High Field Magnet R&D Program
A view from CERN

Presented by L. Bottura

With crucial contributions from CERN TE-MSC and FCC collaborators

~~US-MDP Workshop Washington, DC, 4-5 December 2019~~

FCC Magnets Collaboration Meetings/Kick-off, 10 December 2019

Outline

- The nature of the program
- The leading questions for the R&D
- The R&D lines responding to the questions
- The R&D vehicles
- Deliverables and timeline
- Summary

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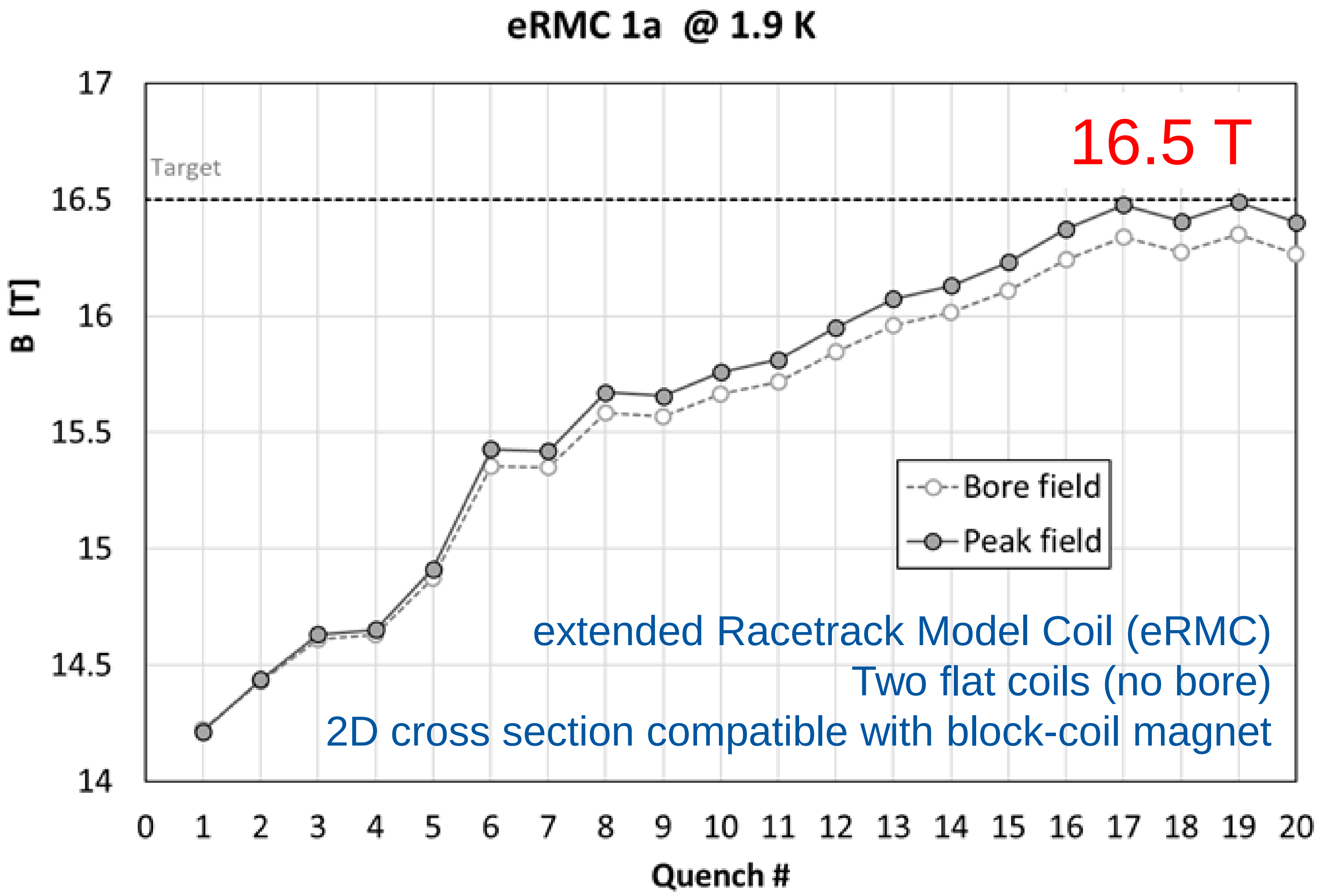
A program responding to demands

- FCC-hh, including the specific demands from HE-LHC, has been **the main driver of the development of HFM**
  - We have shown that a field of 16 T can be generated by Nb_3Sn (RMC-03, 2015)
  - We have produced 14.6 T in a 100 mm aperture (FRESCA2, 2018) and 14.1 T in a 60 mm aperture (US-MDP CT1 2019)
  - We have demonstrated that the J_C target of 1500 A/mm^2 at 16 T and 4.2 K is within reach (2018, 2019), and we have two additional potential suppliers of HL-LHC class wire (TVEL, JASTEC)
- All of the above **in collaboration** with the whole-world community
- The HFM development activities have been **instrumental to HL-LHC**, and in particular the success of the 11T MBH long magnet

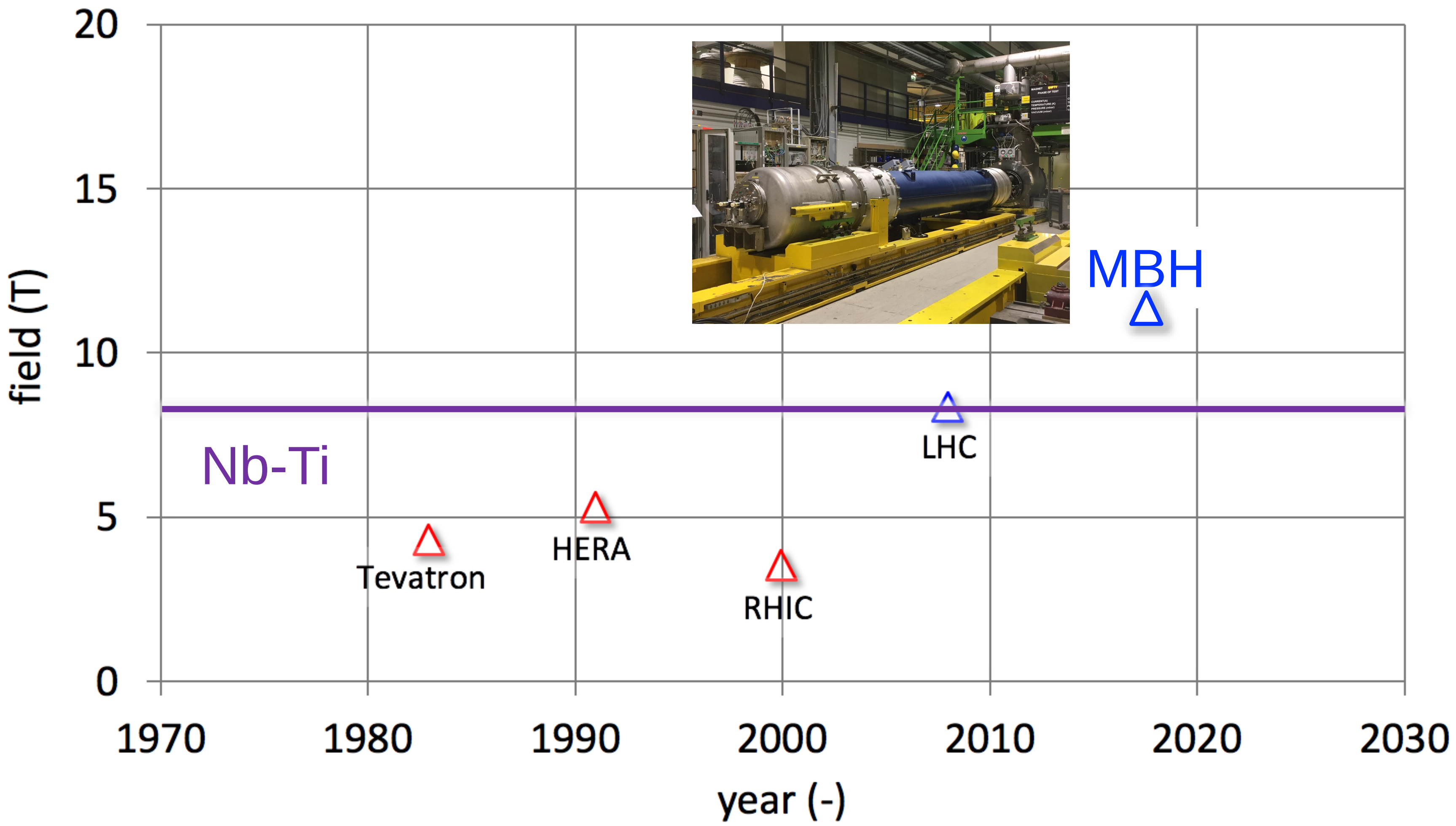
CERN has completed the production of the first accelerator Nb_3Sn dipole magnet, **an historical milestone for accelerator technology**.

