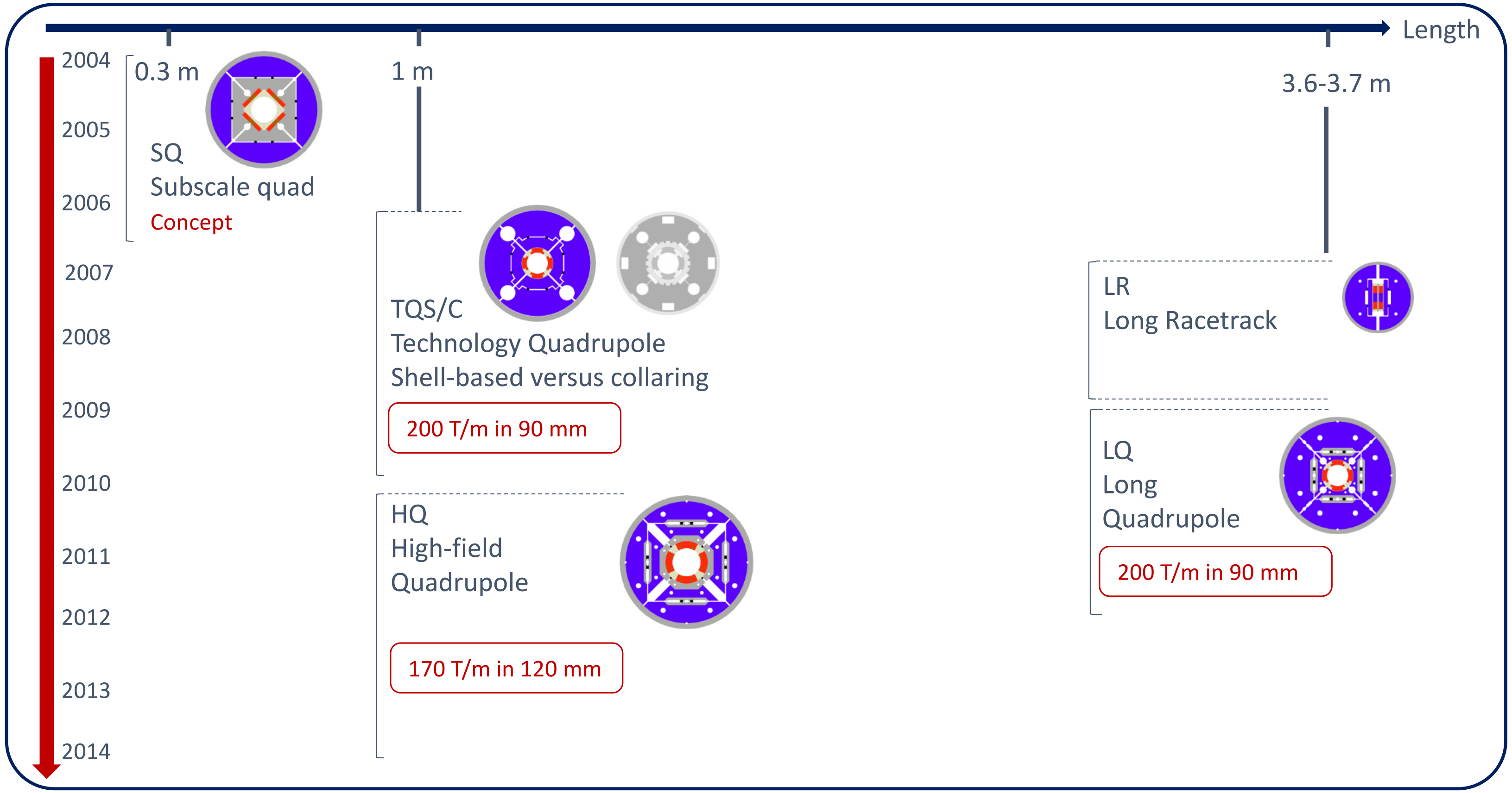


LARP Main contributions

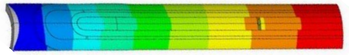
LARP

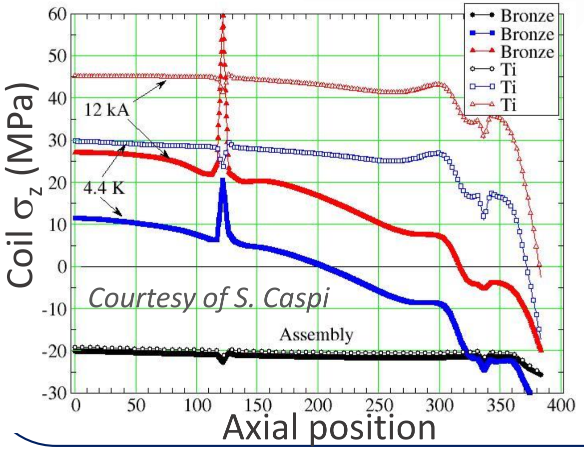
Develop reliable coil technology

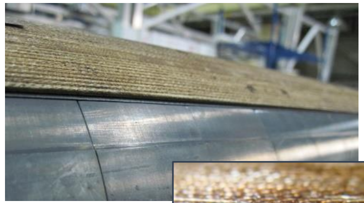
Minimization of the strain

- after coil HT
- due to axial tension after cooldown and energization

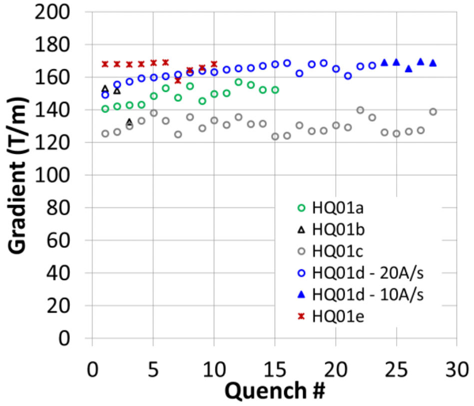
⇒ Ti pole in Nb_3Sn coils to limit stress concentration at the gaps

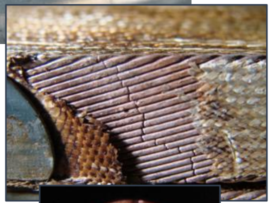


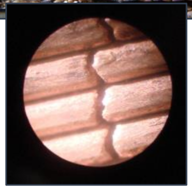




Permanent coil cross-section and length change after HT





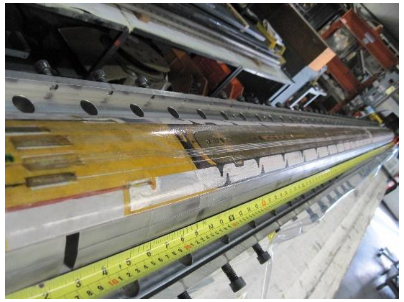


Reacted cable dimension

- in tooling design
- In components design
- ***in magnetic design***

3.7 m Long Coil technology

Courtesy of J. Schmalzle, BNL



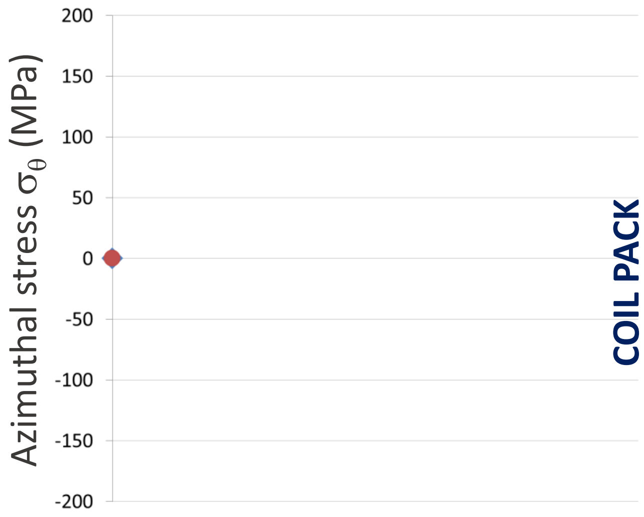
Process, Design and material choices adopted by the community

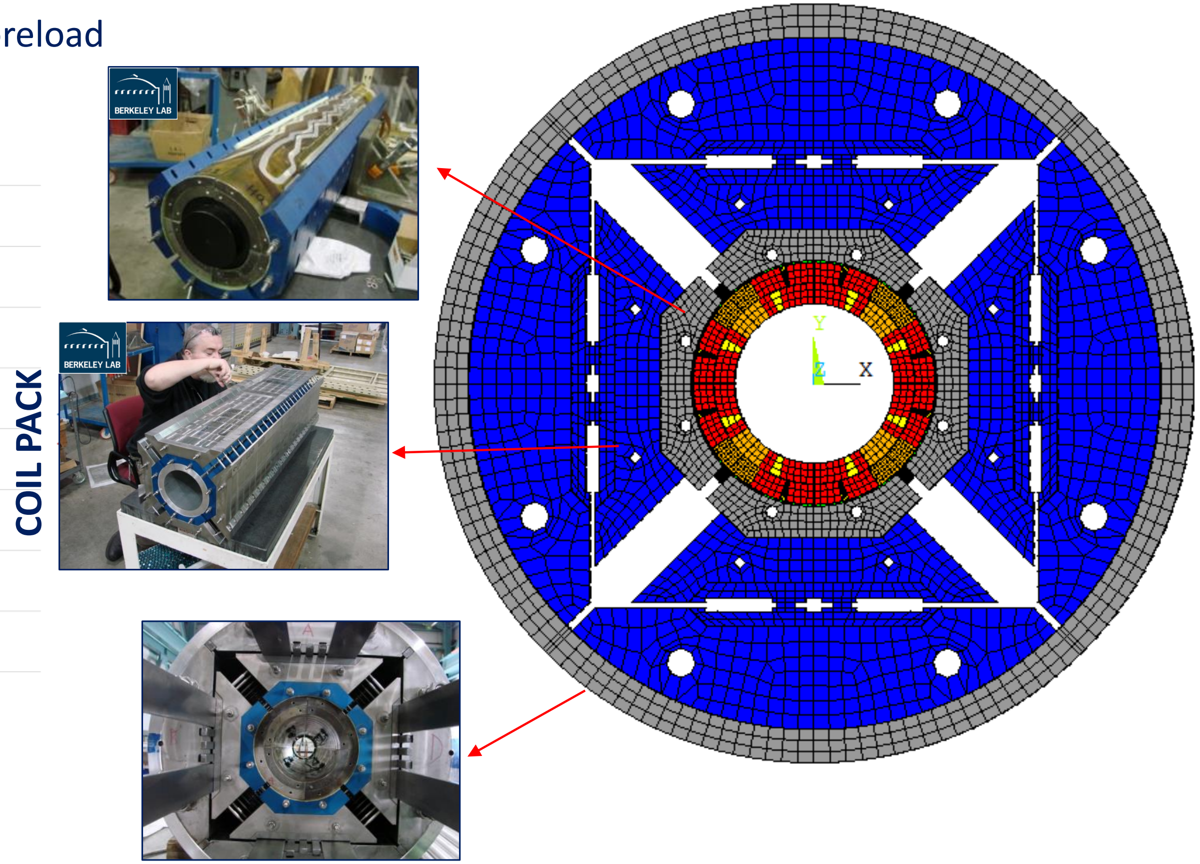
LARP Main contributions

Develop reliable assembly process
Control of coil transverse stress during all stages of magnet assembly and operation

➡ ***Maturation of an innovative support structure: Shell based a.k.a Bladder&Key support structure***

1) Progressive and reversible application of the preload





LARP Main contributions

LARP

Develop reliable assembly process
Control of coil transverse stress during all stages of magnet assembly and operation

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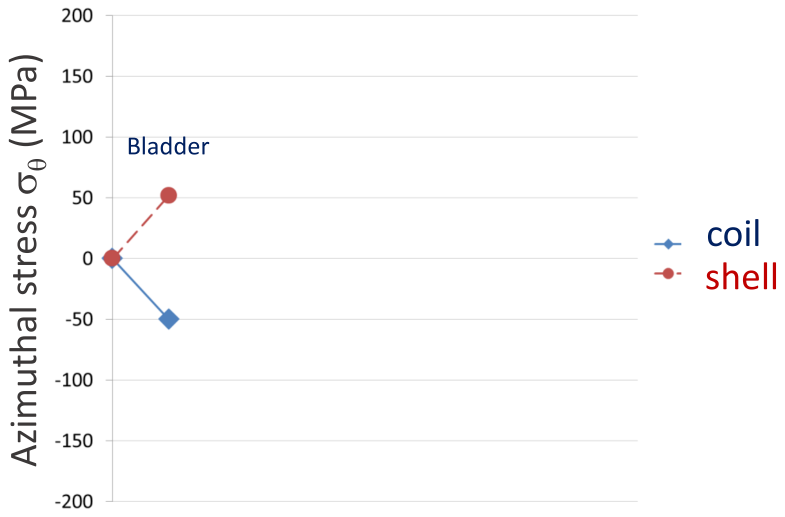
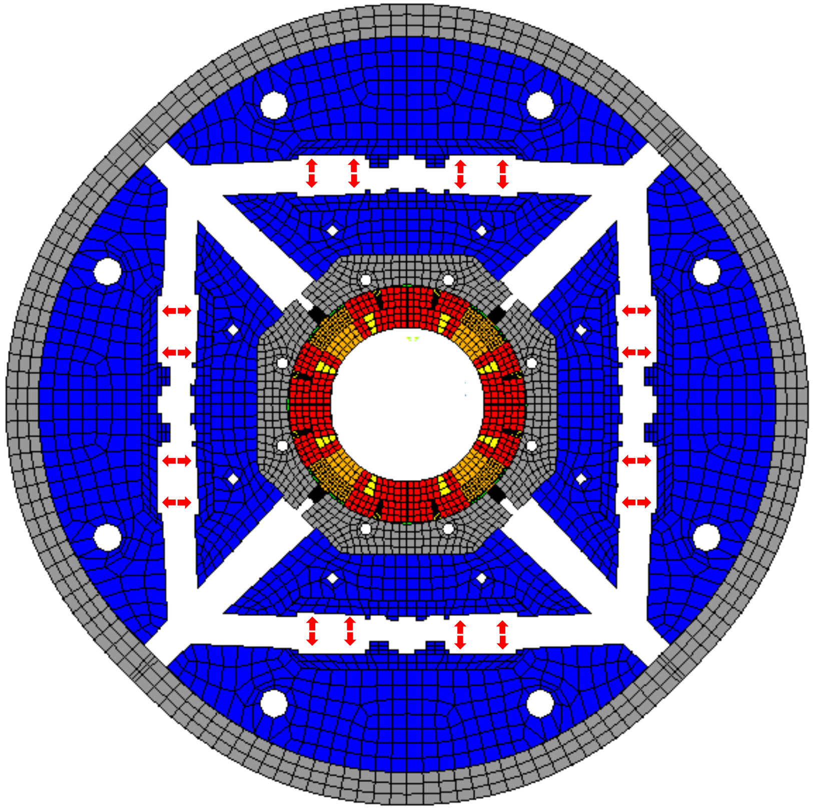




Inflated bladders

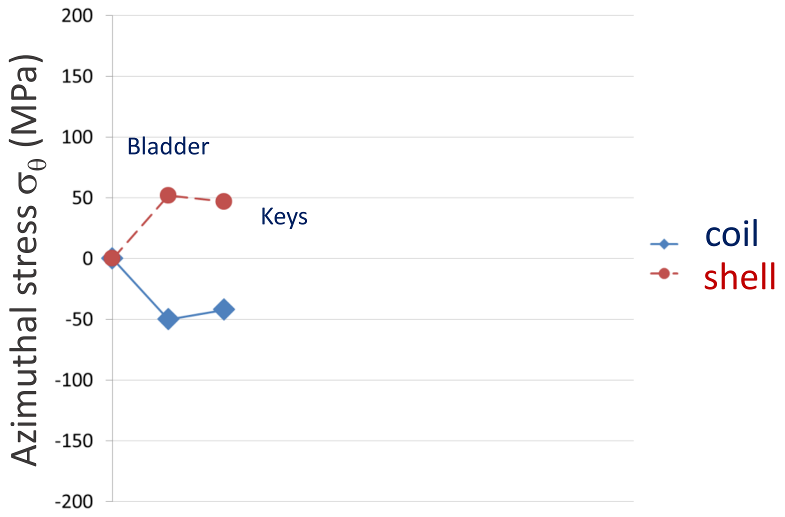
LARP Main contributions

LARP

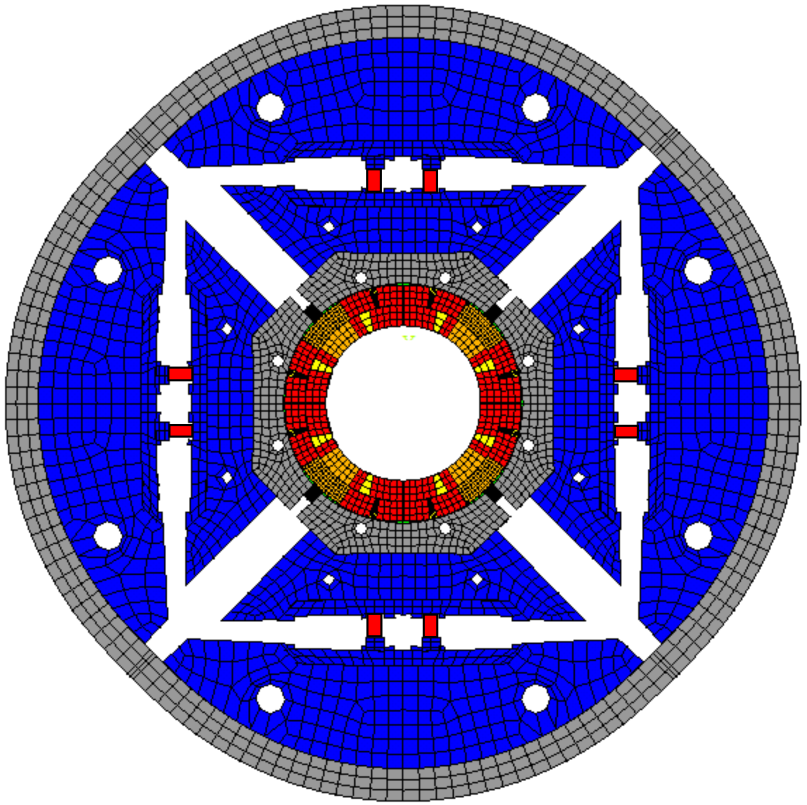
Develop reliable assembly process
Control of coil transverse stress during all stages of magnet assembly and operation

➡ ***Maturation of an innovative support structure: Shell based a.k.a Bladder&Key support structure***