Latest from HFM R&D



extended Racetrack Model Coil (eRMC)
Two flat coils (no bore)
2D cross section compatible with block-coil magnet

HL-LHC 11T significance



The 11T MBH is a technology breakthrough !

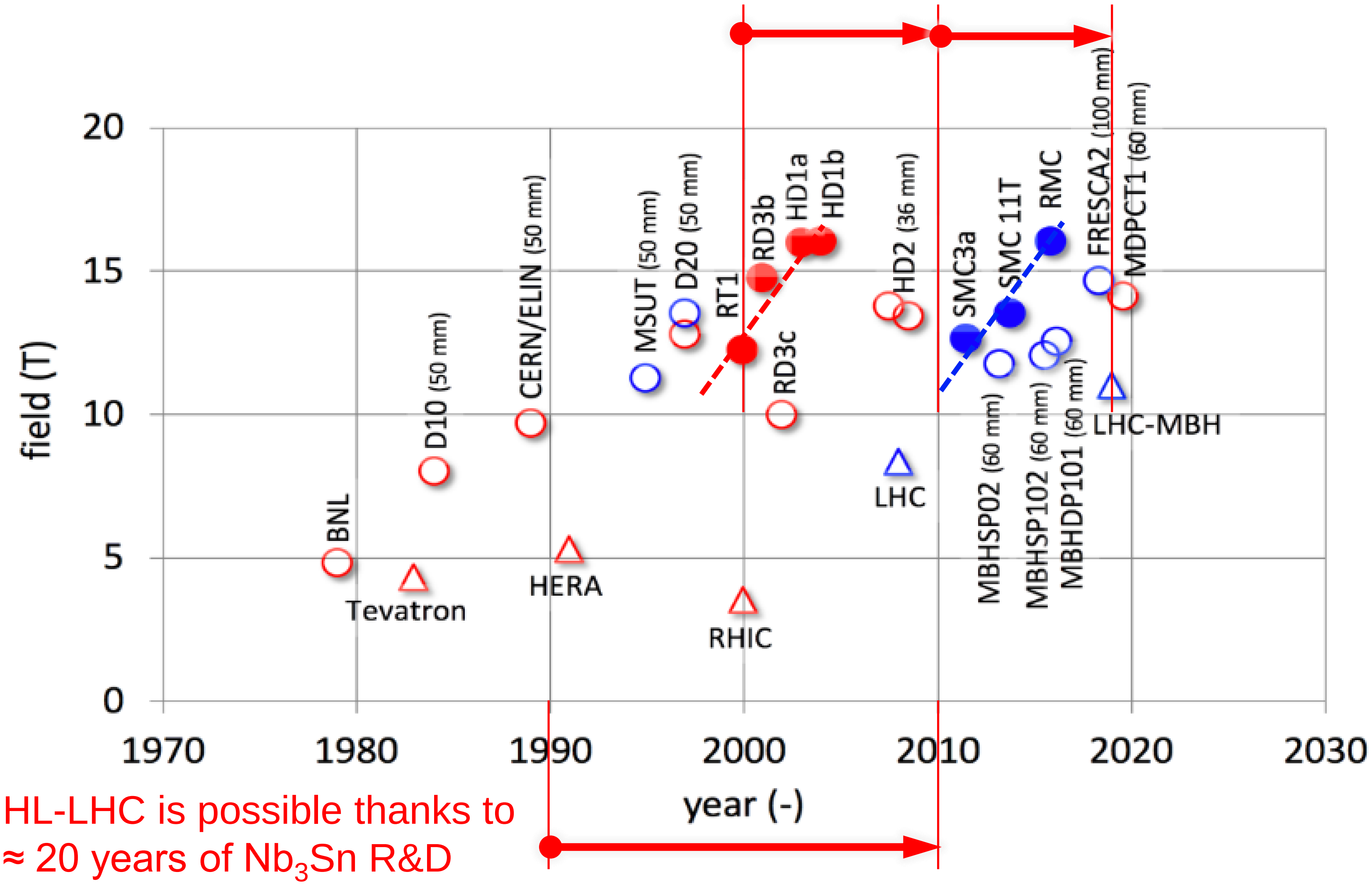
A program for the long term

- The long and winding road of 11 T has reminded us that **there is a long way from demonstrators to model, prototype magnets, pre-series and industrial production.** We need continuity, because:
    - **Lead times for the development of high-field magnets are long**, a typical cycle lasts ten years. Another ten years will be required for industrialization (see later). Not pursuing technology R&D in-synch with HEP scoping studies of new accelerators may result in missed opportunities.
    - Development of high-field superconducting magnet technology requires **infrastructure of large size and cost**. A program that requires such infrastructure is most profitable if pursued with continuity, rather than executed in bursts.
    - High-field superconducting accelerator magnet development relies on many fields of science and engineering, i.e. **a team that is assembled in collaboration with organizations**. Such research team also operates most effectively in a continuous mode

Cycle time

It took ≈ 10 years to establish Nb_3Sn magnet technology

It took ≈ 10 years to make Nb_3Sn accelerator magnets



HL-LHC is possible thanks to ≈ 20 years of Nb_3Sn R&D

A program in collaboration

- This is a proposal for a **collaborative program.** We wish to profit from the competences developed and the team built over the last 15 years (EU-FP6 CARE and NED-JRA, EU-FP7 EuCARD and EuCARD2, EU-H2020 ARIES), and boosted by the FCC activities (EU-H2020 EuroCirCol)
- Today, collaborators have key roles in:
  - Conductor development and characterization (FCC Conductor Development Program)
  - Develop, demonstrate and decide the technology suitable for future accelerator magnets (model developments at CEA, INFN, CIEMAT, CHART/PSI)
- CERN is also a collaborator

What is next ?

- **The HL-LHC Nb3Sn program has set a new benchmark**: we have completed the initial model and prototype magnet development for operation in the 11-12 T field range and the next step is to capitalize on it, **use this benchmark to develop industrial, robust and efficient techniques**.
- We have a few demonstrators showing that Nb3Sn has the potential to operate at fields beyond 14 T, the next step is to **confirm this potential with model magnets and prototypes**.
- We have not yet had the opportunity to explore the potentials of HTS, the next step is to **develop demonstrators to assess this technology**.

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The "leading questions" – 1/3

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- **On Nb_3Sn magnet technology:**
  - Q1: What are the **performance limits** ?
    - Is the target of 16T for accelerator magnets realistic ?
  - Q2: Can we improve **training** ?
  - Q3: How do we manage the **forces and stresses** in a high-field accelerator magnet ?
  - Q4: How do we **protect** a high-field accelerator magnet ?
  - Q5: Can we improve the design and manufacturing processes to **achieve robustness, reduce risk, increase efficiency and decrease cost** as required by a large-scale industrial production ?

The “leading questions” – 2/3

- On HTS magnet technology:
  - Q6: What is the potential of HTS materials to **extend the performance reach** of high-field superconducting accelerator magnets ?
    - Basic material and conductor properties
  - Q7: Are HTS conductors, cables, coils **suitable** for accelerator magnet applications ?
    - Cable concept
    - Field quality
  - Q8: What **engineering** solutions are required to build such HTS magnets, including consideration of material and manufacturing **cost** ?
    - Winding and mechanics
    - Quench detection and protection
    - Splice and joint technology
    - Insulation and impregnation

The “leading questions” – 3/3

- Q9: What is the specific **infrastructure** required for this conductor and magnet R&D, production and test ?

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From leading questions to R&D lines

- R&D-1: Nb_3Sn **conductor** research and development
- R&D-2: Nb_3Sn **magnet technology** research and development, exploring performance limits

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- R&D-3: Nb_3Sn **accelerator magnet** development for robust and cost-effective industrial production at large scale
- R&D-4: HTS **material, conductor and coil technology and accelerator magnet** research and development
  - R&D-4.1: Review engineering specifications for HTS conductor (wires, tapes and cables) and pursue the ensuing development
  - R&D-4.2: Develop HTS coil and magnet technology in the form of small-scale demonstrators
- R&D-5: **Insulating materials**, polymers and composites.
- R&D-6: **Infrastructure** for development, manufacture, test and measurement.

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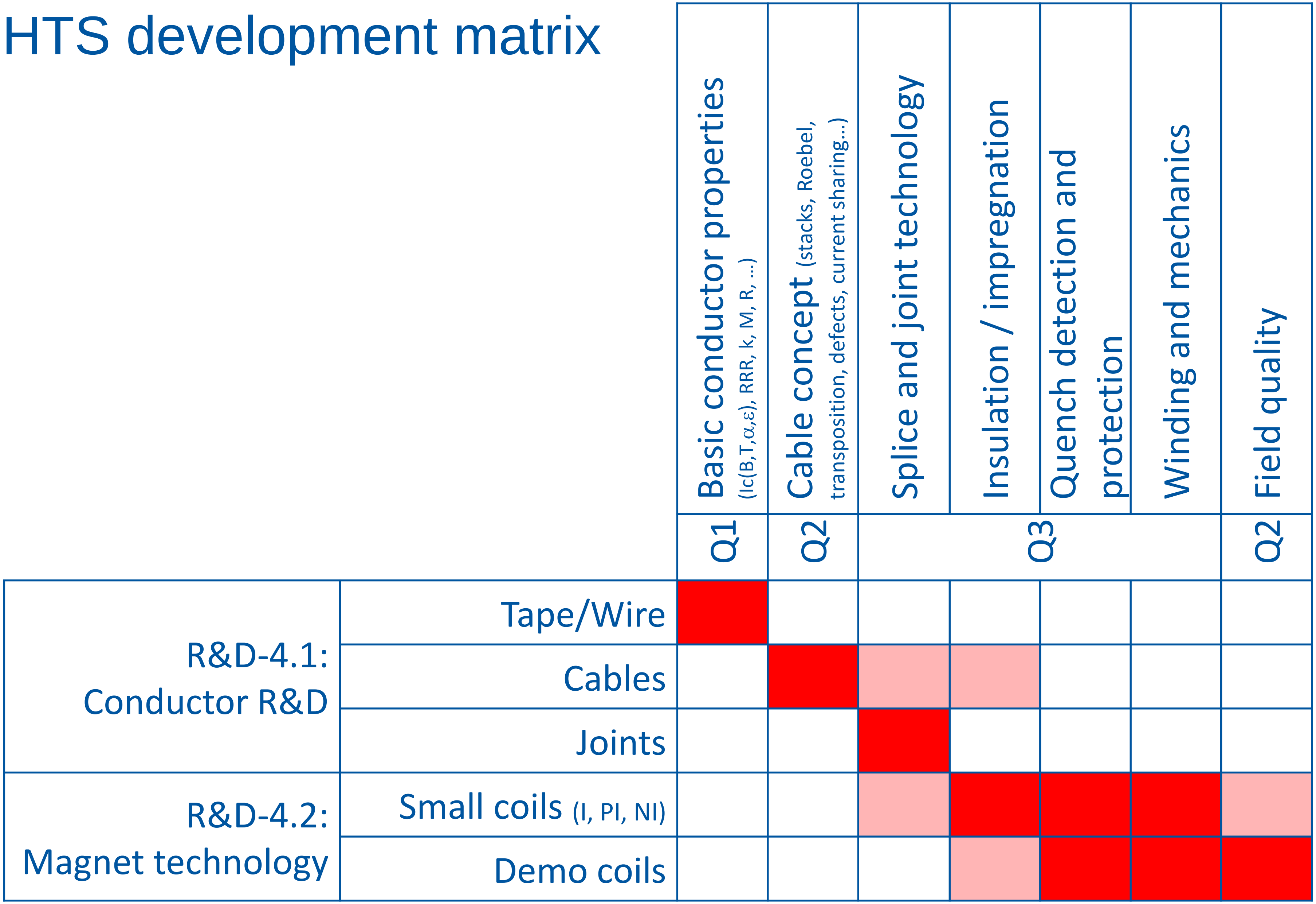
LTS (Nb_3Sn) development matrix

		Q1: Performance limits of Nb_3Sn	Q2: Training origins and cures	Q3: Mechanics	Q4: Protection	Q5: Production robustness, risk, cost
R&D-1: Wire and conductor R&D		🟥	▨			
R&D-2: Magnet technology	SMC	▨	🟥	▨		
	eRMC/RMM	▨	🟥	🟥	▨	
	Models		▨	🟥	🟥	▨
R&D-3: Accelerator magnet development (VE)				▨	🟥	🟥

HTS development matrix



		Basic conductor properties (Ic(B,T,α,ε), RRR, k, M, R, …)	Cable concept (stacks, Roebel, transposition, defects, current sharing…)	Splice and joint technology	Insulation / impregnation	Quench detection and protection	Winding and mechanics	Field quality
		Q1	Q2	Q3				Q2
R&D-4.1: Conductor R&D	Tape/Wire	🟥						
	Cables		🟥	▨	▨			
	Joints			🟥				
R&D-4.2: Magnet technology	Small coils (I, PI, NI)			▨	🟥	🟥	🟥	▨
	Demo coils				▨	🟥	🟥	🟥

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R&D Vehicles – overview

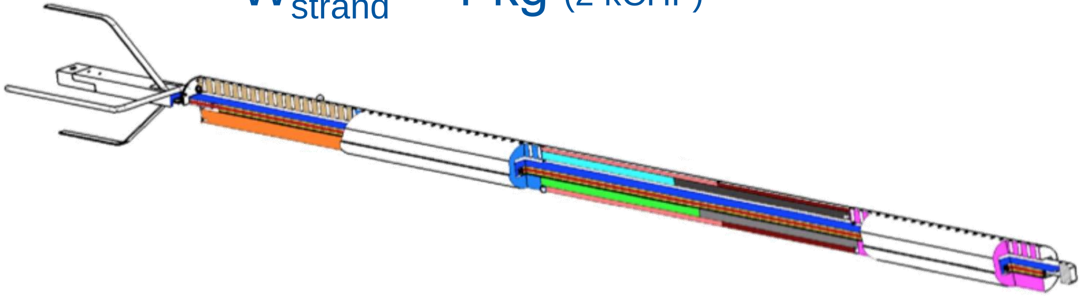
- Cables
- Model Coils
  - Short Model Coil (SMC)
  - Racetrack Model Coil (RMC)
  - Racetrack Model Magnet (RMM)
- Ultimate Nb_3Sn Dipole Models
- Value Engineered Dipole Prototype
- HTS Demonstrator Magnets

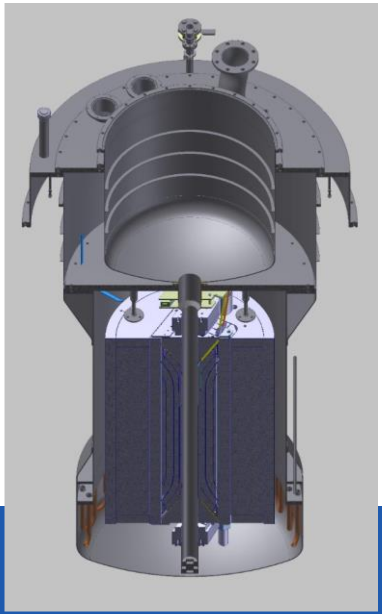
Heritage realizations

- Very High Field Test Station for high field inserts
- HTS wiggler/undulator

Cable tests

- Measurement of properties and validation of variants at cable level
  - Critical current and stability in FRESCA (FRESCA2) under relevant operation conditions, including sample preparation (resin), deformation, transverse stress and strain, joints
    - B_{peak} = 12 T (16 T)
      - L_{sample} = 2 m
      - W_{strand} ≈ 1 kg (2 kCHF)





SMC technology exploration

- The “Short Model Coil” is an intermediate step between cable and magnet, used to test rapidly technology and manufacturing variants (turnover of three months):
  - Conductor variants
  - **Insulation systems**
  - **Impregnation resins**
  - **Sliding and separating surfaces**