1) Progressive and reversible application of the preload



Gradual application of the preload



shimming

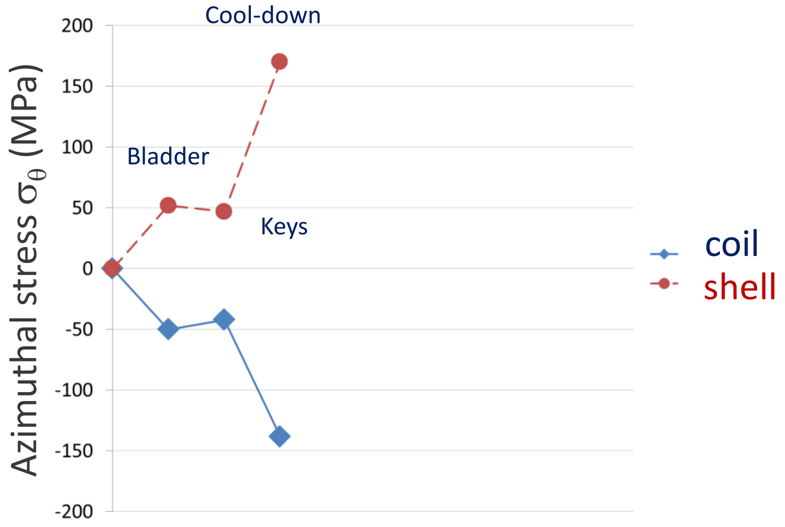
LARP Main contributions

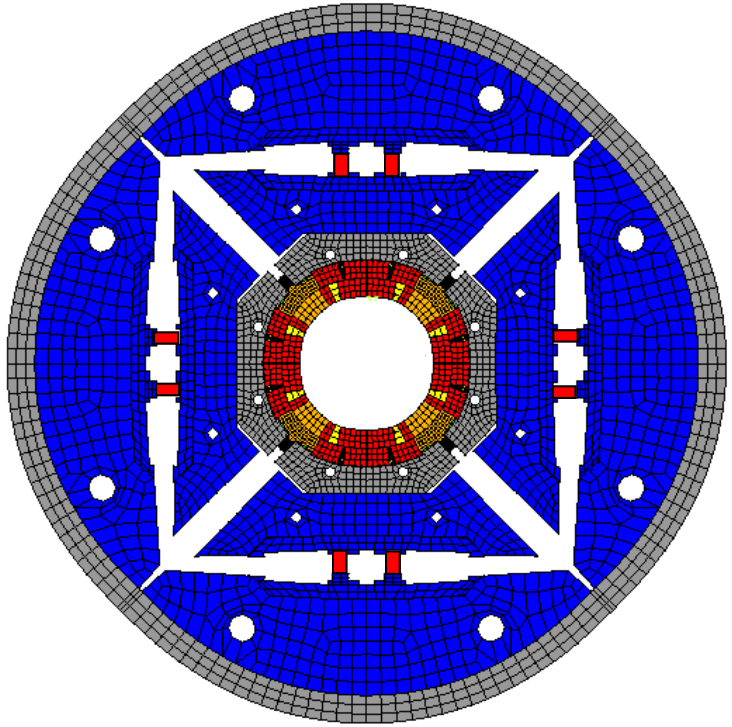
LARP

Develop reliable assembly process
Control of coil transverse stress during all stages of magnet assembly and operation

➡ ***Maturation of an innovative support structure: Shell based a.k.a Bladder&Key support structure***

1) Progressive and reversible application of the preload





Cool-down

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

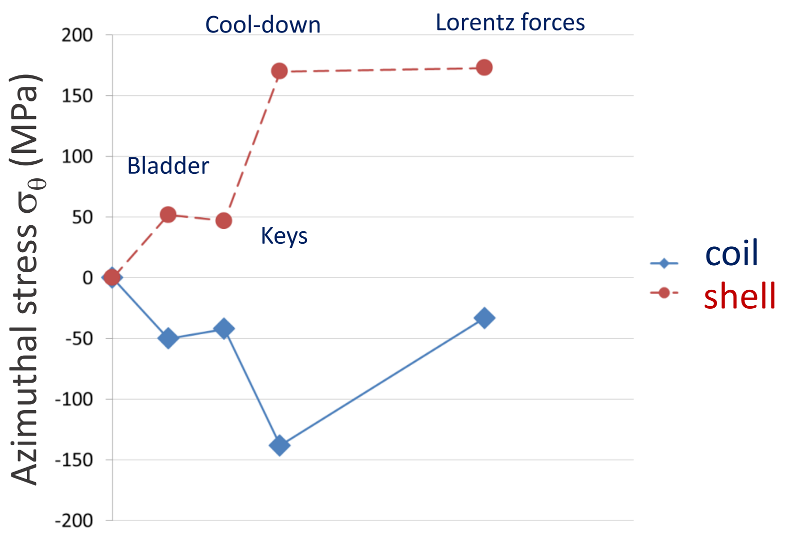
LARP Main contributions

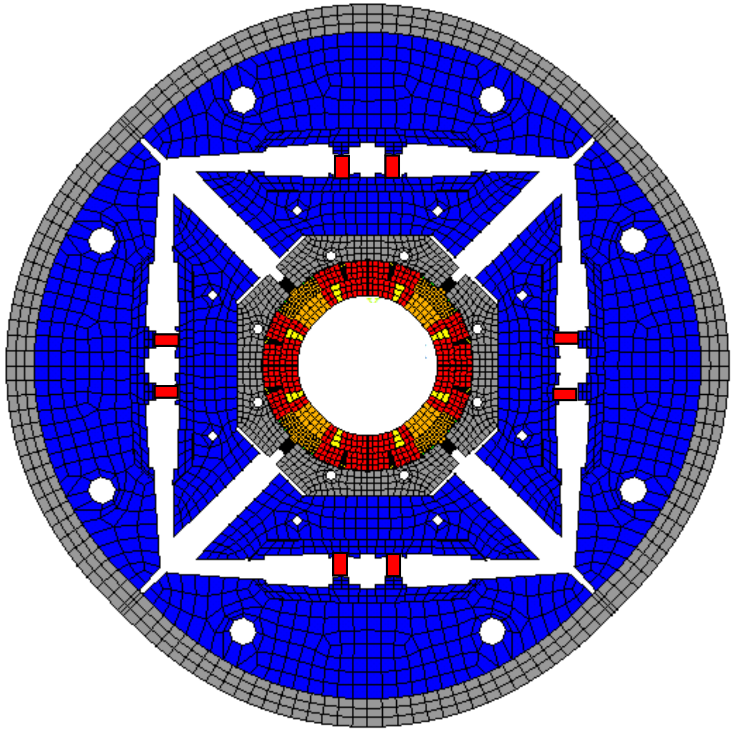
LARP

Develop reliable assembly process
Control of coil transverse stress during all stages of magnet assembly and operation

➡ ***Maturation of an innovative support structure: Shell based a.k.a Bladder&Key support structure***

1) Progressive and reversible application of the preload





Energization

LARP Main contributions

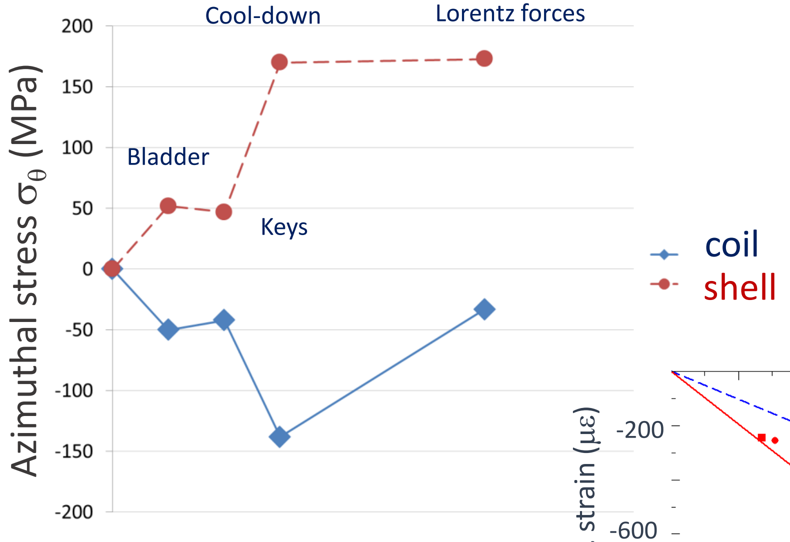
LARP

Develop reliable assembly process
Control of coil transverse stress during all stages of magnet assembly and operation

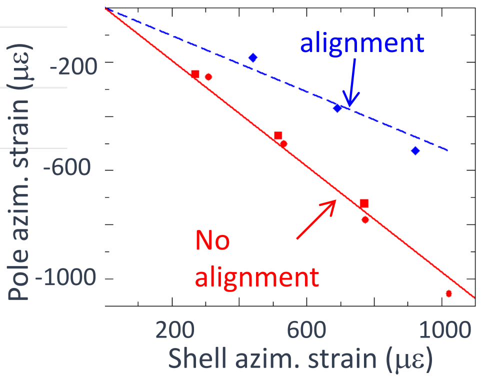
➡ ***Maturation of an innovative support structure: Shell based a.k.a Bladder&Key support structure***

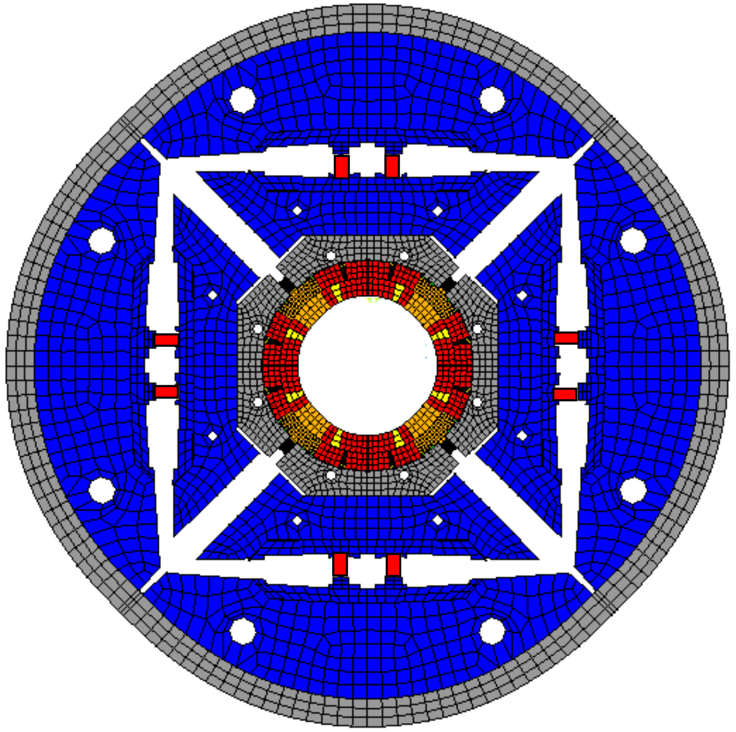
1) Progressive and reversible application of the preload

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



Definition of a preload transfer function

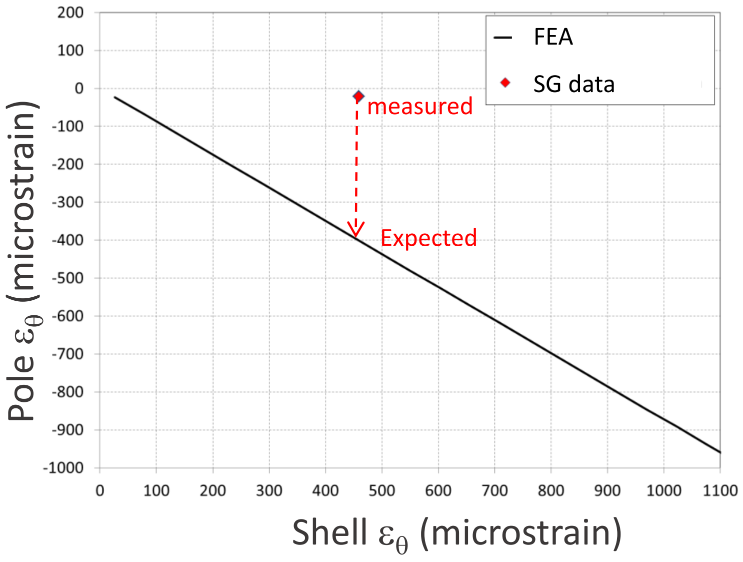




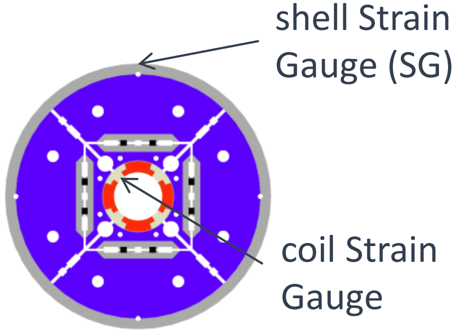
LARP Main contributions

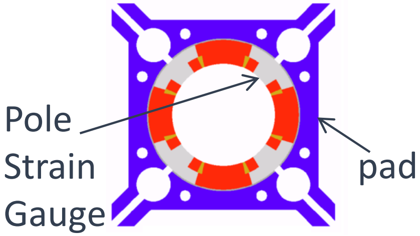
LARP

Developping assembly process for reliable magnet performance



Discrepancy model/SG data





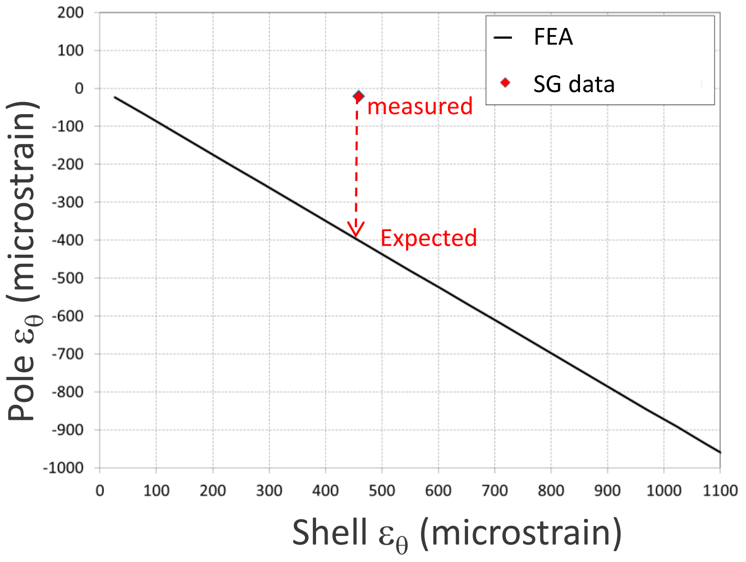
Nominal

Courtesy of P. Ferracin

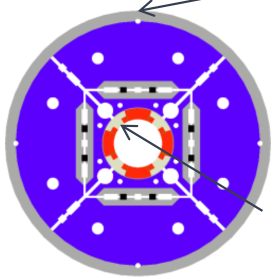
LARP Main contributions

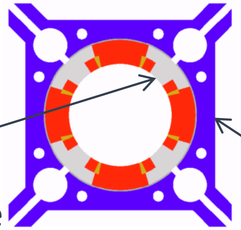
LARP

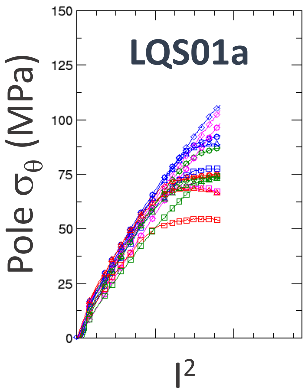
Developping assembly process for reliable magnet performance

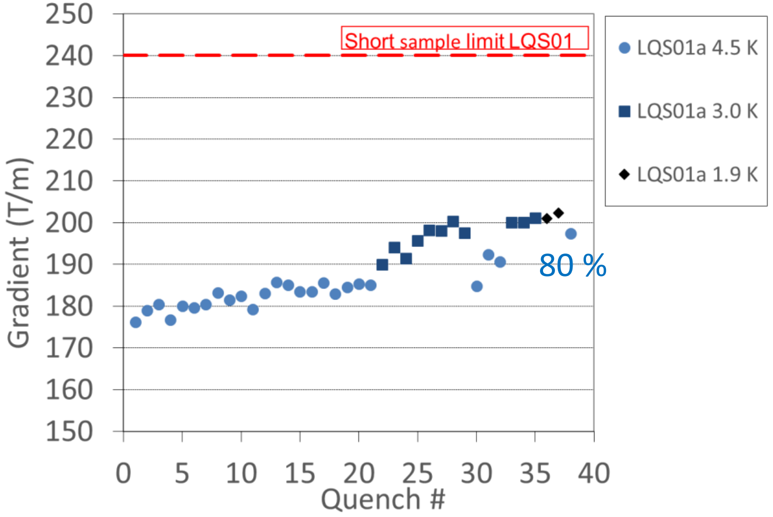


Discrepancy model/SG data







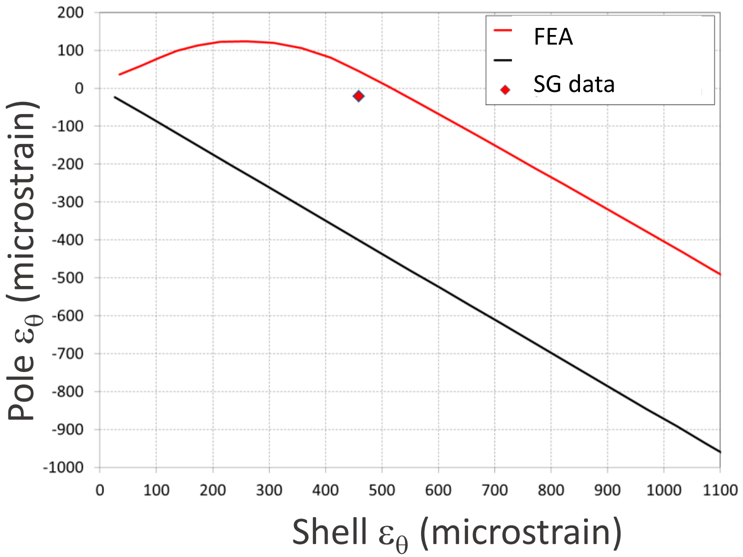


Courtesy of P. Ferracin

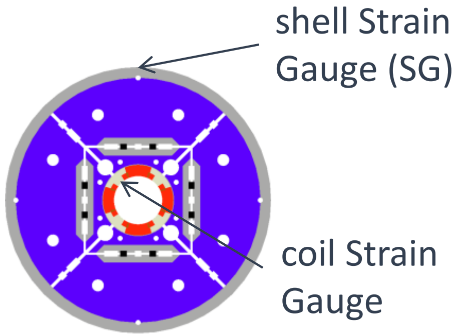
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation Tue-Mo-PL2-01 given at MT26, 22 – 27 September 2019, Vancouver, Canada.