OD = 530 mm

L = 500 mm

No free bore

B_{ultimate} = 14 T

W_{strand} ≈ 10 kg (20 kCHF)

eRMC high-field operation

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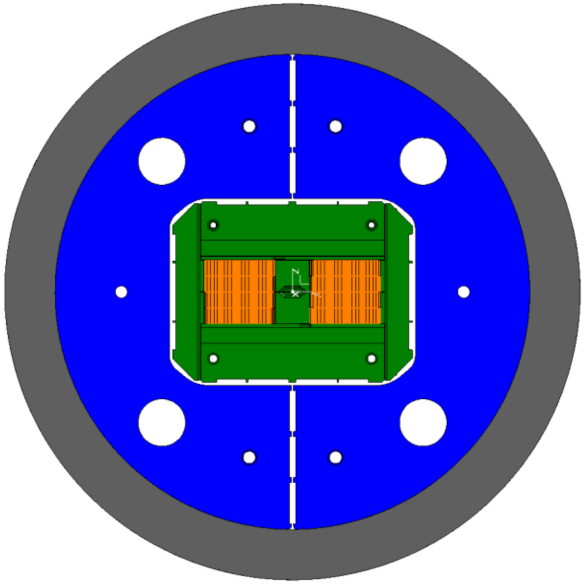
- The “extended Racetrack Model Coil” is a test-bed for full size conductors reproducing full field and force conditions over a representative length, including transitions, used to test manufacturing solutions:
  - **Conductor grading**
  - **Layer jumps and splices**
  - **Loading conditions**
  - Conductor interfaces to pole and end-spacers
  - Heat treatment and impregnation



OD = 800 mm

L = 1.5 m

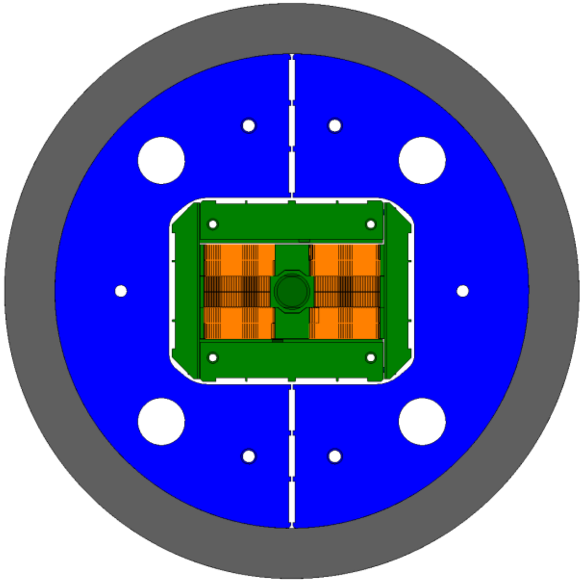
No free bore

$B_{ultimate}$ = 18 T

$W_{strand} \approx$ 120 kg (250 kCHF)

RMM x-section demonstration

- The "Racetrack Model Magnet" is a full size test of a block-coil magnet, including a reproduction of the 2D cross section (with a cavity, no bore), and optimized ends (0.5 T field drop) used to validate and test:
  - Force and stress management
  - **Magnet loading in 3D**
  - **Field quality in 2D**



OD = 800 mm

L = 1.5 m

50 mm free cavity

B_{ultimate} = 18 T

$W_{\text{strand}} \approx$ 180 kg (350 kCHF)

Models – 1/2

INFN Istituto Nazionale di Fisica Nucleare

cea

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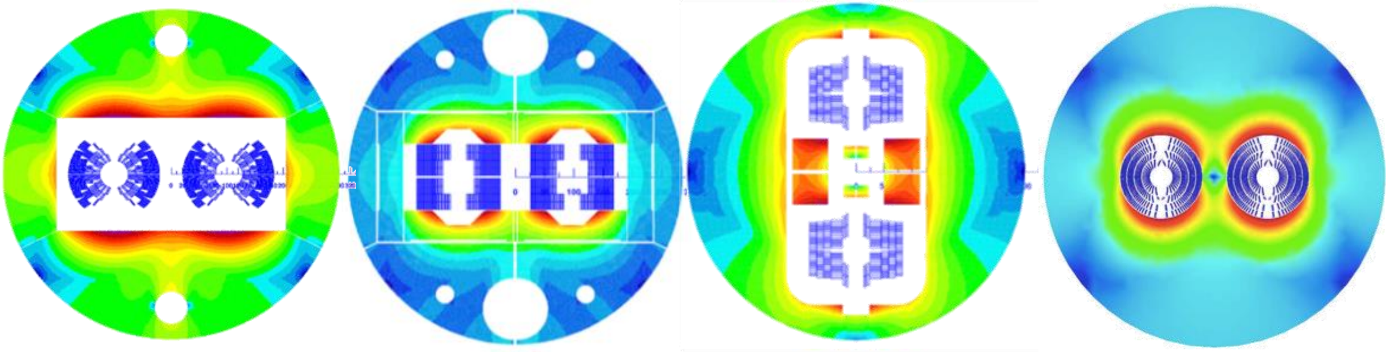
PAUL SCHERRER INSTITUT PSI



OD = 600 mm

L = 2 m

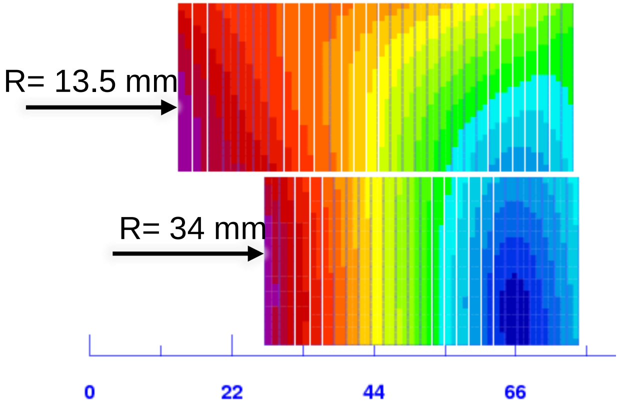
50 mm aperture

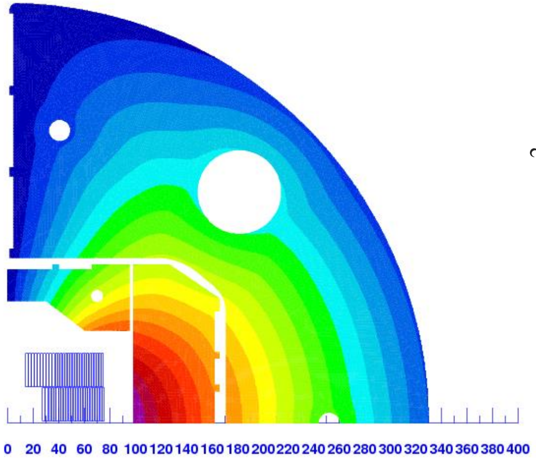
$B_{ultimate}$ = 16 T

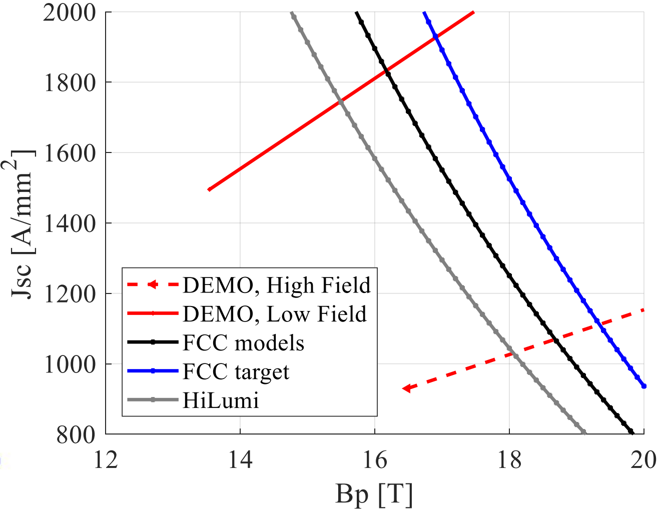
W_{strand} ≈ 350 kg (700 kCHF)

		cos(θ)	blocks	common coil	CCT
Current	(A)	10000	11230	16100	18055
Inductance	(mH/m)	50	40	19.2	19.2
Stored energy	(kJ/m)	2500	2520	2490	3200
Coil mass	(tons)	7400	7400	9200	9770

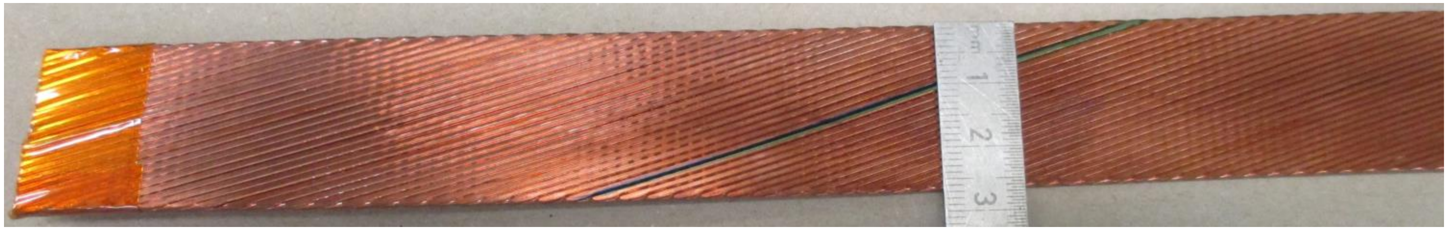
Models – 2/2





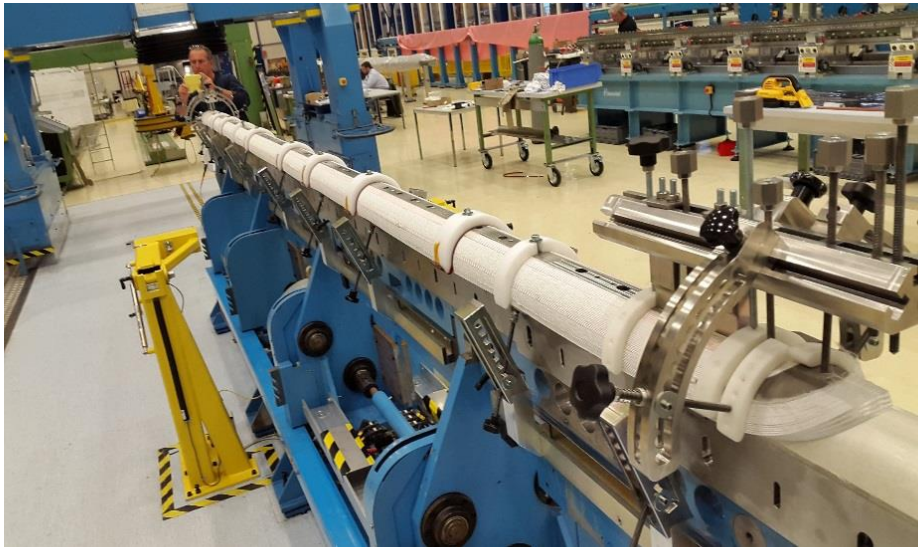


		Strands	Dstrand	CU/SC	Width	Thickness
		(-)	(mm)	-	(mm)	(mm)
Cable geometry	DEMO HF	44	1.10	0.8	25.700	2.002
	DEMO LF	56	0.85	1.2	25.700	1.547



DEMO-HF prototype
Courtesy of I. Pong
LBNL

Value Engineered Dipole



- Insulation system, fibers, sizing, binder and resins
- Coil handling (especially after heat treatment)
- Coil geometry measurement and shimming
- Splices and instrumentation
- …

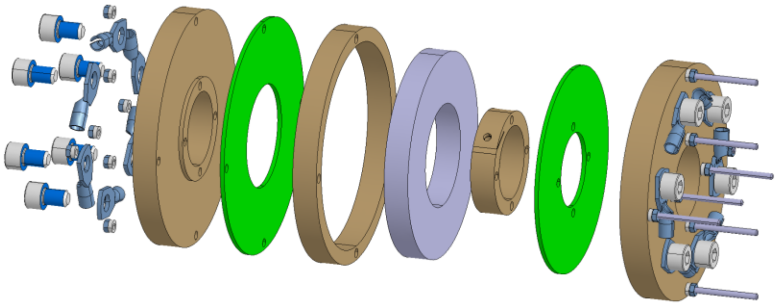
- One mold for HT and impregnation
- *Armored* coils
- Magnet assembly (collaring, bladder-and-keys, …)
- Cold mass construction
- …

Just ideas for the moment

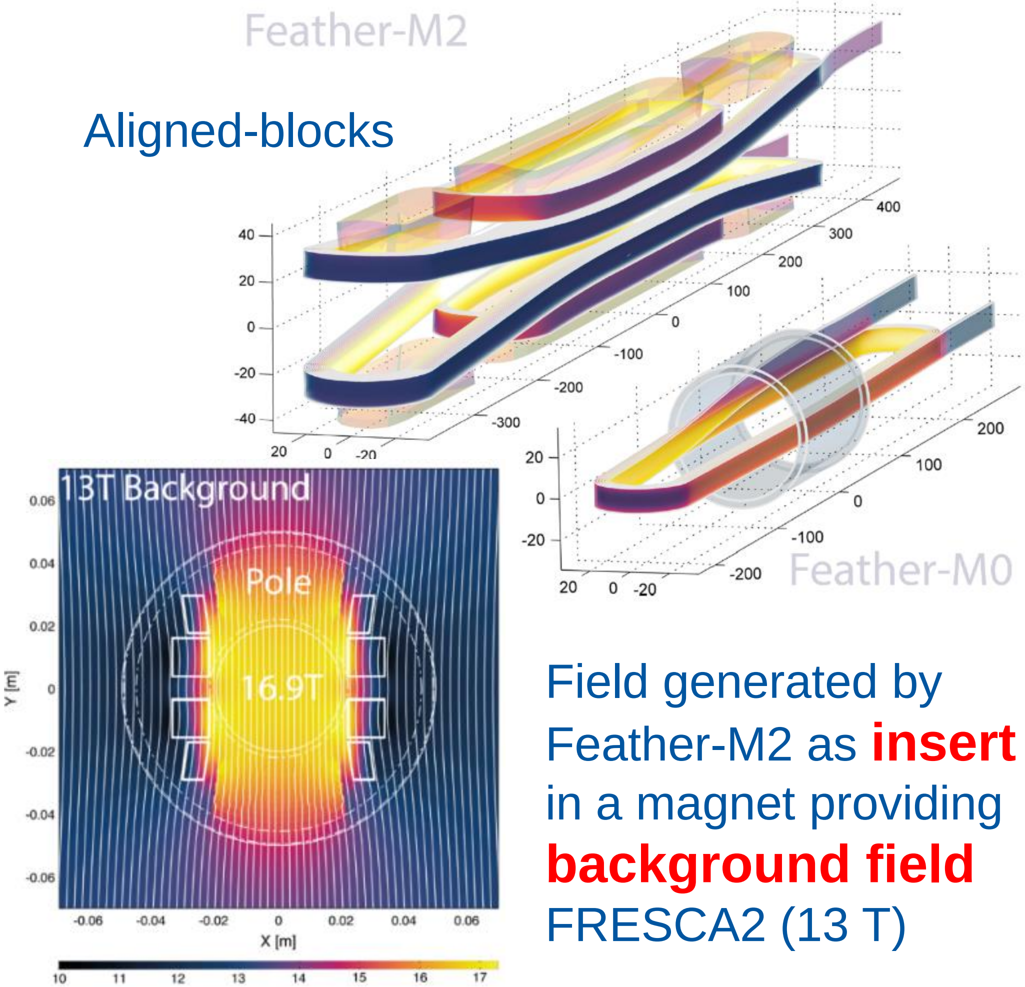
HTS demonstrator magnets

Small coils to test basic magnet properties and technology variants

Insert coils to test in-field behavior and performance reach

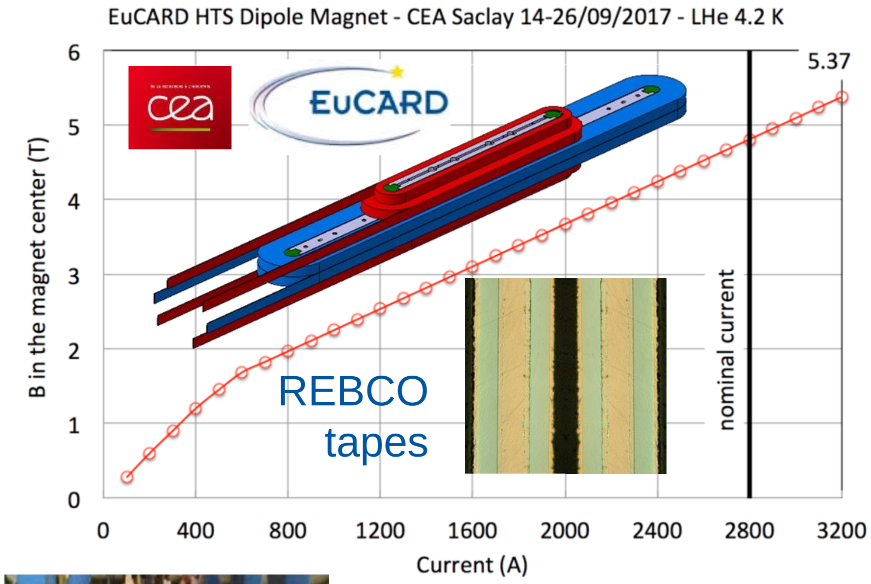


Test solenoids with insulation variants



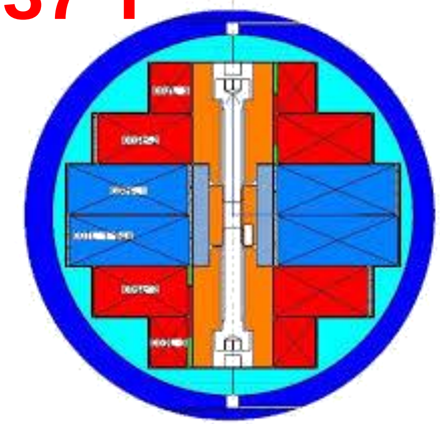
Field generated by Feather-M2 as **insert** in a magnet providing **background field** FRESCA2 (13 T)