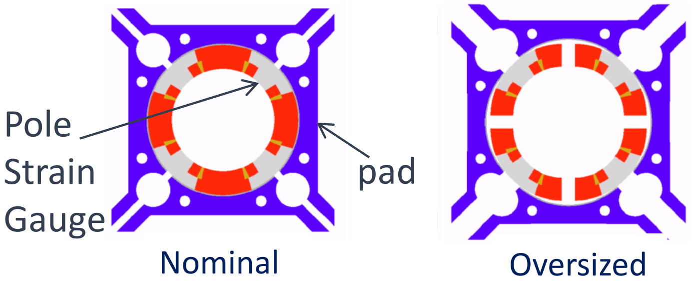
LARP Main contributions

LARP



Developping assembly process for reliable magnet performance





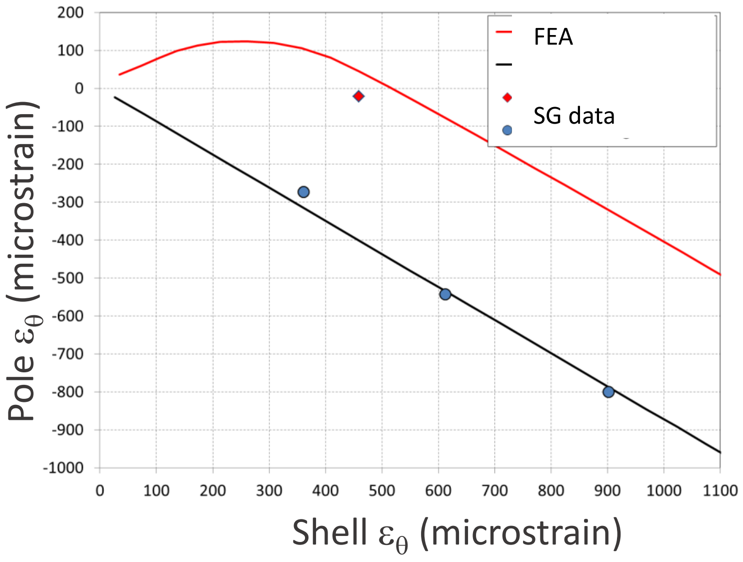
Oversized coils
Change of prestress distribution

Courtesy of P. Ferracin

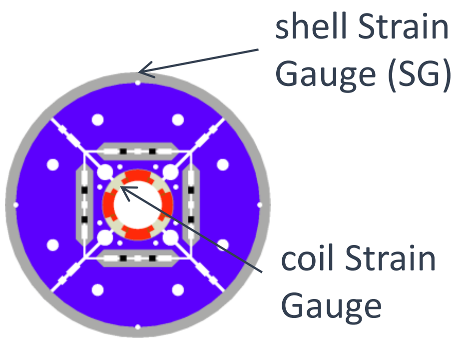
LARP Main contributions

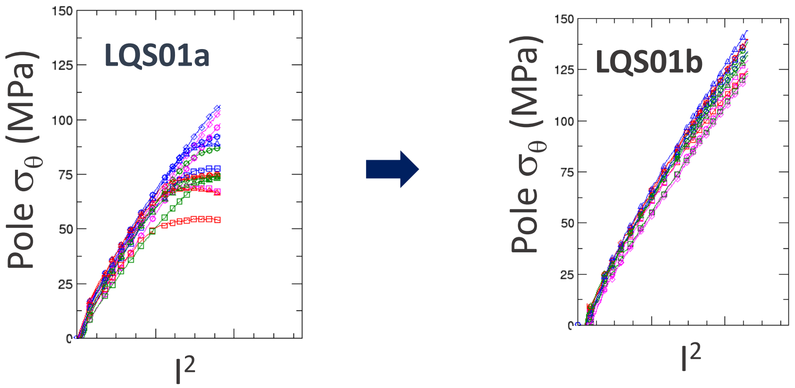
LARP

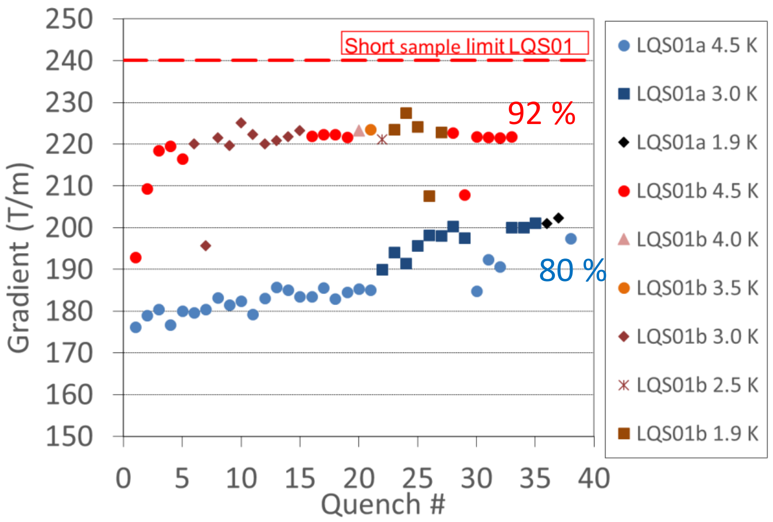
Developping assembly process for reliable magnet performance



- Agreement modeling/strain gauges
- Strain gauges as a strong assembly tool



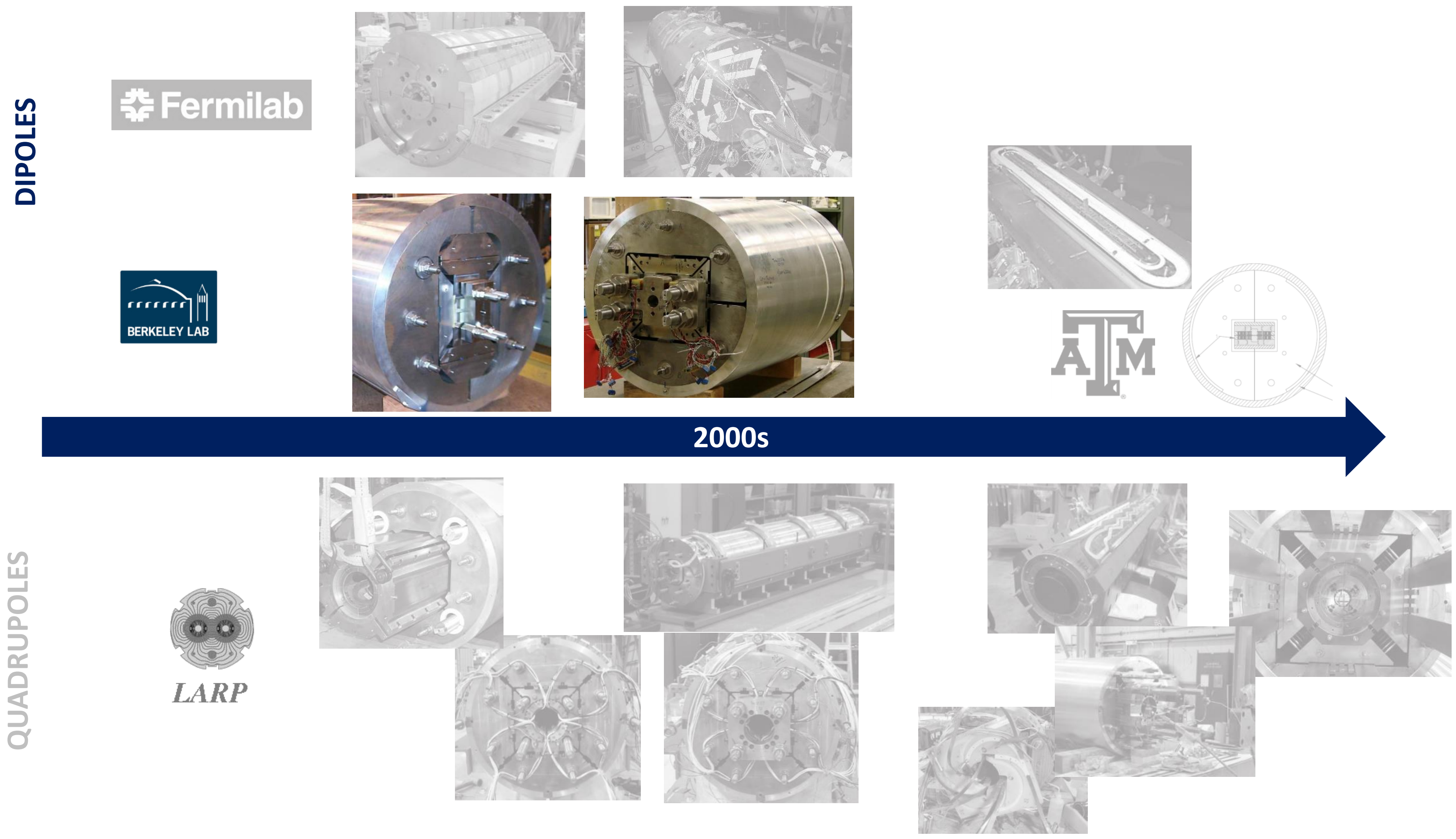




Preload, Strain gauges, modeling and performance correlation

Courtesy of P. Ferracin

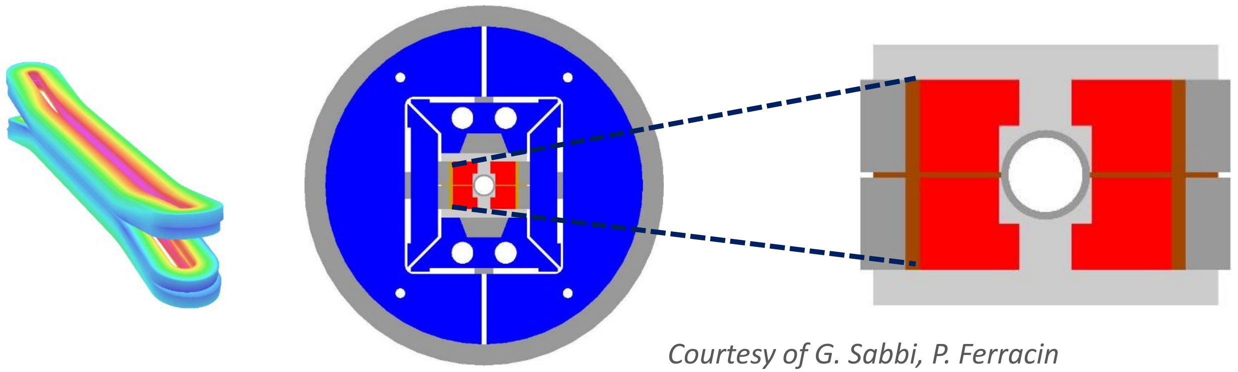
2000s: progress on dipoles and quadrupoles

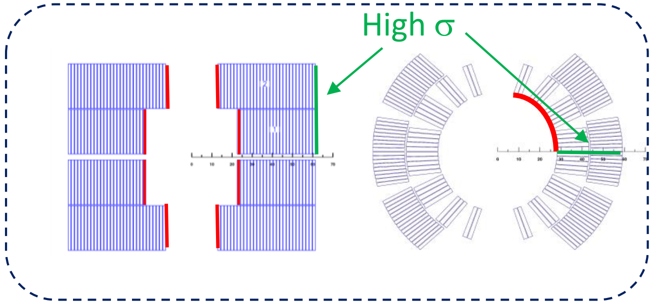


IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation Tue-Mo-PL2-01 given at MT26, 22 – 27 September 2019, Vancouver, Canada.

Block configuration: an option for high field dipoles

Following the quest toward simplicity : Dipoles for future colliders (energy frontier)
=> **Block configuration**





Courtesy of G. Sabbi, P. Ferracin

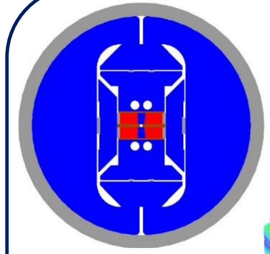
Pros
- Flat cable
- Coil width controlled by number of turns => high field
- Low number of coil components
- No end spacer (3D)
- High field versus high stress location

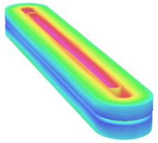
Challenges
- Inner support required
  - Smaller clear bore
  - Coil Assembly can be delicate
- Flared ends to clear the beam

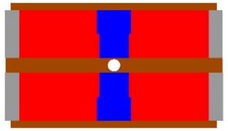
Block type magnets

2000s — 2010s — 2020s

HD1





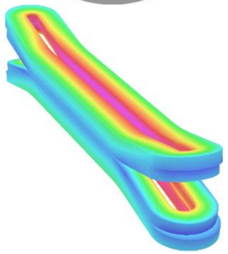


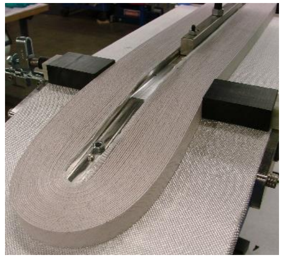
- 8 mm aperture
- Racetrack, 1-m
- 155-185 MPa

16 T bore field @ 4.3 K in 2003

HD2-3

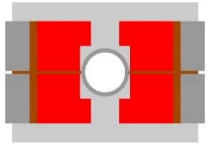
BERKELEY LAB

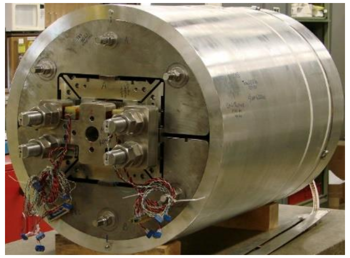


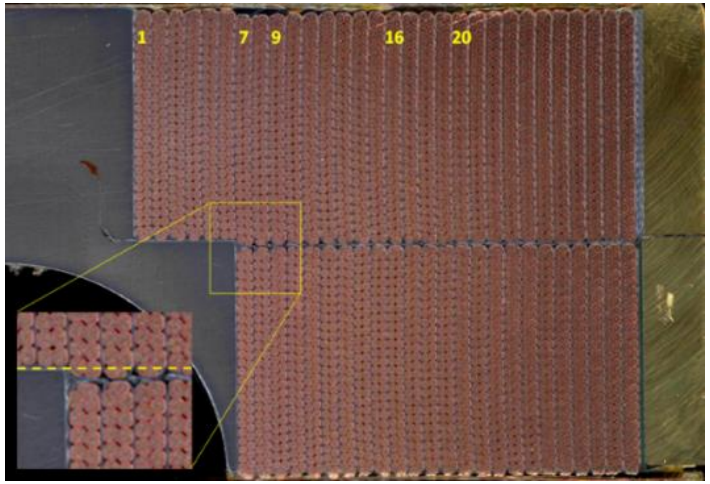


- 36 to 43 mm aperture
- Flare ends
- 1m-long
- 140-180 MPa

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







Courtesy of G. Sabbi, LBNL

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
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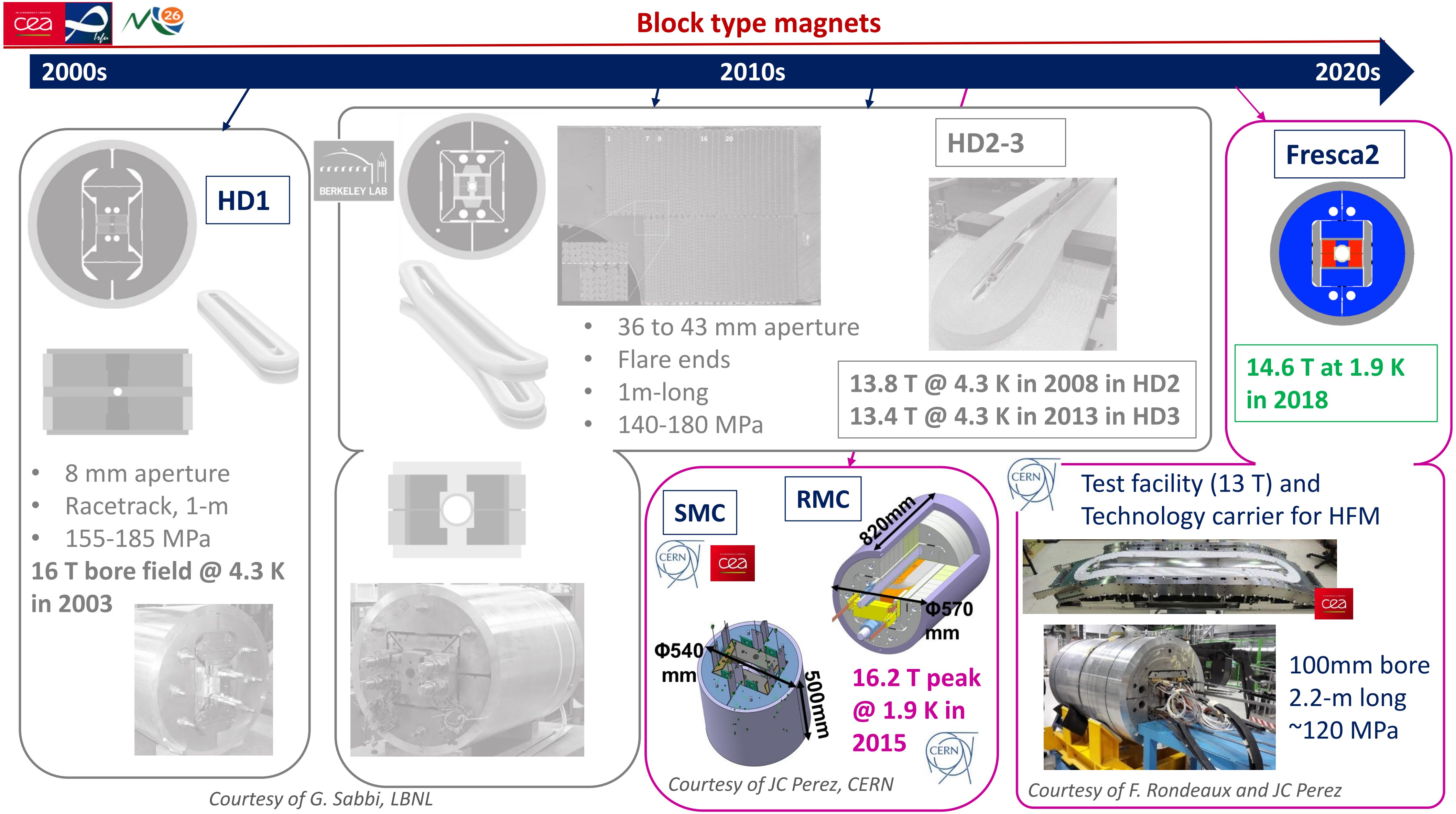