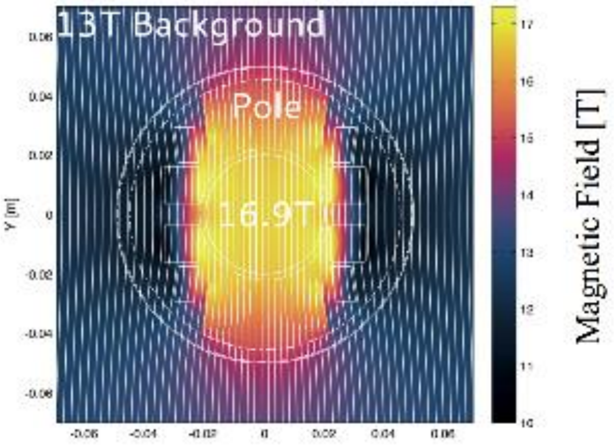
EuCARD/EuCARD^2 - HTS inserts

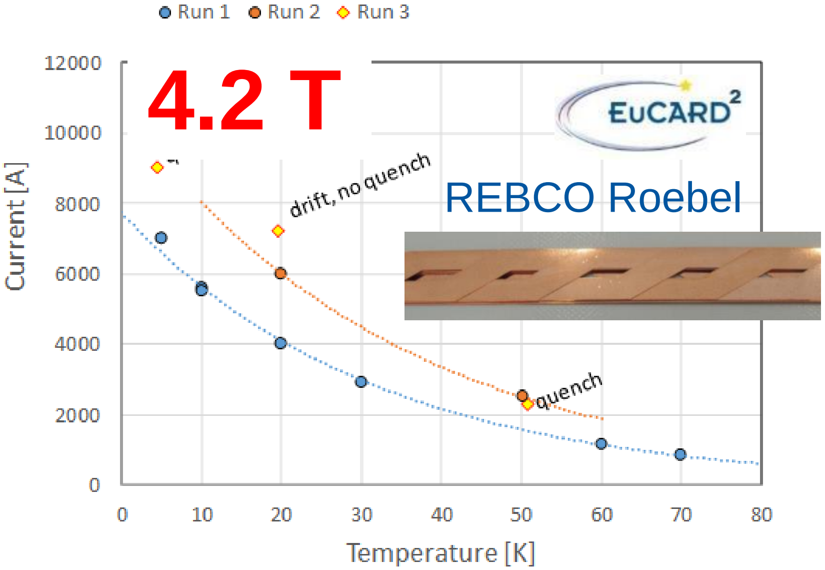


REBCO tapes

5.37 T







4.2 T

REBCO Roebel

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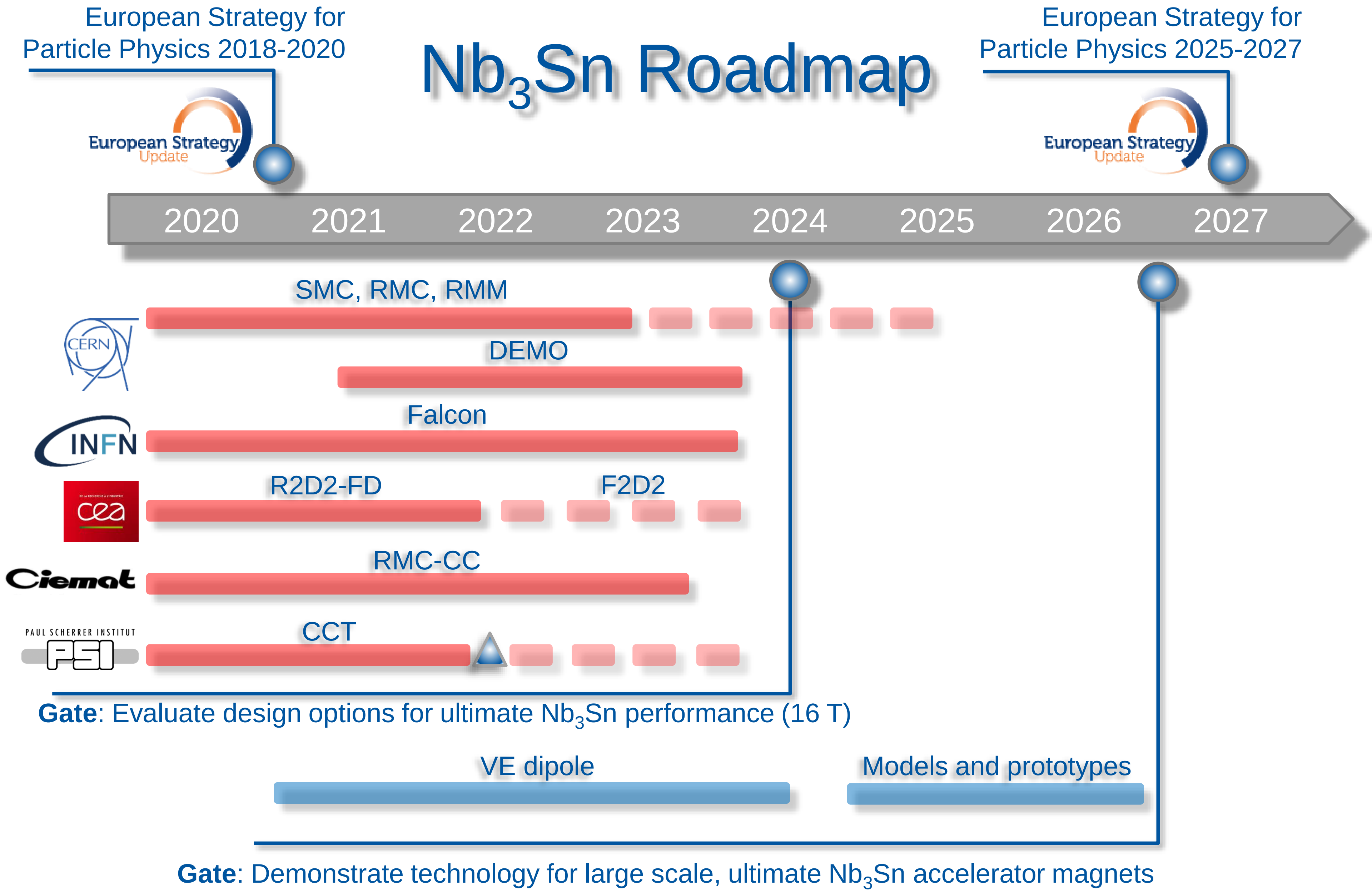
After 5 years – PROVISIONAL

- LTS program deliverables
  - Conductor R&D → HL-LHC Nb_3Sn at multiple suppliers, reduced cost. Superconductor with properties approaching FCC targets
  - Insulating materials R&D → Upgrade of the insulation scheme
  - Magnet technology R&D → An answer to basic questions on training, protection, and mechanics (SMC, eRMC, RMM). Model magnet results beyond HL-LHC (model magnet results) ready for *critical decision*
  - Accelerator magnet R&D → Engineering upgrade and optimization of design, methods, materials and tooling for large series production of long magnets, ready for long magnet prototyping
  - Infrastructure R&D → Workshops and a new very high-field test station
- HTS program deliverables
  - Conductor R&D → Consolidated development targets. Exploration of alternatives for materials and cables, and associated characterization
  - Coil and magnet technology R&D → exploration of basic design concepts. Coil and magnet fabrication technology. An answer to basic questions on suitability for accelerator operation (small coils, coil inserts, small models)
  - Demonstrator undulator ready for test in a beam line
- Review the High Field Magnet program at the end of this phase (Gate Review in 2024)