On the way to HiLumi

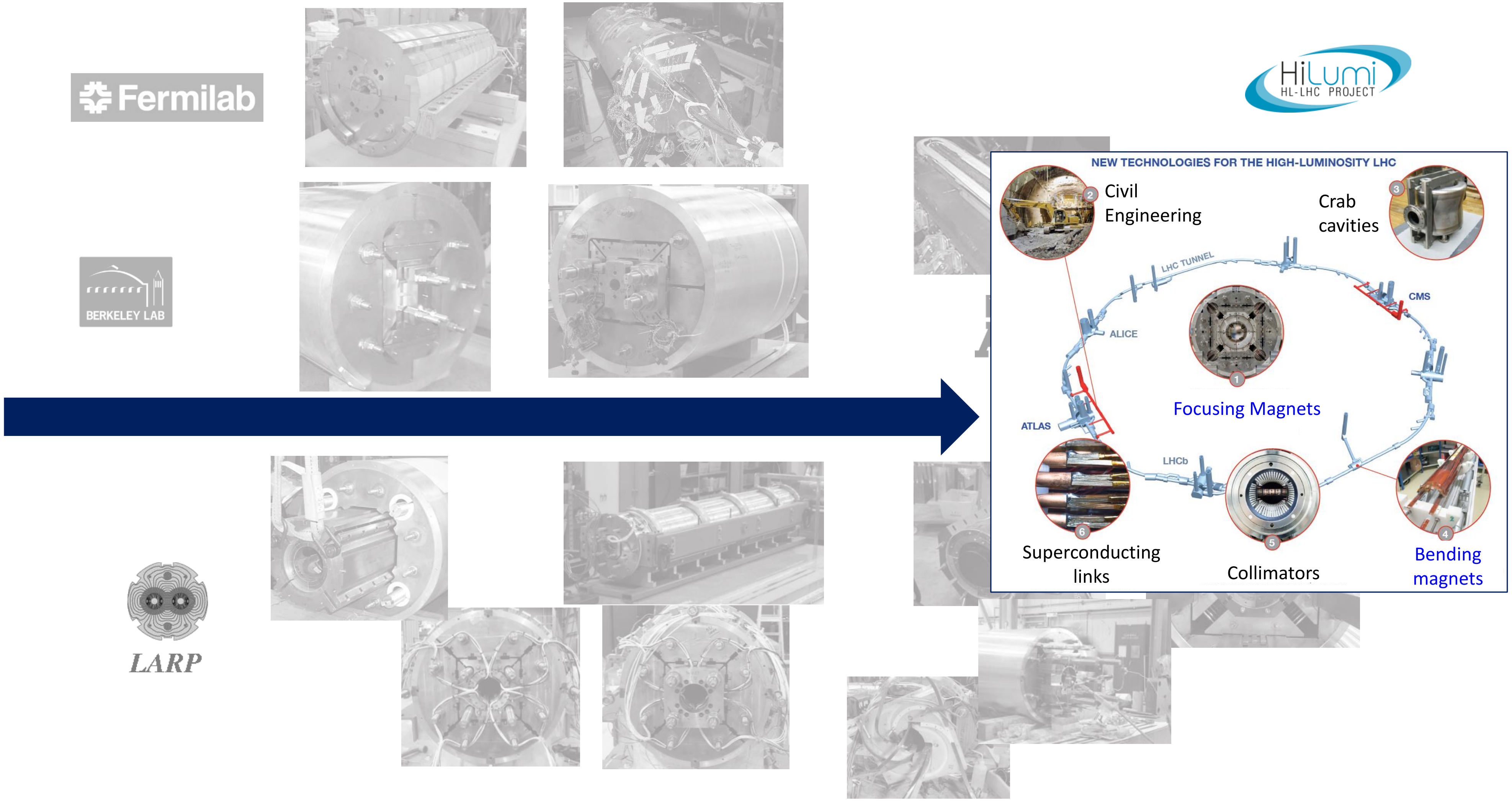
DIPOLES

Fermilab

BERKELEY LAB

QUADRUPOLES

LARP



Nb_3Sn in HL-LHC: MQXF an outcome of LARP

LARP

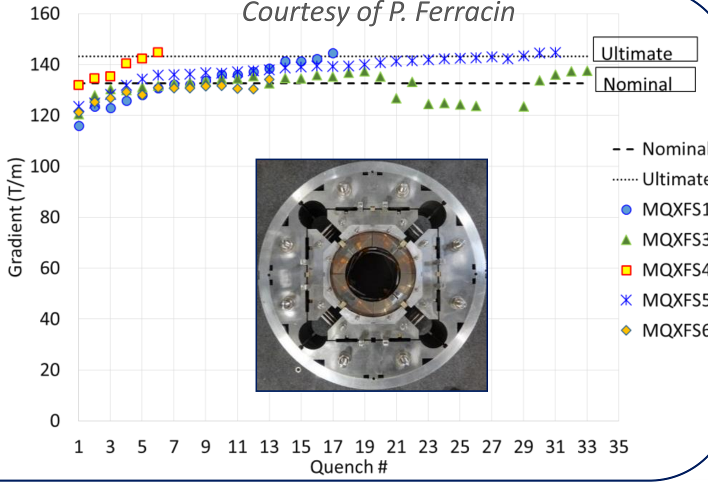
CERN

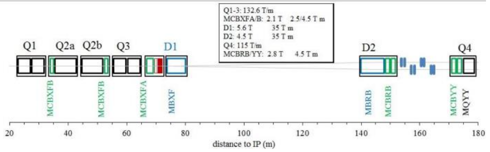
HiLumi HL-LHC PROJECT

Short Model program

Courtesy of D. Cheng, LBNL

- RRP and PIT (CERN) coils
- Exploration of preload parameter space





150 mm aperture

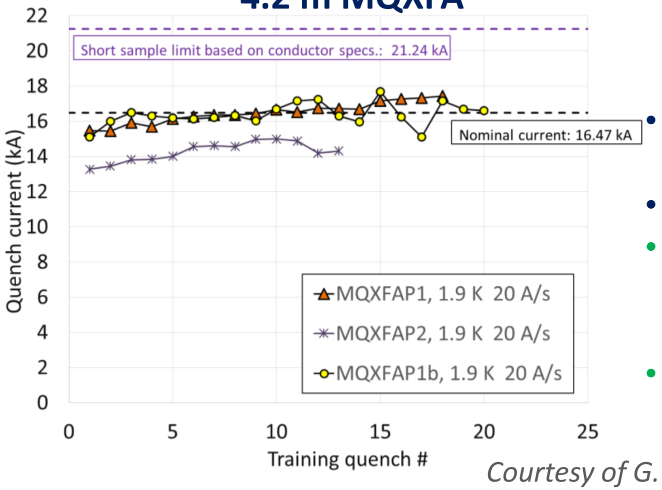
G_{op} 132 T/m @1.9K

B_{peak} 11.4 T

77 % on the LL

US HL-LHC AUP

4.2 m MQXFA



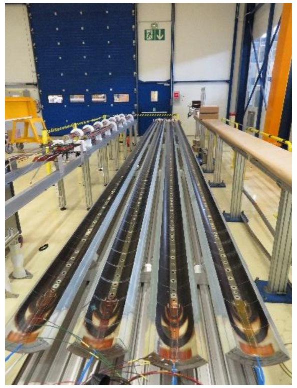
Prototypes

- 2 MQXFA prototypes tested
- Pre-series on its way
- MQXFA3 to be tested in October 2019
- MQXFBP1 to be tested early 2020

7.15 m MQXFB

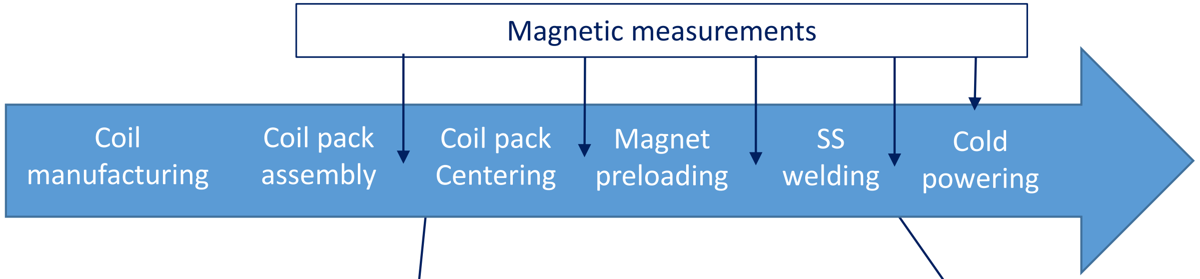
CERN

HiLumi HL-LHC PROJECT

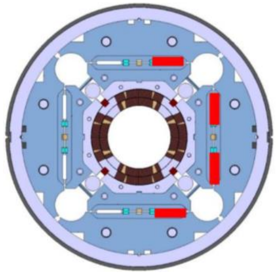


Courtesy of G. Ambrosio, FNAL and P. Ferracin, CERN

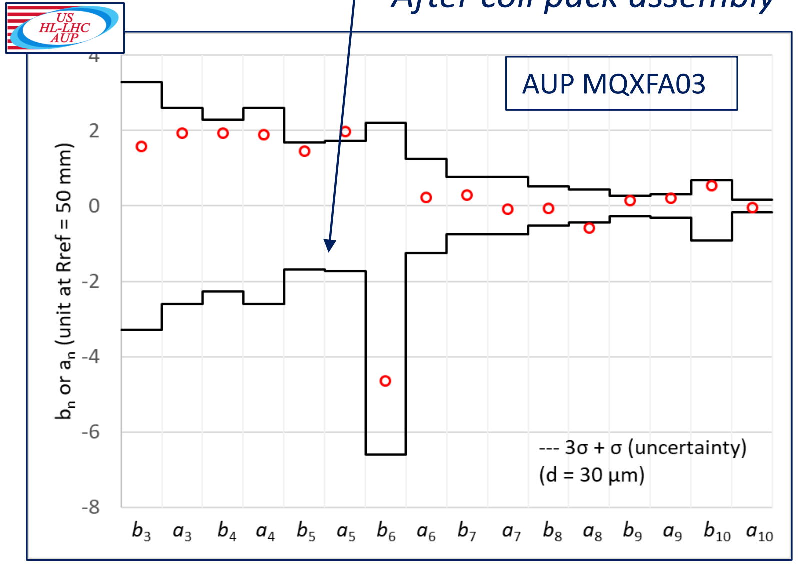
MQXF : a word on field quality



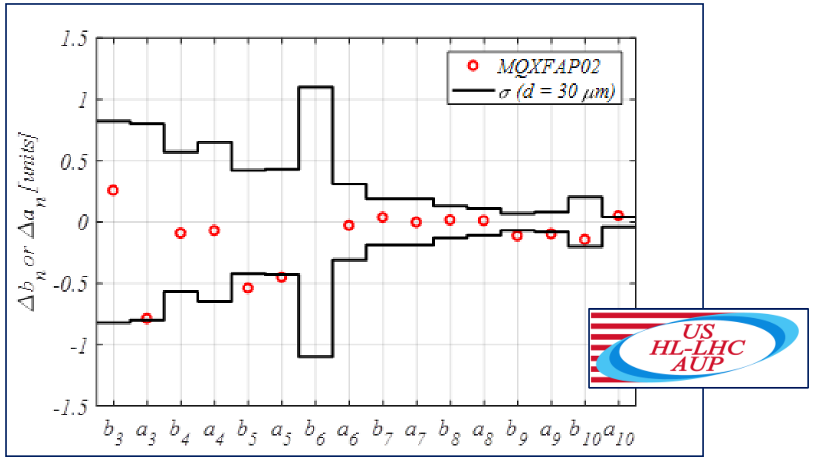
- Systematic b_6 => cross-section tweaking
- Good correlation warm/cold allowing for partial correction of non allowed harmonics by magnetic shims



After coil pack assembly



Change of harmonics due to cold powering

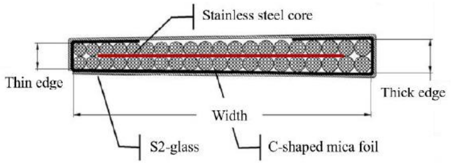


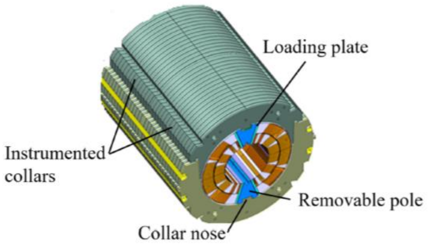
Ready for HL-LHC

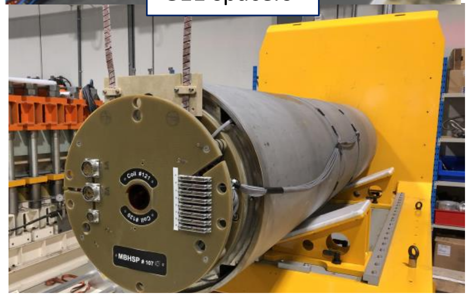
Courtesy of S. Izquierdo Bermudez (CERN), X. Wang (LBNL) and H. Song (BNL)

Nb_3Sn Dipole in HL-LHC: 11 T dipole

Double aperture magnets (5.5 m)
Short model program (Single and 2-in-1 model)



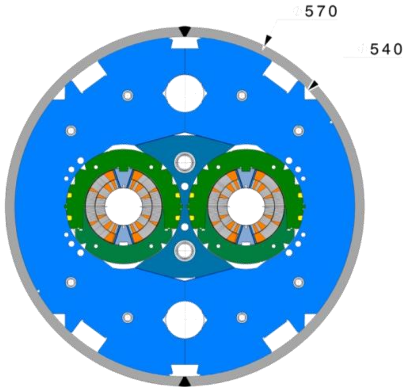


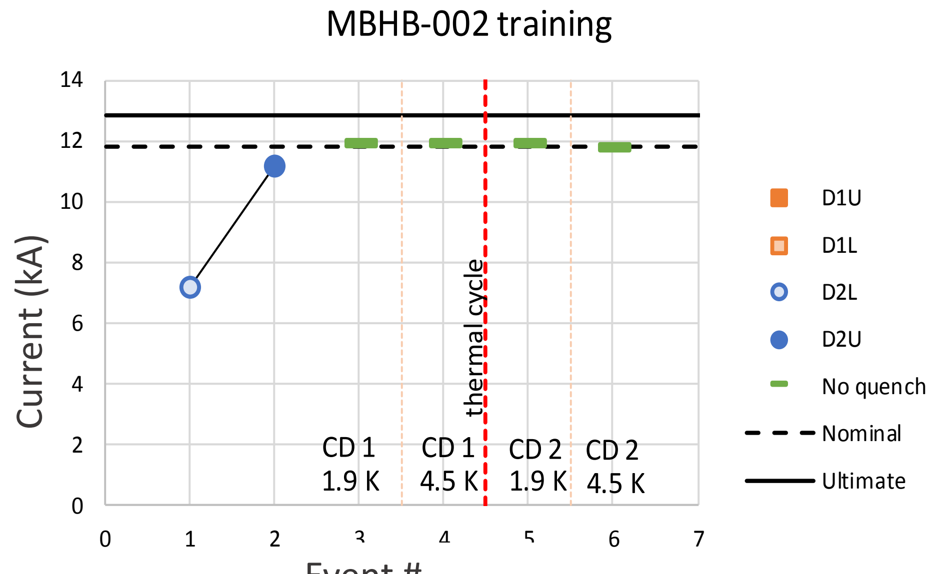


Courtesy of S. Izquierdo Bermudez

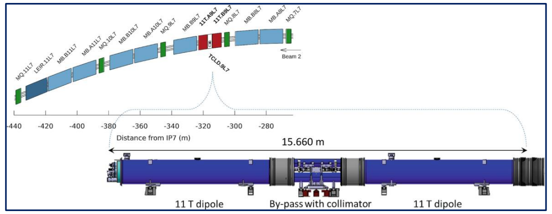
Optimisation of the insulation scheme
Optimisation of the collaring process through:

- Mock ups
- Instrumentation
- Pressure sensitive films



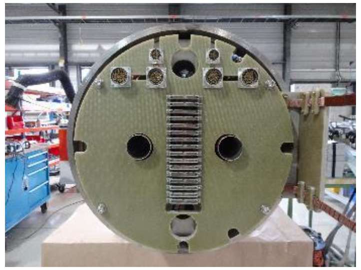


Courtesy of A. Devred



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

Courtesy of F. Savary



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

All four dipoles should be ready in April 2020

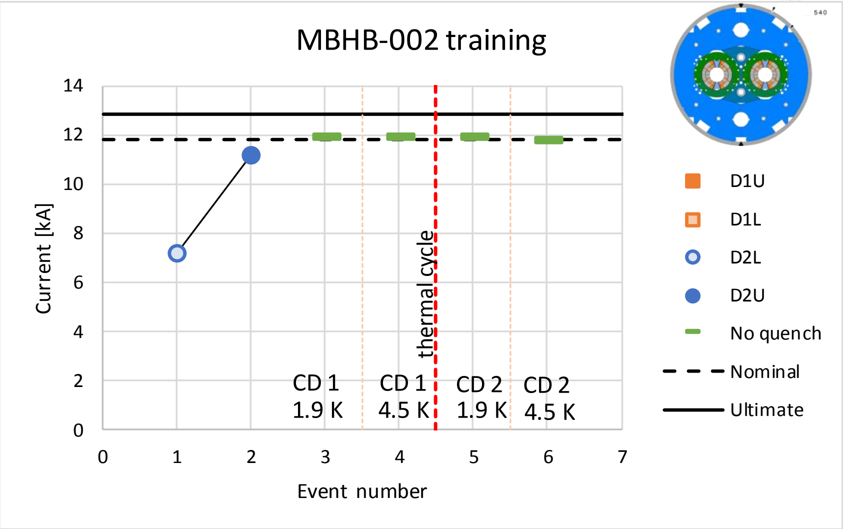
Looking closely at performance

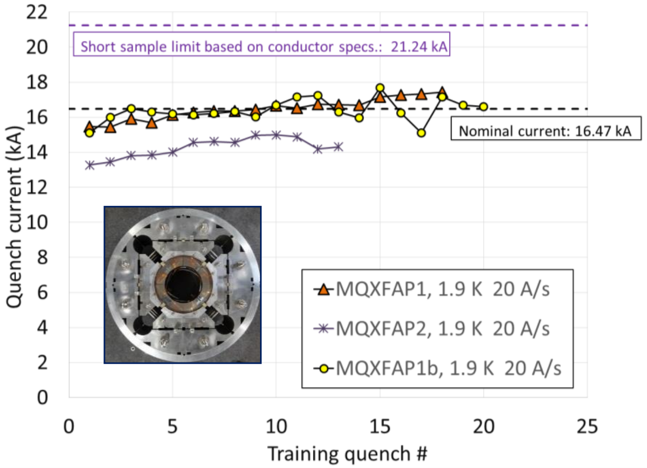
Successful 11⁺ T Nb_3Sn **long** dipoles and quadrupoles

⇒ **User point of view**: operating field and gradient

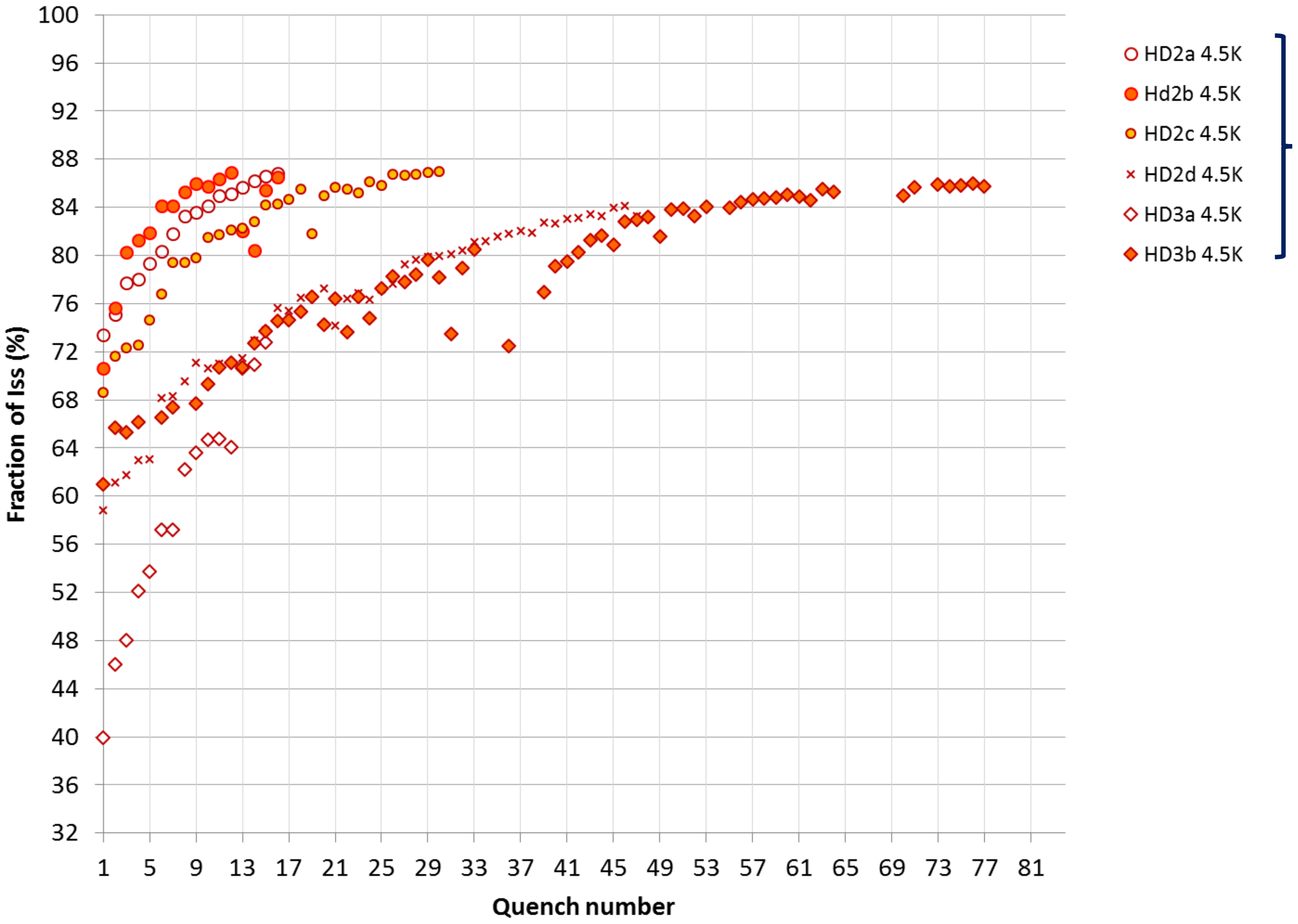
⇒ **Magnet engineer stand point**: how close are we from the critical surface/ maximum performance?

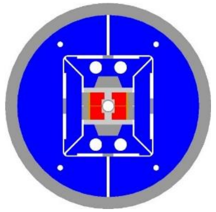
Short models are a great tool!





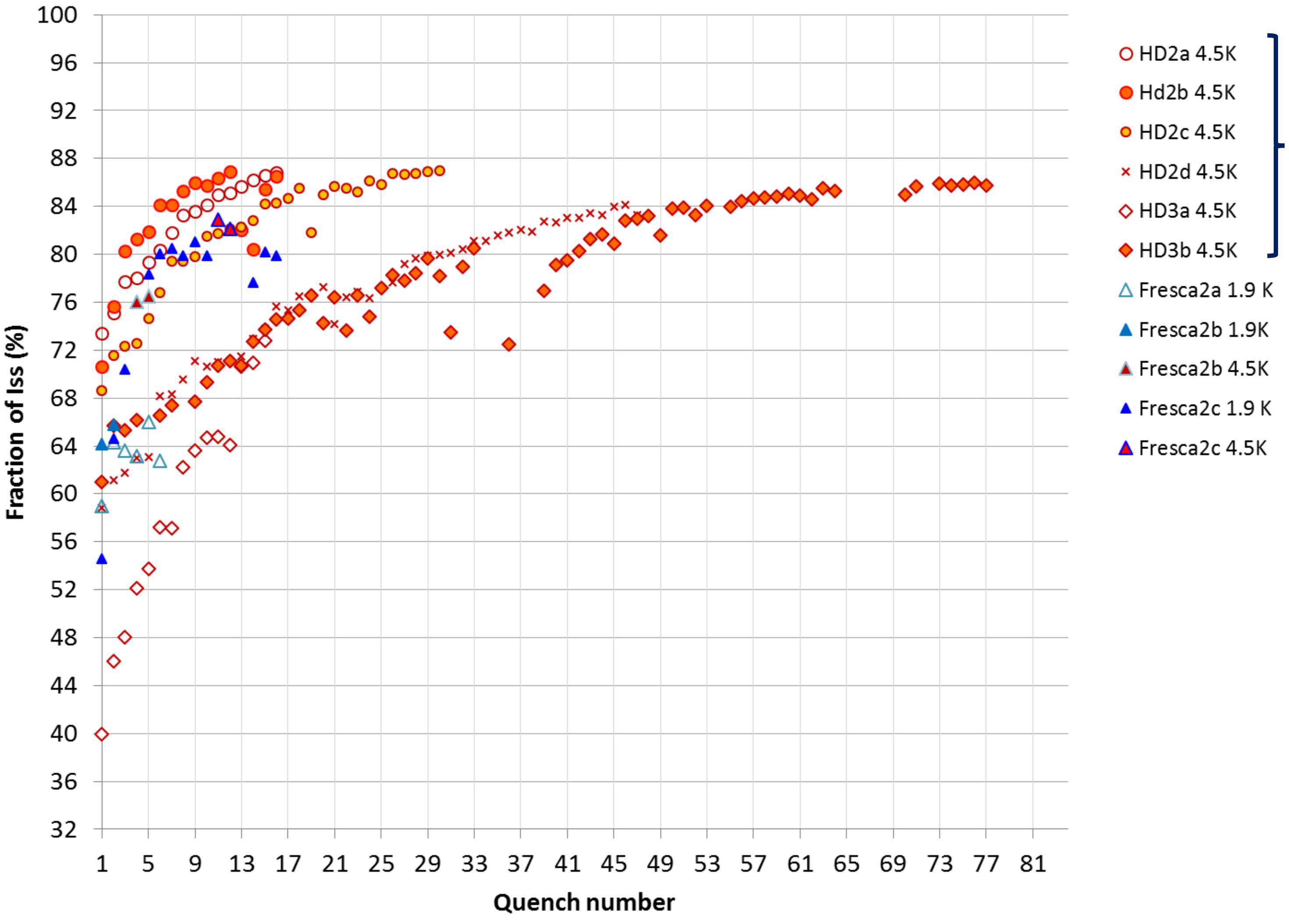
Dipoles with bore: training performance summary

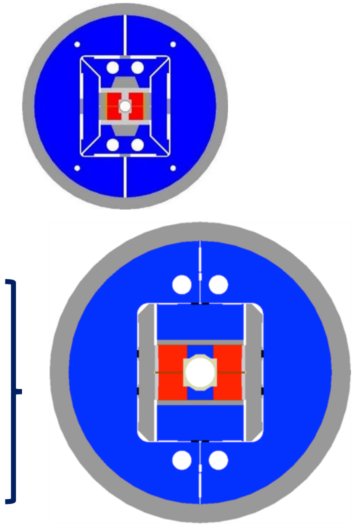




Data are courtesy of LBNL and CERN

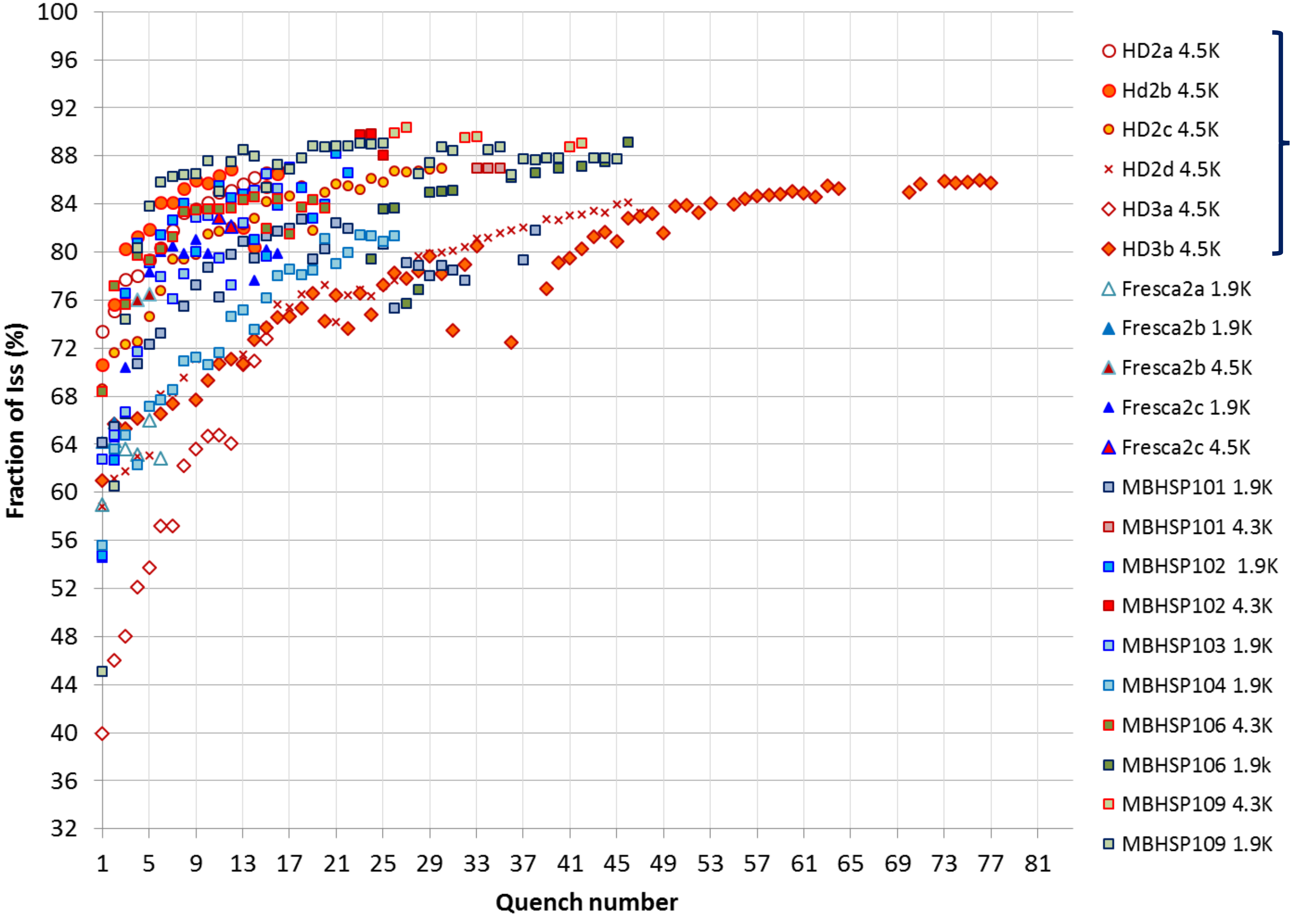
Dipoles with bore: training performance summary

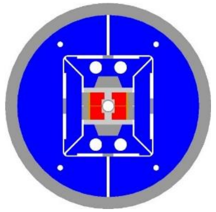


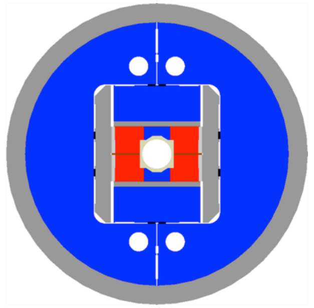


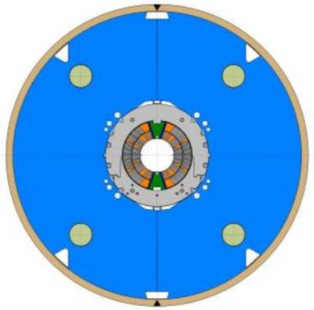
Data are courtesy of LBNL and CERN

Dipoles with bore: training performance summary



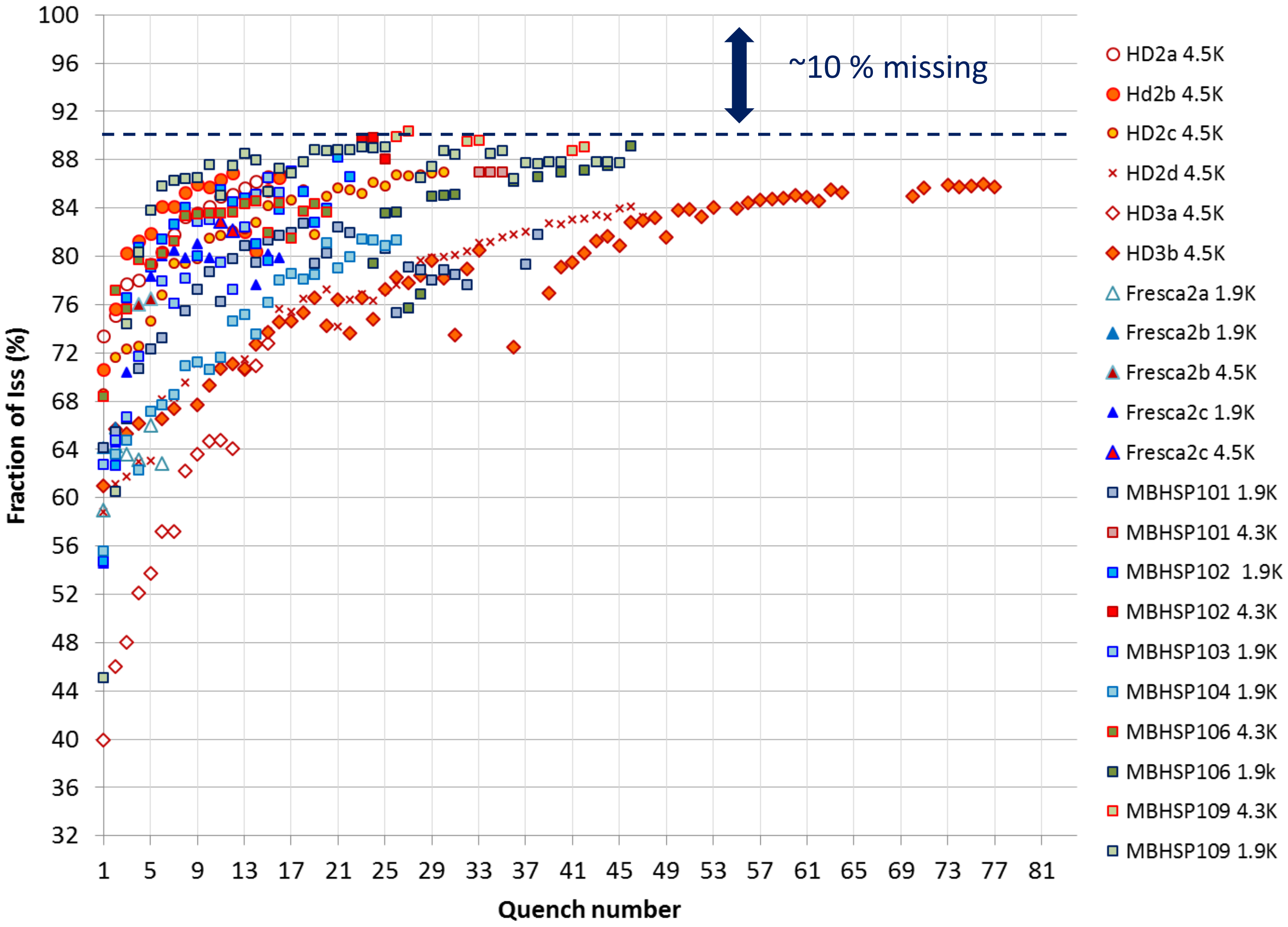






Data are courtesy of LBNL and CERN

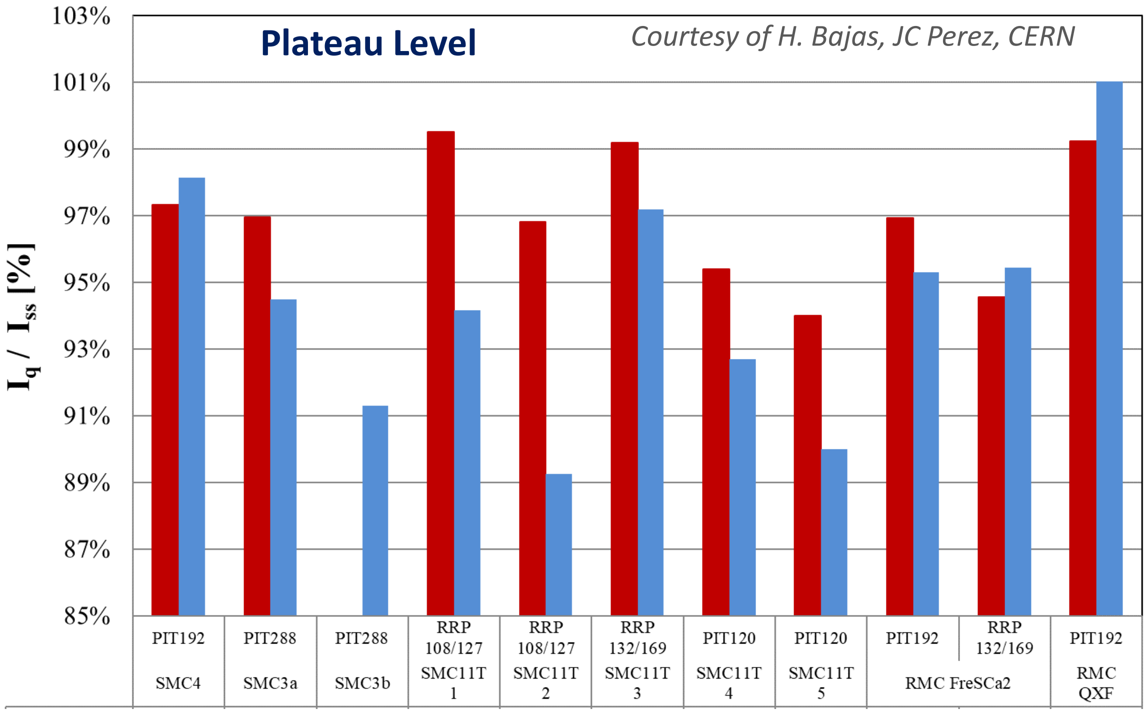
Dipoles with bore: training performance summary



- Magnet typically designed for 20 % margin
- Magnet with an effective margin of 10%
- Future Colliders => which margin?

Data are courtesy of LBNL and CERN

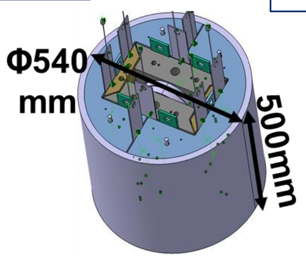
Search for the missing margin



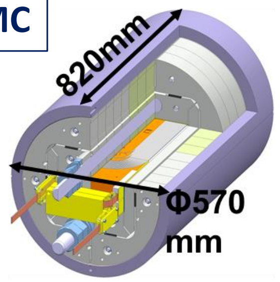
- Magnet typically designed for 20 % margin
- Magnet with an effective margin of 10%
- Future Colliders => which margin?
- Magnet without bore reach higher plateaus

=> The conductor should be able to get there

SMC



RMC



Performance limitation and Long training

- Conductor degradation
- Disturbance spectrum?