Nb$_3$Sn Roadmap



European Strategy for Particle Physics 2018-2020

European Strategy for Particle Physics 2025-2027

SMC, RMC, RMM

DEMO

Falcon

R2D2-FD

F2D2

RMC-CC

CCT

Gate: Evaluate design options for ultimate Nb$_3$Sn performance (16 T)

VE dipole

Models and prototypes

Gate: Demonstrate technology for large scale, ultimate Nb$_3$Sn accelerator magnets

We need to develop a similar roadmap for HTS

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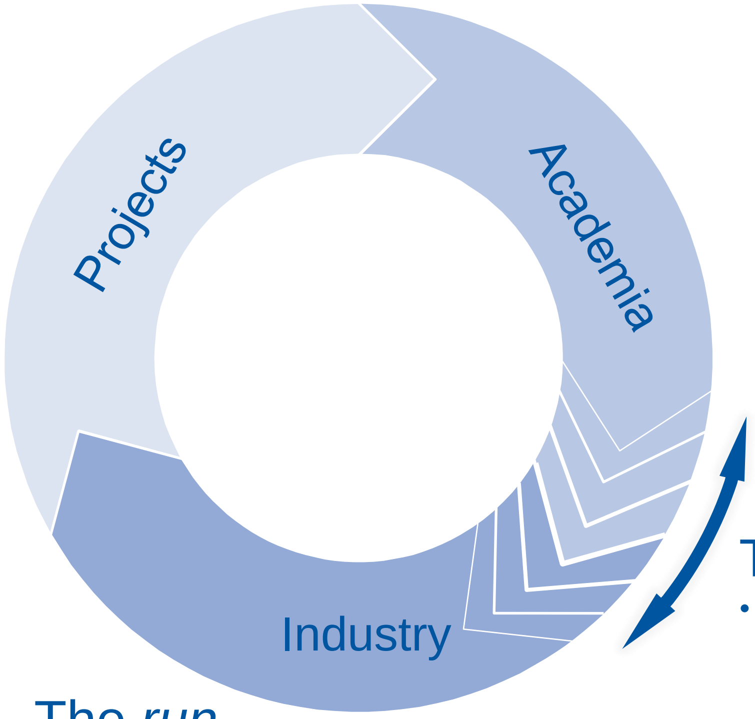
- Two main aims:
  - Exploit Nb_3Sn magnet technology up to its practical upper limit, both in terms of maximum performance (maximum field target 16 T) as well as scale (production in large series o(10^3) units)
  - Provide a proof-of-principle for HTS magnet technology beyond the reach of Nb_3Sn, with a target of 20 T dipole field, and sufficient field quality for accelerator application
- The program targets to reach critical results for the *next season* of the European Strategy for Particle Physics (2025-2027)
- It will be highly beneficial to integrate programs into a joint High Field Magnet Development Plan

Here Be Dragons

The “Virtuous Circle” of SC R&D



The *pull*

- Set the performance targets for the specific project
- Provide a finite time scale, quantity and budget for the realization
- Exploit the technology in the scope of the specific project

The *scout*

- Search for the materials that have the potential to meet the performance targets
- Perform material R&D and characterization

The *bridge*

- Overlap between the fields of academia (material research) and industry (large scale production)
- **Demonstrate the viability of the technology on a small scale**

The *run*

- Adopt and **adapt the technology for scaling-up to production needs**
- Produce as from the project demands
- Exploit the opportunities and alternative applications

Future Needs of SC materials

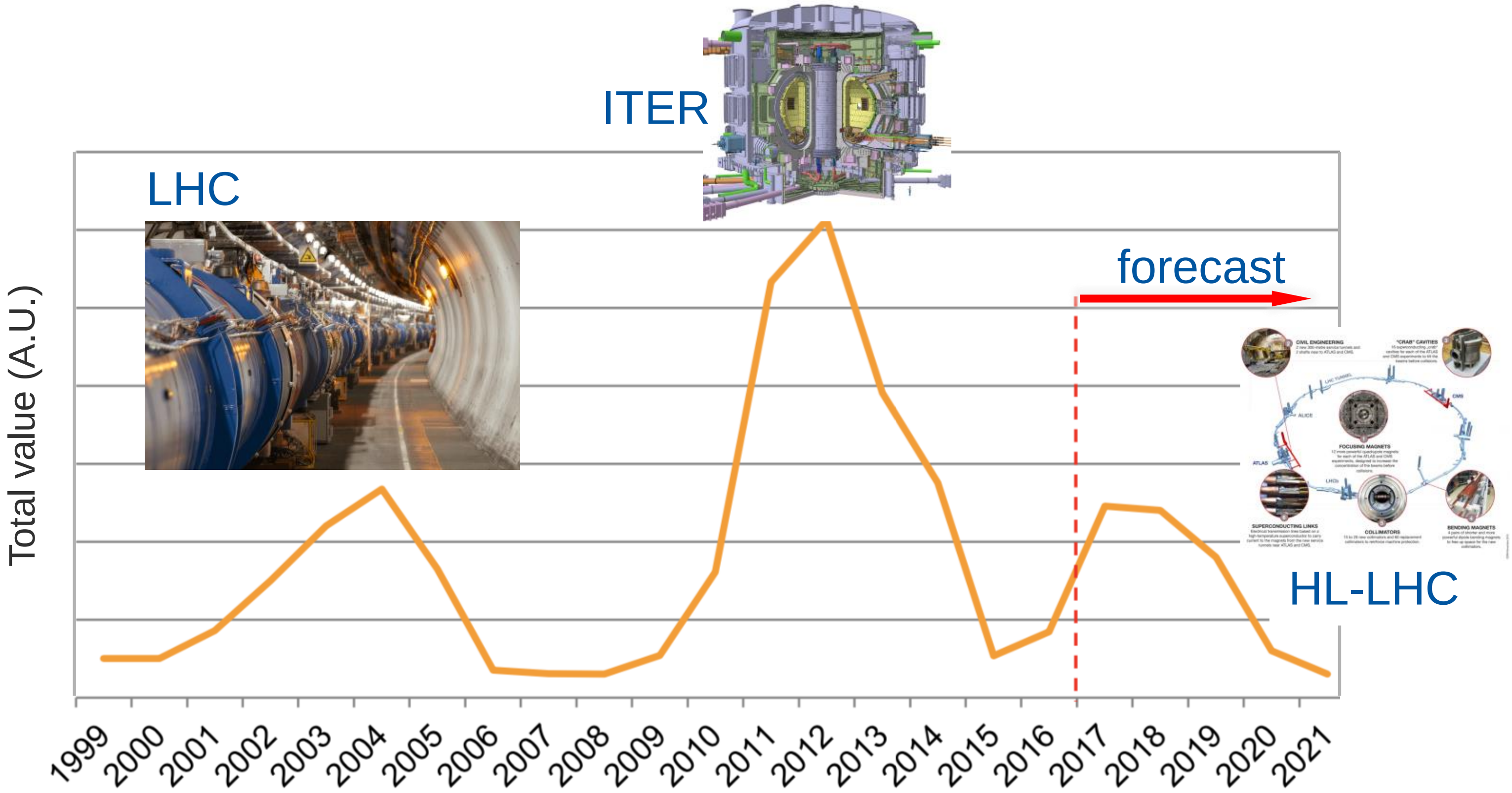
- Realize **ultimate performance in Nb_3Sn**, as it has been specified for the main magnets of a Future Circular Collider in a new (FCC) or existing (HE-LHC) tunnel
- Demonstrate the **potential of HTS** materials to complement and possibly surpass LTS accelerator magnet technology, providing efficient very-high-field or high operating margin options for specific locations in existing and future colliders, and eventually extending the energy reach of circular synchrotrons
- **Preserve our accelerators** in the long-term, including LHC and HL-LHC

The SC landscape today

- Expertise and IP on superconducting wires and tapes is essentially localized in industry
- The industry of superconductors produces
  - LTS for MRI, NMR and science as a *commodity*: highly competitive, under pressure for continuous cost-reduction, relatively small profit margins
  - Advanced superconductors, LTS and HTS as a *niche*: small production volume, material cost negligible, wires/tapes sold under cost, highly subsidized to support operations
  - Big Science (e.g. LHC and ITER) as *one-off*: these productions call for specific arrangements, fast production scaling up, and are often followed by dramatic consolidation among suppliers
- The market of advanced superconductors is not sustainable (missing *killer application*), and industry is no longer willing to pay material R&D (superconductivity is no longer a *high-tech jewel* as it was the case 30-50 years ago)
- Academia is attracted by fundamental physics (e.g. "*anomalous electronic properties"* rather than "superconductivity"), not by metallurgy
- The virtuous circle is broken, **a gap has formed between academia and industry**(1). In practice we witness
  - High volatility of scientific engagements, results and prices
  - Loss of general knowledge, specific IP and technology of relevance for HEP (e.g. recent examples of PIT Nb_3Sn, BSCCO powders and wires, Rutherford cables)

(1) China may represent an exception, in that government has promoted a new supplier to fulfill the in-kind superconductor contribution to ITER, and is now moving aggressively into the commercial market while maintaining a very high level of R&D.