- Quantification of Nb_3Sn degradation during magnet life cycle
- Innovative magnet configuration
- Innovative diagnostics

Programs and collaborations aiming at tackling these topics

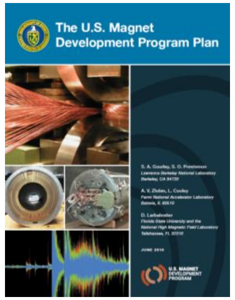
U.S. MAGNET DEVELOPMENT PROGRAM *ASC/NHMFL, BNL, FNAL, LBNL*

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

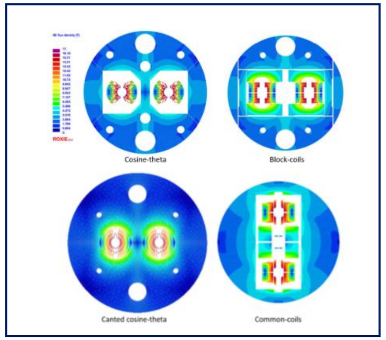
Item 2.5: Superconducting Materials -Conductor Procurement and R&D (CPRD)



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



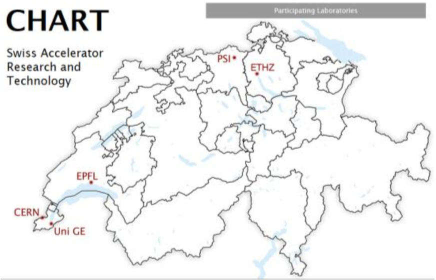
Series of Worskhops on Nb_3Sn technology for accelerator magnets

- **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

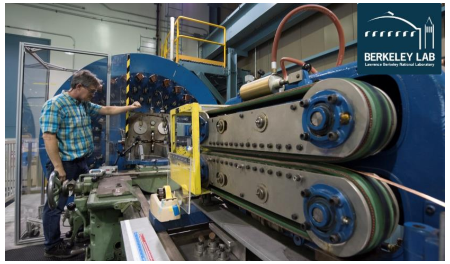
CHART
Swiss Accelerator Research and Technology



High field magnets development
Focus on innovative concept

What is the effective strain state of Nb_3Sn during its life cycle? Impact on I_c?

CABLING

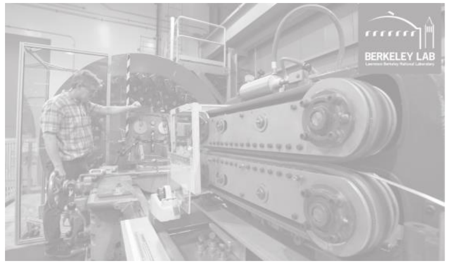


- Optimization of the cabling process
- Extracted strand I_c measurements

Post cabling I_c (includes cabling degradation)

What is the effective strain state of Nb_3Sn during its life cycle? Impact on I_c?

CABLING



- Optimization of the cabling process
- Extracted strand I_c measurements

→

COIL TECHNOLOGY

- Dimensional changes during HT
- Empirical quantification

↓

Post cabling I_c (includes cabling degradation)

↓

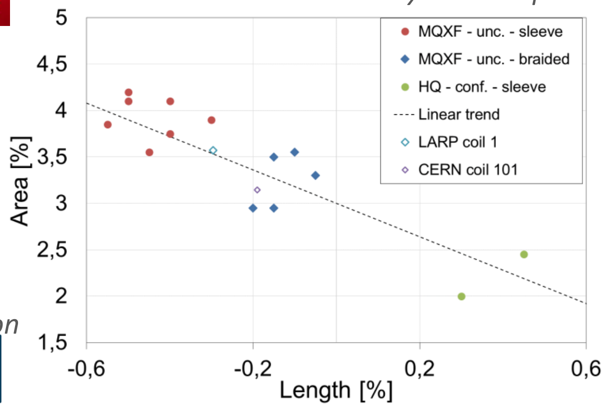
Assumption
$\varepsilon_{post\ HT} = 0$

Study of Nb_3Sn cable dimensional changes during HT

Empirical approach to assess cable dimensional changes during HT

Courtesy of M. Durante

Courtesy E. Rochepault



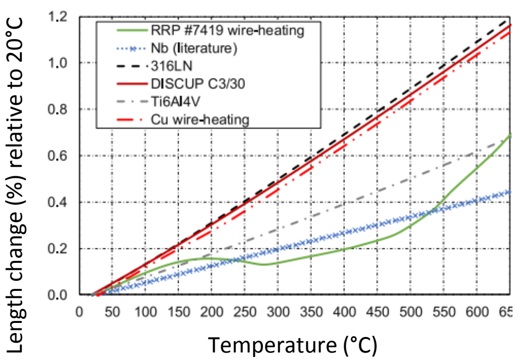
Courtesy of S. Prestemon

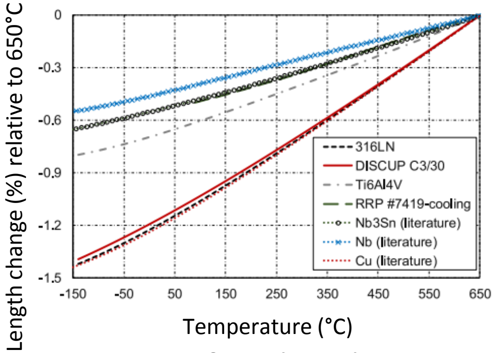
We know how to empirically minimize post-HT strain

We do not know (yet):

- how to predict dimensional changes w/o direct measurement
- the Nb_3Sn strain state at the end of the HT

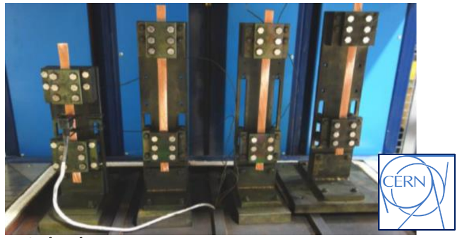
In situ measurements of thermal expansion/contraction





Courtesy of C. Scheuerlein, CERN

In situ length change tracking via extensometers



Courtesy of M. Michels

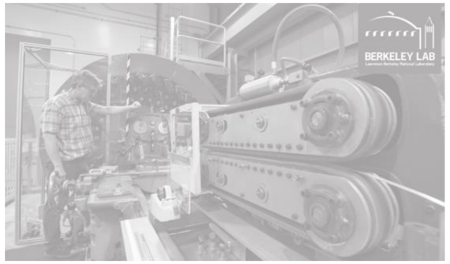
- In situ tracking of the displacement field via Digital Image correlation
- Modeling

=> Ultimate goal: predictive model

Courtesy of M. Abdel Hafiz, E. Rochepault

What is the effective strain state of Nb_3Sn during its life cycle? Impact on I_c?

CABLING



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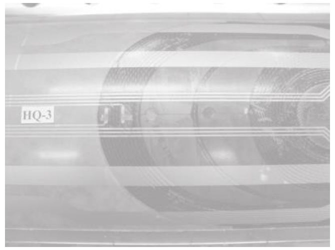
Post cabling I_c (includes cabling degradation)

COIL TECHNOLOGY



- Dimensional changes during HT
- Empirical quantification

Assumption $\varepsilon_{post\ HT} = 0$

ASSEMBLY & Cool-down

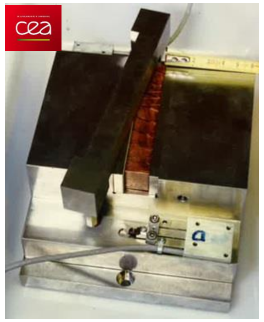
- 3D FE Models
- Mechanical instrumentation

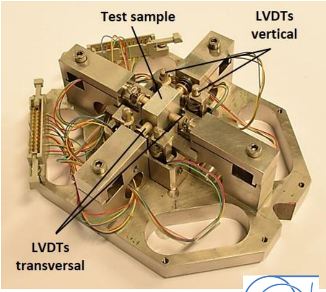
Some correlation

Precise properties of Epoxy impregnated Nb_3Sn? Implementation in FEM

Ongoing progress on mechanical behavior characterization of Epoxy impregnated Nb_3Sn

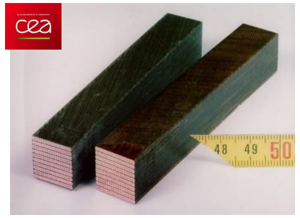
Coil ridigity used in FEA so far: Linear assumption with elastic modulus value in the stress range of interest

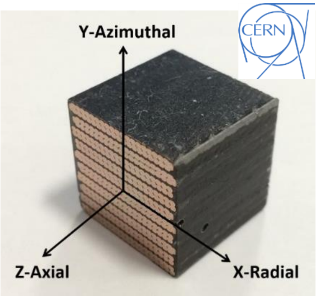


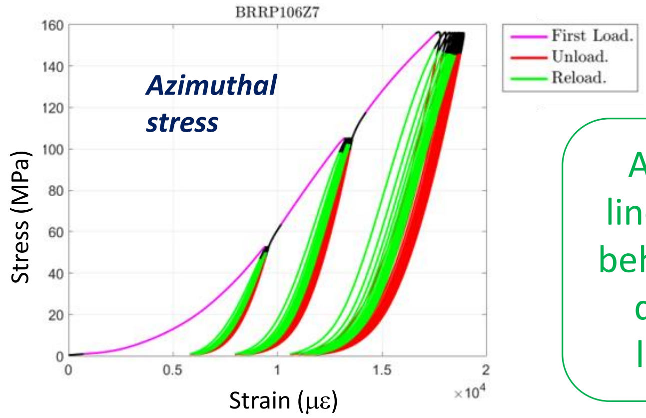


σ–ε curves along the 3 sample directions

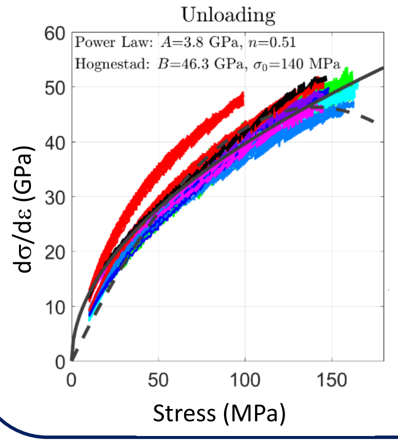
10-stack of impregnated insulated reacted cable

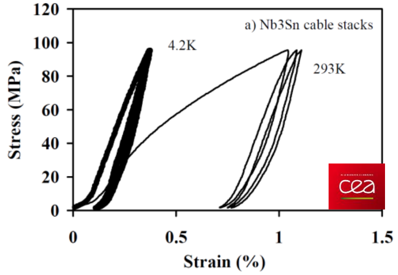






A complex non linear orthotropic behavior observed dependant on loading phase





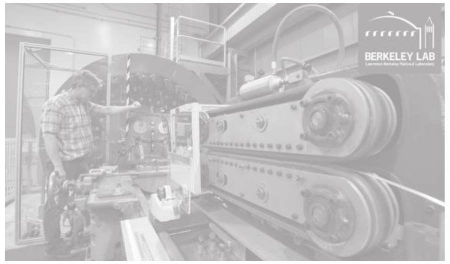
Ongoing attempt to have a coil rigidity formulation in FE

Courtesy of M. Durante (CEA) and C. Fichera (CERN)

Ongoing detailed characterization => FEA

What is the effective strain state of Nb_3Sn during its life cycle? Impact on I_c?

CABLING



- Optimization of the cabling process
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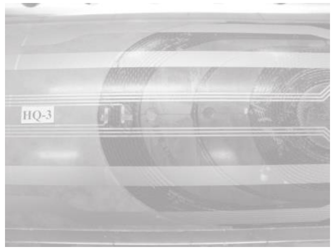
Post cabling I_c (includes cabling degradation)

COIL TECHNOLOGY



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ASSEMBLY & Cool-down

- 3D FE Models
- Mechanical instrumentation

Some correlation

Precise properties of Epoxy impregnated Nb_3Sn? Implementation in FEM

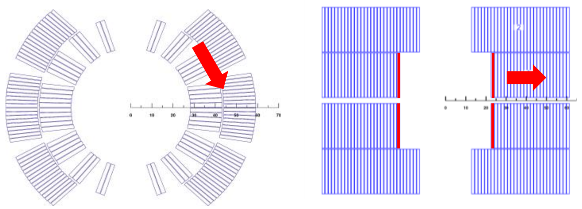
OPERATION

- 3D FE Models
- Mechanical instrumentation

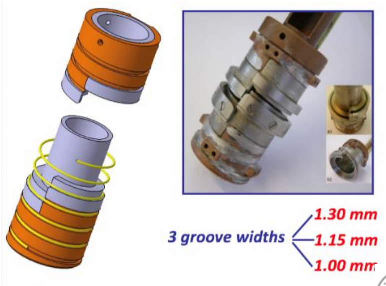
Some correlation

- I_c => as $I_c(B,T,\varepsilon)$
- Quench induced stress

Ic reduction versus transverse stress

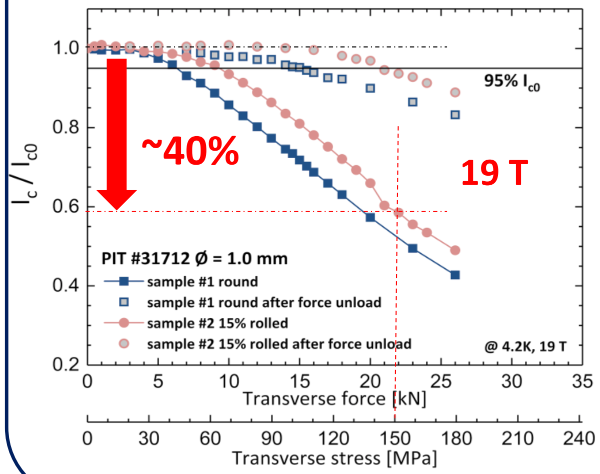


Strand electromechanical characterization

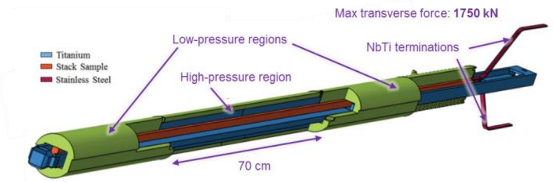


Courtesy of C. Senatore

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

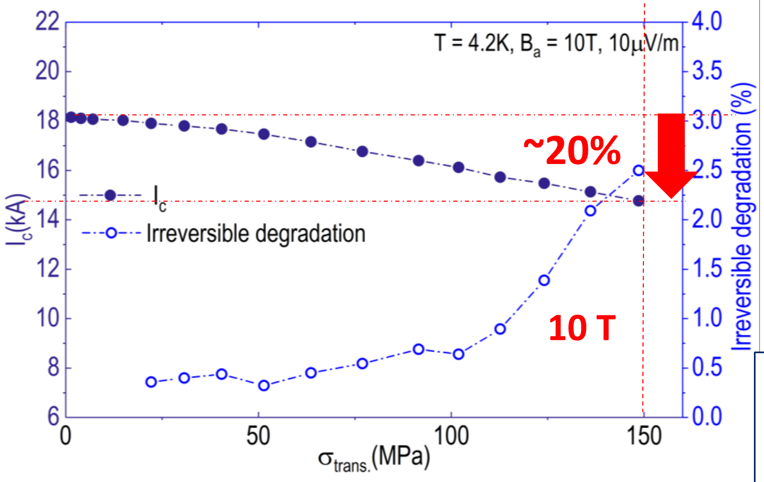


Cable electromechanical characterization

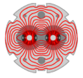


Courtesy of B. Bordini

UNIVERSITY OF TWENTE.

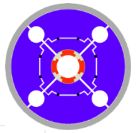


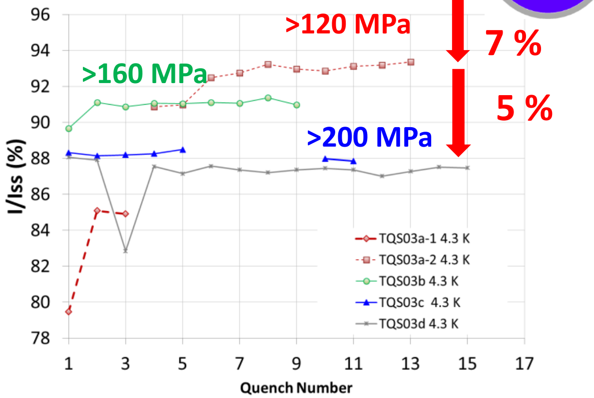
Courtesy of. M Dhallé



Magnet performance

LARP





88 % of I_{ss} operation with >200 MPa

~ 12 T

I_c reduction due to transverse stress:

- Reversible (B_{c2} reduction)
- Irreversible (filament breakage)

Challenge: from conductor to magnet

Accounting for I_c reduction in the magnet design

Scaling Law to fit I_c (B,T,ε)

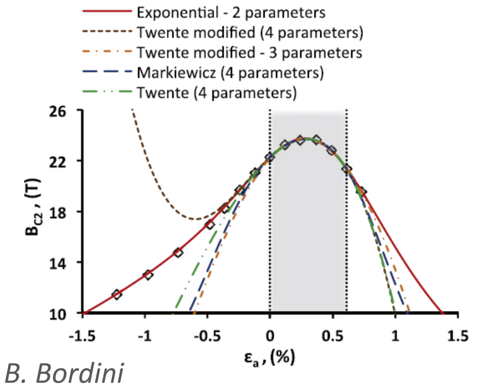
$$J_c(B,T,\boldsymbol{\varepsilon}) = C_0 \frac{B_{c20}}{B}(s(\boldsymbol{\varepsilon}))^{\sigma}\left[(1-t^{1.52})(1-t^{2})\right]^{\alpha} b^{0.5}(1\text{-}b)^2$$

Where: $b = \frac{B}{B_{c2}(\varepsilon)}$; σ and α are parameters very close to 1 and; C_0 is a constant

Where $B_{c20} = B_{c2}(0,0)$, $\boldsymbol{\varepsilon}$ is the strain tensor, $t = \frac{T}{T_c(\varepsilon)}$

$$s(\varepsilon) = \frac{e^{-C_1\left(\frac{J_2+2}{J_2+1}\right)J_2} + e^{-C_1\left(\frac{I_1^2+2}{I_1^2+1}\right)\frac{I_1^2}{2}}}{2}$$

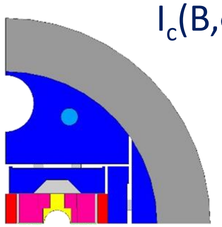
With I_1 the hydrostatic invariant
With J_2 the second deviatoric strain invariant



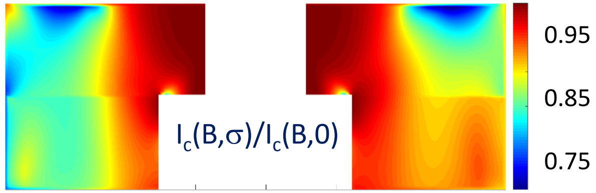
Courtesy of B. Bordini

Fitting experimental data

I_c(B,σ) at operating T

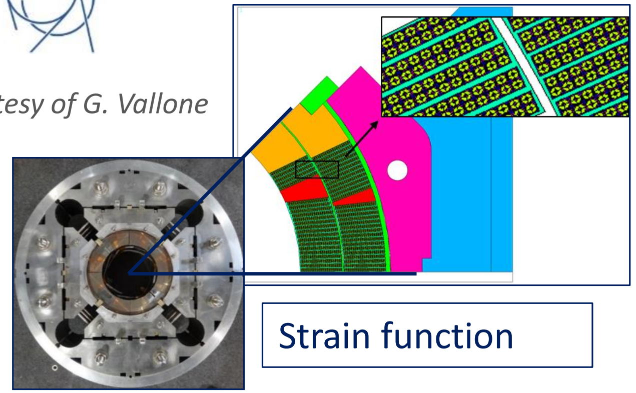


I_c reduction map using present FEM

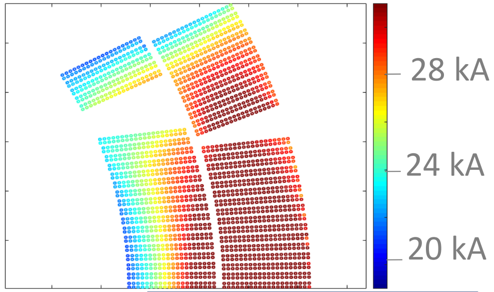


Courtesy of E.Rochepault

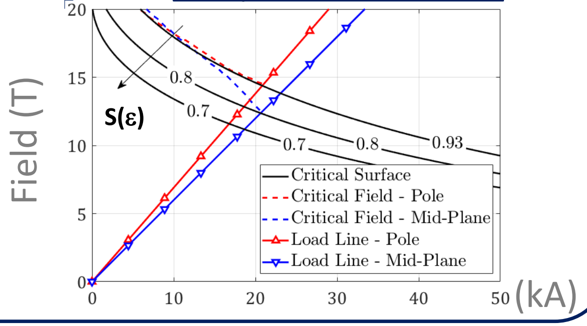
Courtesy of G. Vallone



Strain function



I_c reduction map



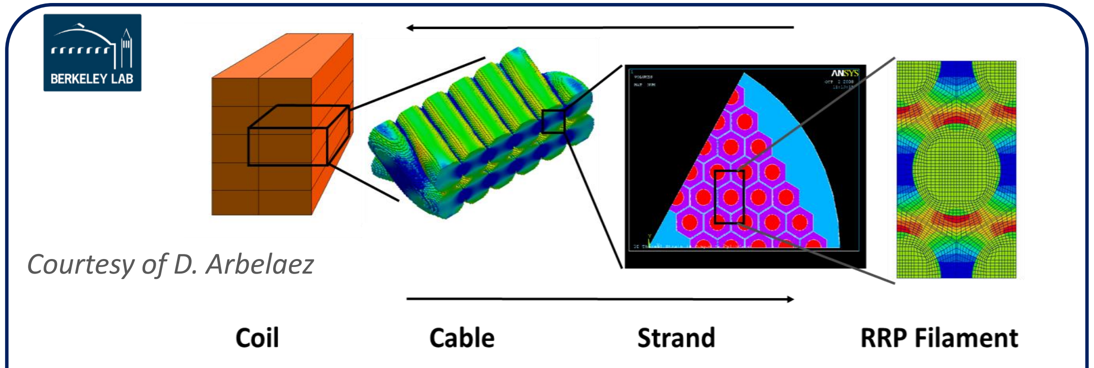
FE Modeling of cable rigidity accounting for Cu plasticization
Validated with experiments

Ongoing comparison with magnet performance

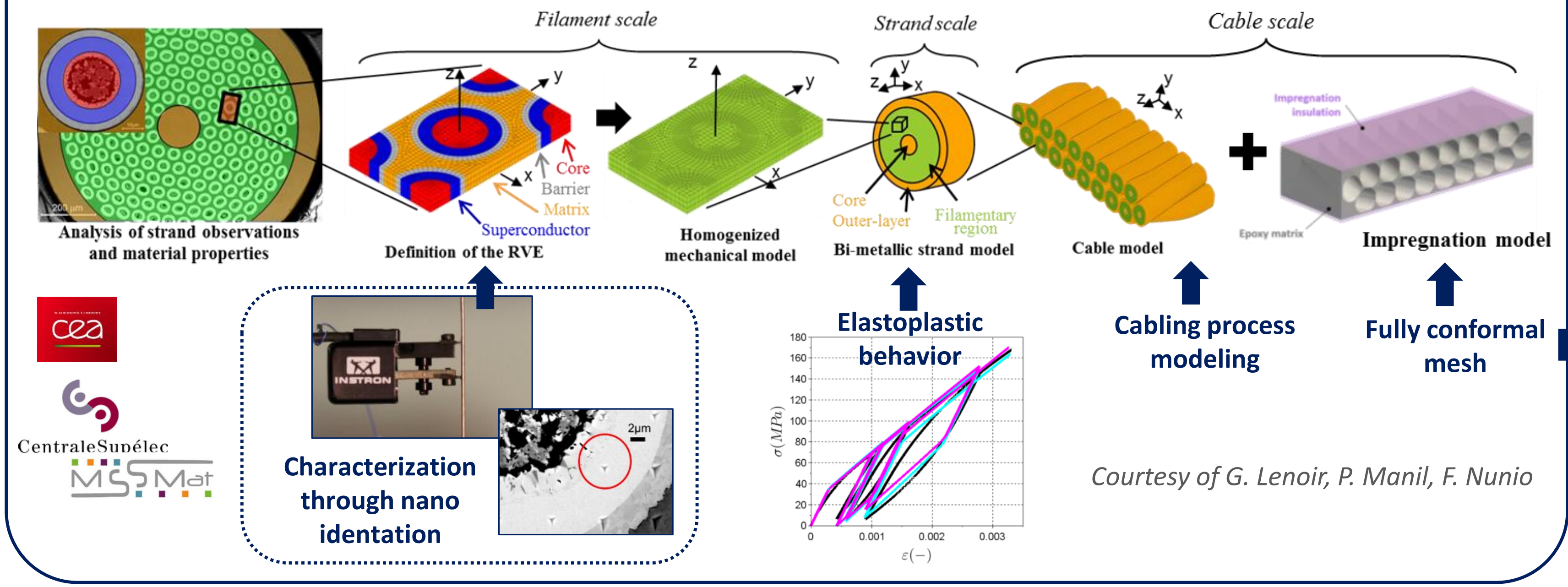
The multiscale approach

Macroscale problem with microscale details

⇒ Multiscale approach
⇒ Relevant physics at different length scales



A multiscale approach based on the material properties at the microstructural scale



Ultimate goal: Estimate the reduction of I_c

Understanding training: a key issue for the accelerator

Filaments
Sub-elements

microstructure

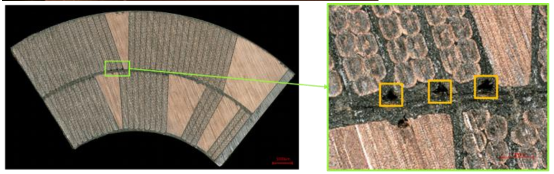
stabilizer

Strand

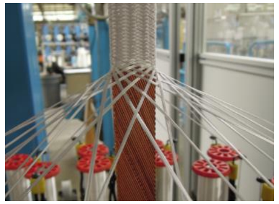
Friction, sintering

Cable

Courtesy of S. Caspi



Courtesy of S. Izquierdo Bermudez



Courtesy of P. Ferracin

Coil

Interfaces with components
Impregnation

Thermal stress due to quench

Magnet

Preload
Macroscopic motions

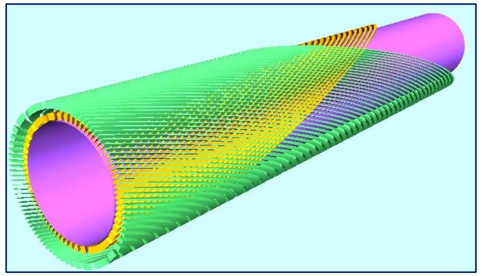
Back to user's point of view:
Key issue is training for installation in an accelerator

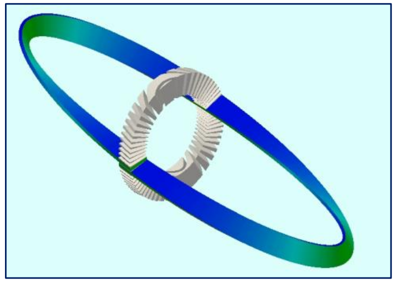
"Physical mechanisms potentially responsible for training coexists at very different length and energy scales"
M. Marchevsky, IDSM01

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation Tue-Mo-PL2-01 given at MT26, 22 – 27 September 2019, Vancouver, Canada.

A reborn concept: the Canted Cosine Theta (CCT)

Presented in 1970 by D. Meyer, U. of Michigan => redescovered in the 2010s



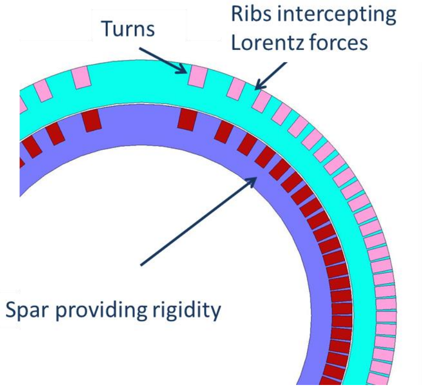


Courtesy of L. Brouwer, S. Capsi, R. Hafalia (LBNL)

Pros'
- Structure "embedded" in the coil
- Less components
- Field quality
- Easy grading

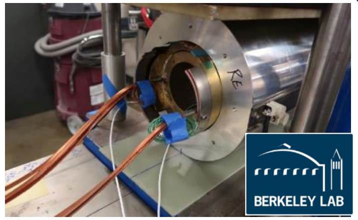
Cons'
- Electrical insulation

Potential for Fab Cost reduction



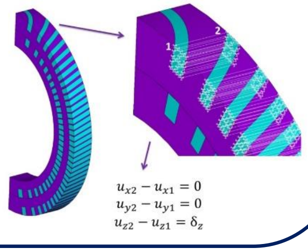
U.S. MAGNET DEVELOPMENT PROGRAM

Courtesy of D. Arbelaez (LBNL)



	CCT3	CCT4	CCT5
Bore size [mm]	90	90	90
Groove design	constant width	1.25 mm gap at pole	1.65 mm gap at pole
Conductor	RRP 54/61 Ta doped	RRP 54/61 Ta doped	RRP 108/127 Ti doped
HT Temp [C]	650	660	665
Potting configuration	full magnet	full magnet	individual layers
Epoxy	CTD-101K	CTD-101K	FSU Mix 61
Layer-to-layer interface	bonded	mold released	bend & shim

- Conductor damage
- Field quality
- Cost and scalability
- Training

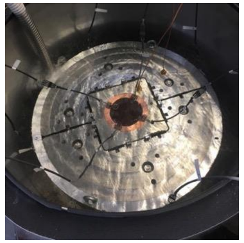


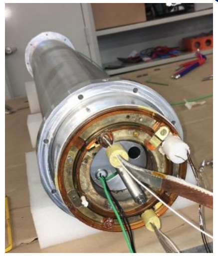
- 10 T technology toward high field
- Analysis tools

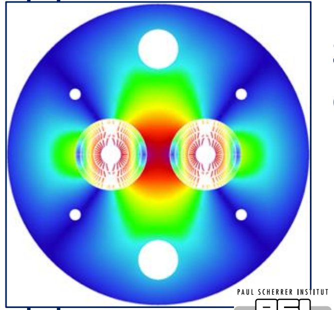
PAUL SCHERRER INSTITUT PSI

Courtesy of B. Auchmann

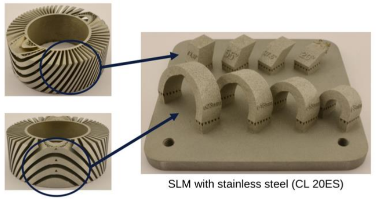
CD1 under construction
11 T in 65.6 mm bore







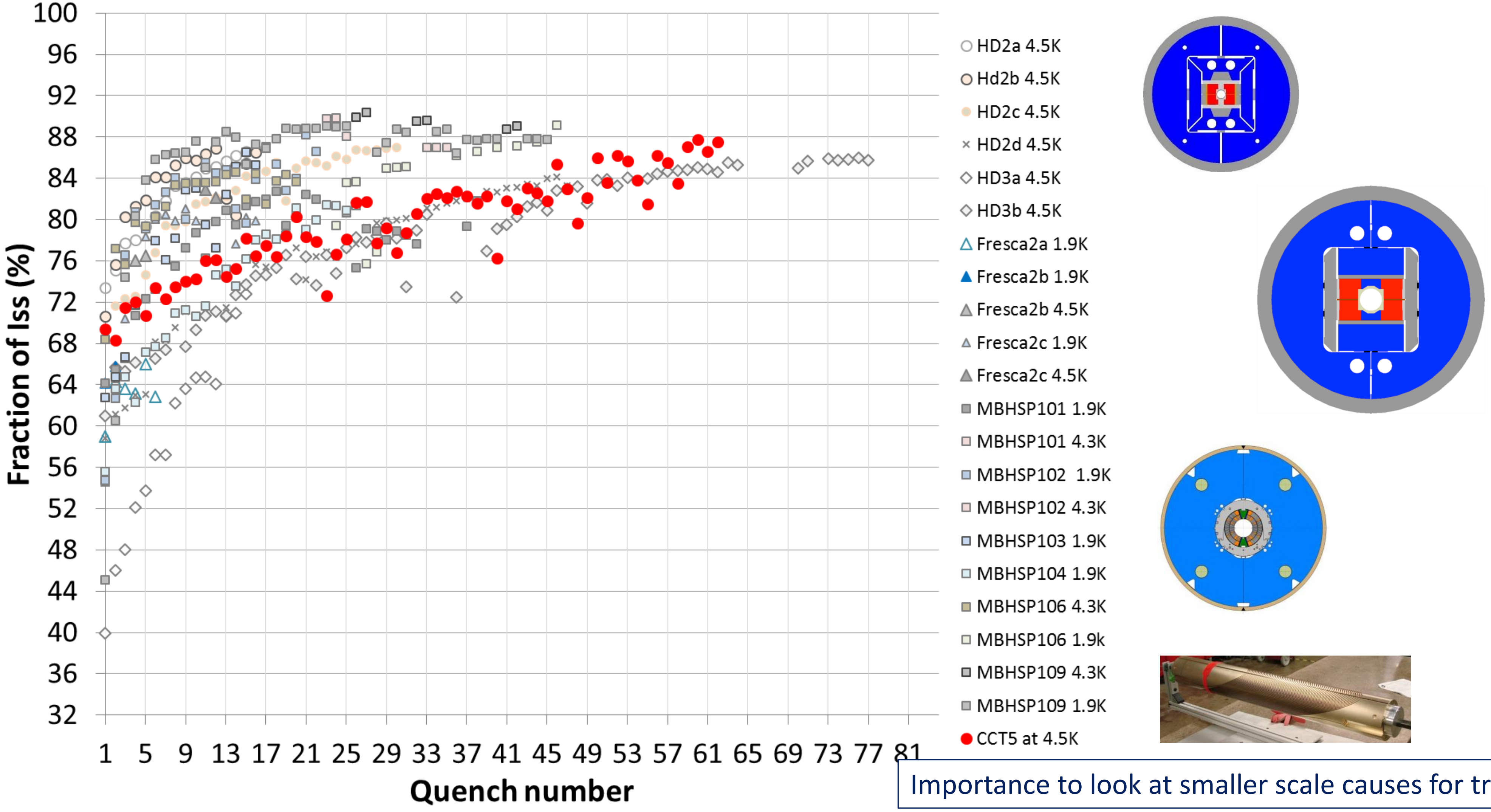
Supporting technology development



ETHZ & Inspire AG

Courtesy of B. Auchmann

Is CCT behavior different?



Importance to look at smaller scale causes for training

Understanding Ic reduction and training

3rd International Workshop of the Superconducting Magnets Test Stands

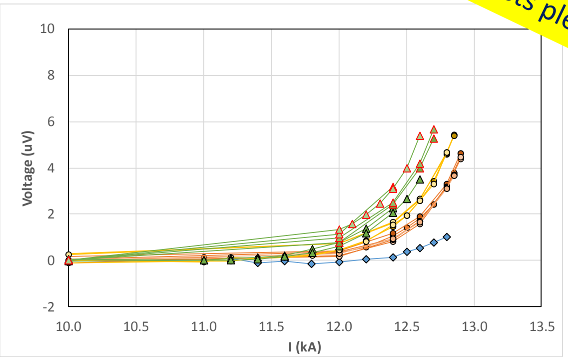
IDSM01 First Workshop on Instrumentation and Diagnostics for Superconducting Magnets
Berkeley, California, USA 24-26 April 2019

Franco Mangiarotti
Young scientists plenary

Key importance of diagnostic tools

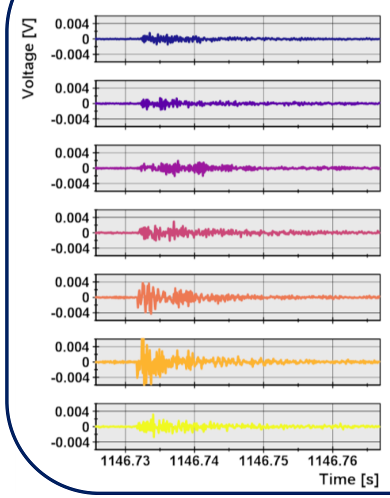
Localizing at Ic reduction

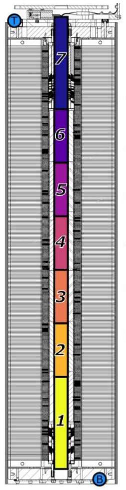
V-I transition in Segments of magnets

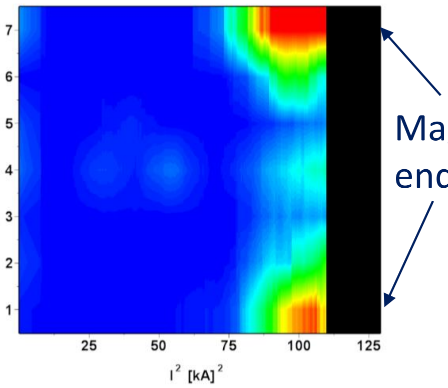


Courtesy of G. Willering

Investigation of Vibration spectrum thanks to pick up coils





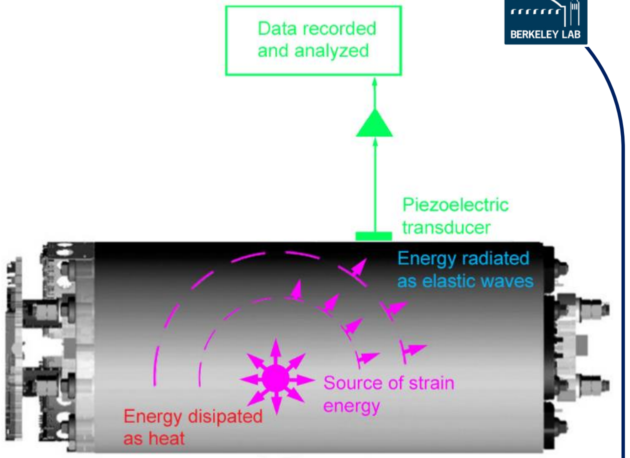


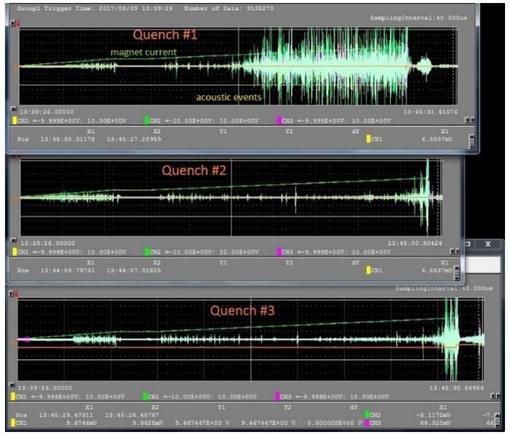
Magnet ends

Courtesy of G. Willering

Accoustic sensors

A tool to localize and understand training sources





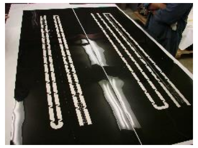
Mechanical memory: Magnet acoustically silent up to the current (stress) level seen in previous quench!

Courtesy of M. Marchevsky

Protection hardware: how to protect?

Protection heaters

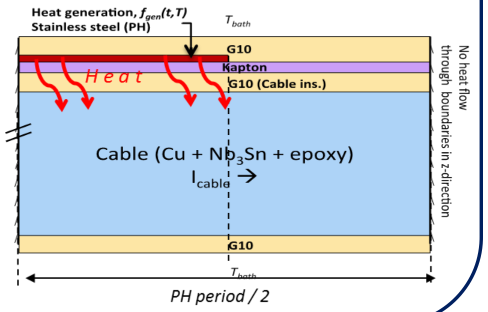
- Flexible circuit
- impregnated
- Long magnets:
  - Active heating stations
- Minimizing area covered by heaters



Courtesy of G. Ambrosio, FNAL

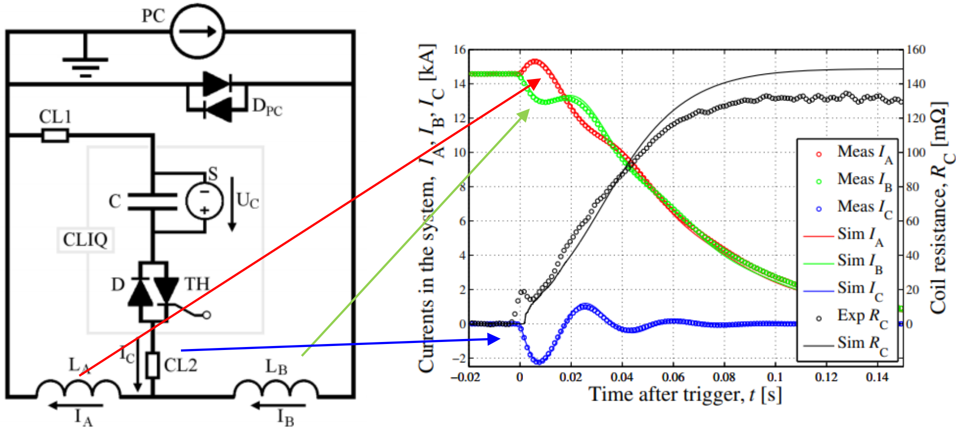
Heater delay computation

CoHDA: Code for Heater Delay Analysis



Courtesy of T. Salmi, Tampere University

Coupling Loss Induced Quench (CLIQ)



Courtesy of G.Kirby, E. Ravaioli

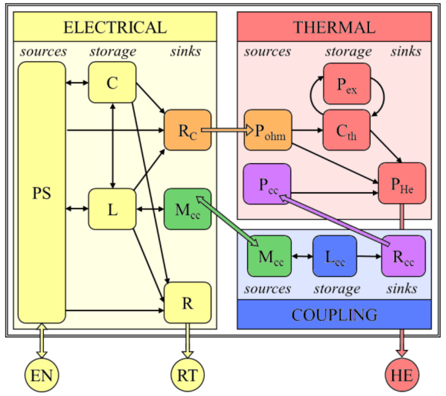
- **Capacitive discharge** inducing short oscillations in magnet transport current
- **Quenching through** inter strand and interfilament coupling losses

Protection hardware => transient effects => importance of simulation

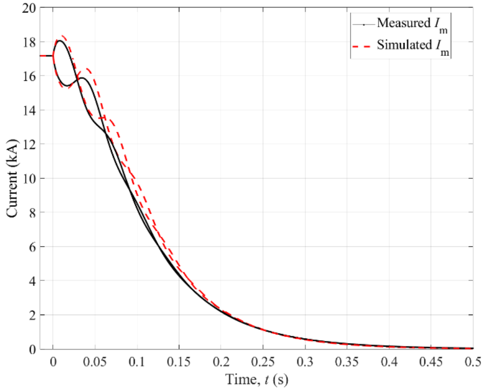
Modeling quench behavior (some examples)

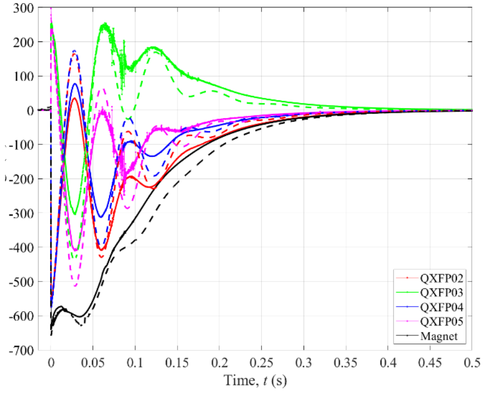
LEDET : Lumped-Element Dynamic Electro-Thermal

- Quench simulation including **coupling losses**
- Allows CLIQ parametrization
- Valid for stand alone magnets
- **Validation with MQXFAP1**



Courtesy of E. Ravaioli

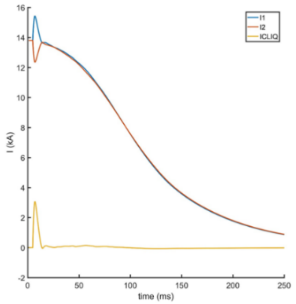




https://espace.cern.ch/steam/

ANSYS® User defined elements

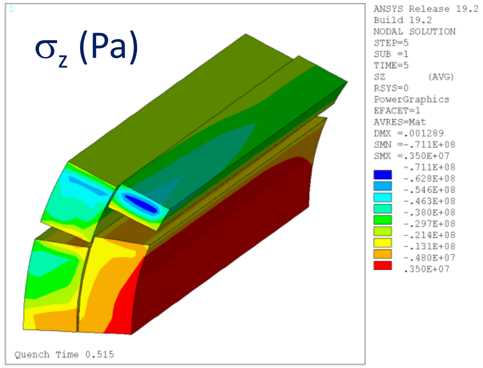
- Modeling **magnetization of the conductor** due to coupling currents
- Combining all the effects into a **single coupled simulation** with B and T dependant properties



Courtesy of L. Brouwer

https://usmdp.lbl.gov/scpack-code/

ANSYS® 3D thermal stress



Ongoing study
3D modeling
AUP/HL-LHC cross-check ongoing

Courtesy of J. Ferradas Troitino

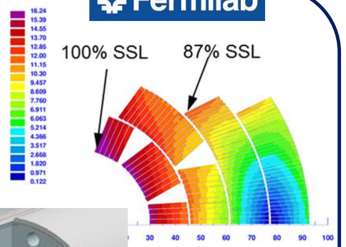
Models development toward 16 T magnets

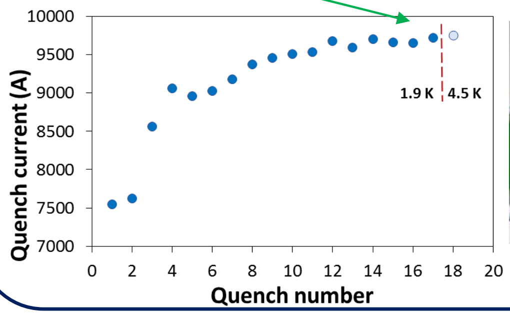
U.S. MAGNET DEVELOPMENT PROGRAM

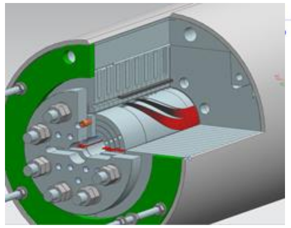
Fermilab

Key milestone: 15 T dipole

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







Courtesy of A. Zlobin, FNAL

Models development toward 16 T magnets

U.S. MAGNET DEVELOPMENT PROGRAM

Fermilab

Key milestone: 15 T dipole

- 4 layer graded magnet, 1-m long
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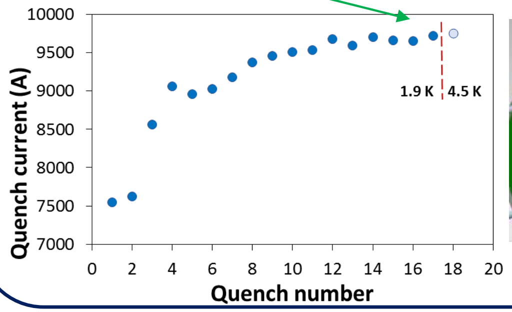
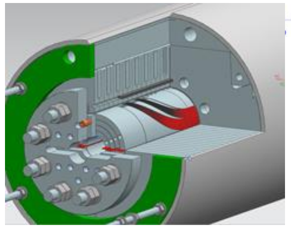
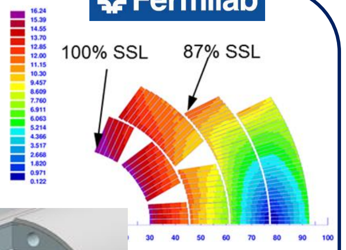
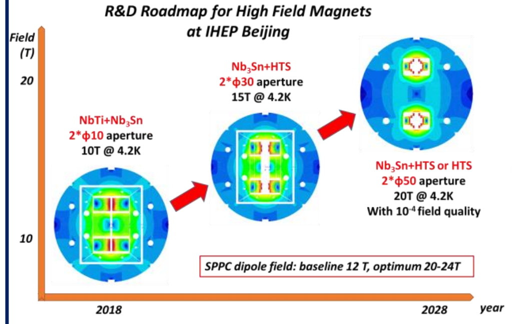


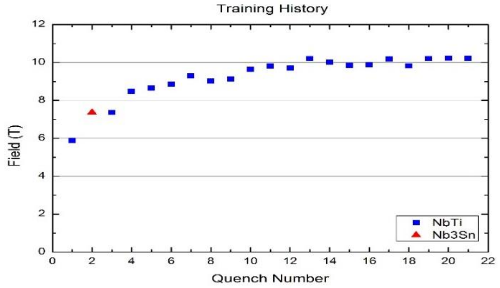




Courtesy of A. Zlobin, FNAL

Institute of High Energy Physics
Chinese Academy of Sciences





Courtesy of Q. Xu, IHEP

10.2 T at 4.2 K in 2 apertures

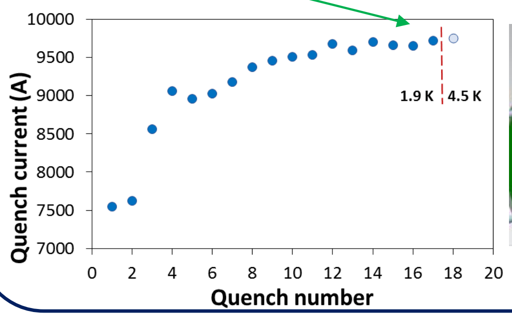
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation Tue-Mo-PL2-01 given at MT26, 22 – 27 September 2019, Vancouver, Canada.

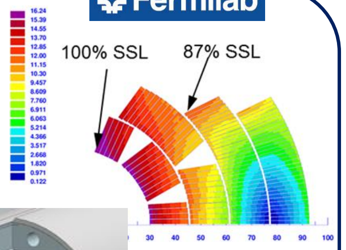
Models development toward 16 T magnets

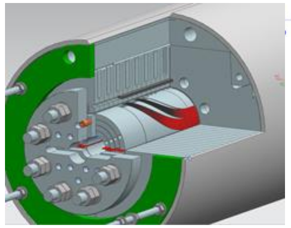
Key milestone: 15 T dipole

U.S. MAGNET DEVELOPMENT PROGRAM — Fermilab

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







Courtesy of A. Zlobin, FNAL

Institute of High Energy Physics
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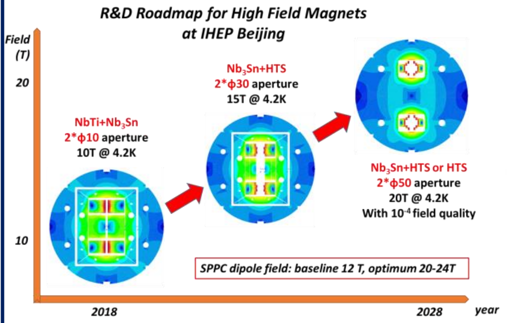
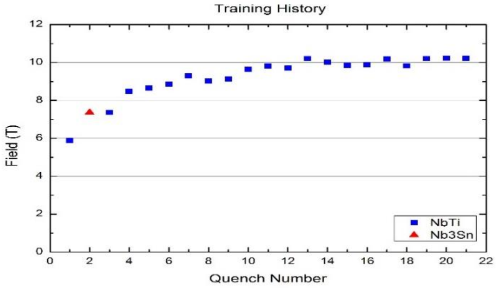
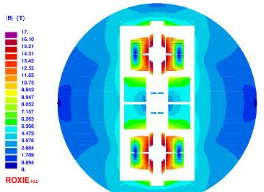


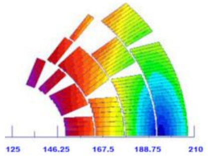


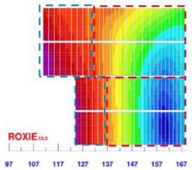
Courtesy of Q. Xu, IHEP

10.2 T at 4.2 K in 2 apertures

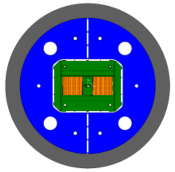
FCC 16 T Model Magnet Development



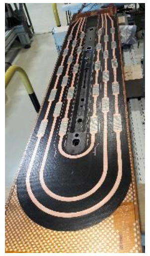


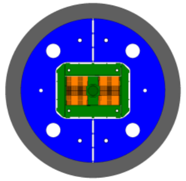


Nb_3Sn GRADING



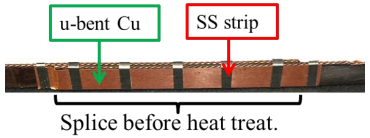
eRMC
No bore
16 T target

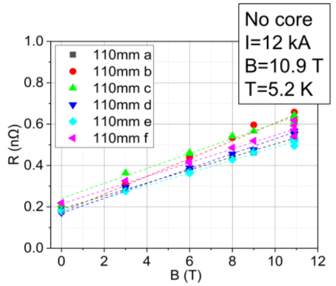




Racetrack Model Magnet = RMM
50 mm bore
16 T target

Nb_3Sn joints





Courtesy of V. D'Auria, EPFL

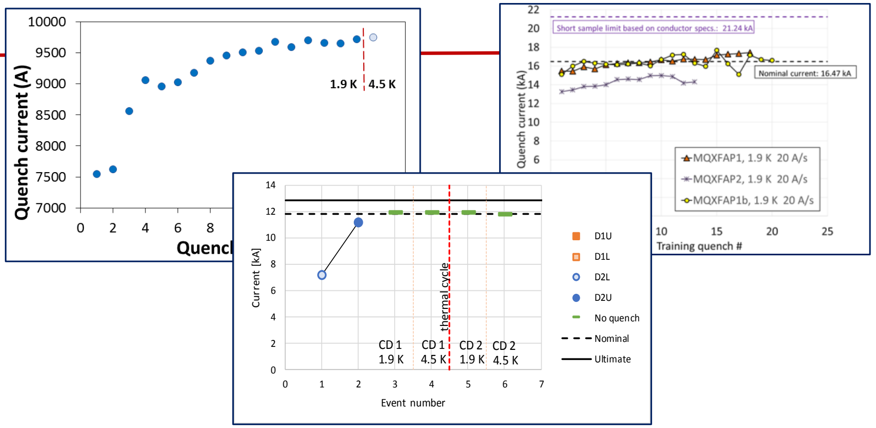
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation Tue-Mo-PL2-01 given at MT26, 22 – 27 September 2019, Vancouver, Canada.

To wrap up

- Target for 16 T dipole: double LHC Main dipole field!!

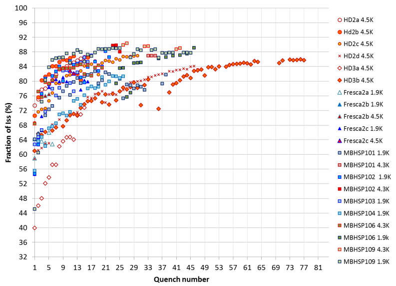
- Successful 16 T Nb_3Sn magnets without bore
- Successful 11$^+$ T Nb_3Sn **long** dipoles and quadrupoles

- Encouraging Nb_3Sn model programs reaching 14$^+$ T bore field
- Excellent memory demonstrated



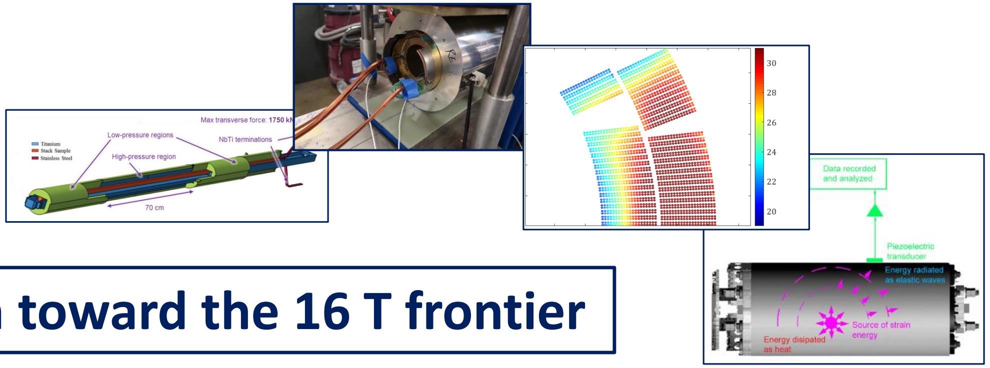
- A « missing » 10% margin is observed quite consistently

- Long training



The community is working
- as an international team
- with a consistent development program

To understand and reduce training
To master these 10% :
- by conquering them?
- by accounting for them in our designs?



We are on a consistent path toward the 16 T frontier

Thank You

Special Thanks to:
Shlomo Caspi, Paolo Ferracin, Soren Prestemon, Ian Pong, Arnaud Devred, Giorgio Ambrosio,
Sasha Zlobin, Giorgio Vallone, Susana Izquierdo Bermudez, Etienne Rochepault, Clément Lorin, Luisa Chiesa

And everybody who provided input and info