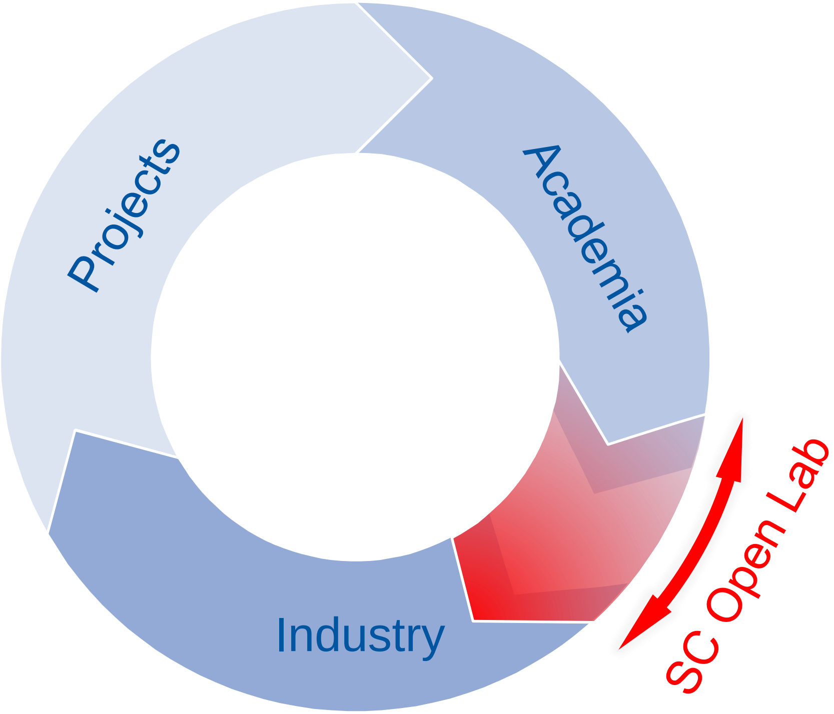
Comments on the present SC landscape



Superconductivity for Big Science
is **not an attractive market**

https://indico.cern.ch/event/765096/contributions/3295748/

The response: SC Open Lab

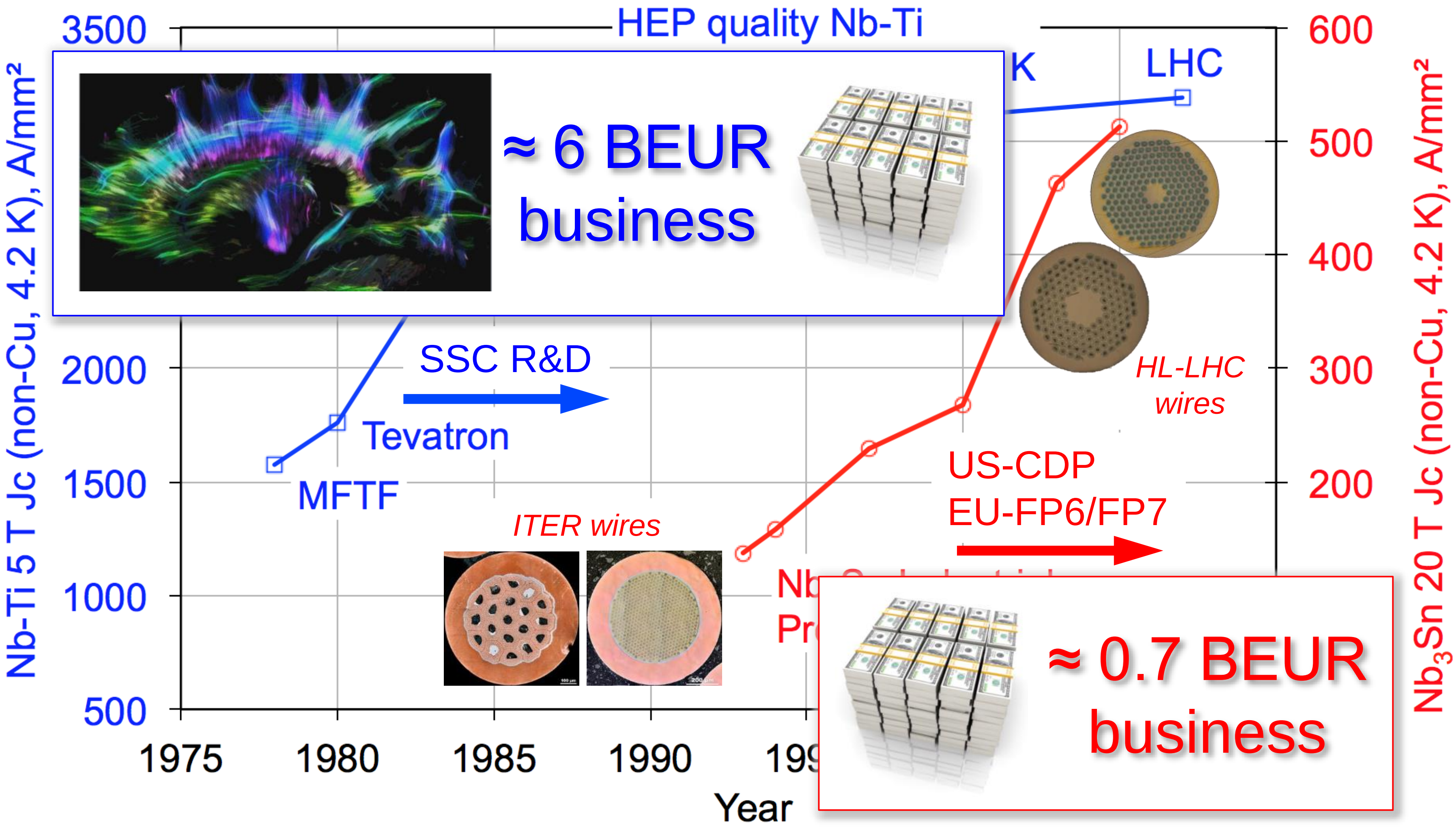


The *bridge*

An *open laboratory* for R&D on applied superconductivity

- Research and development of technical superconductors (LTS and HTS) and cables
- Demonstration on a small scale (10…100 m) of the viability of a technology, in view of the extrapolation to an industrial production
- Secure on the long term the intellectual property and the expertise required for a production on large scale (*SC production kit*)

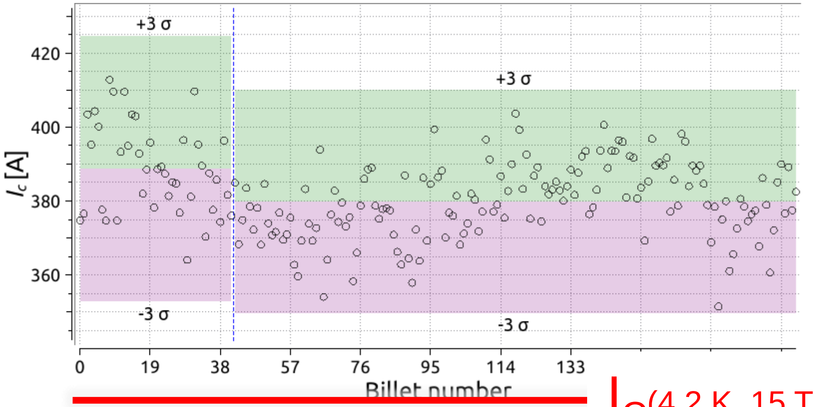
On the unreasonable request of high J_C



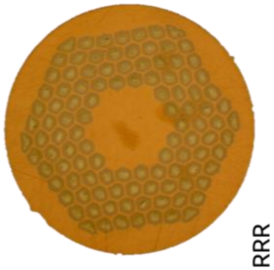
≈ 6 BEUR business

≈ 0.7 BEUR business

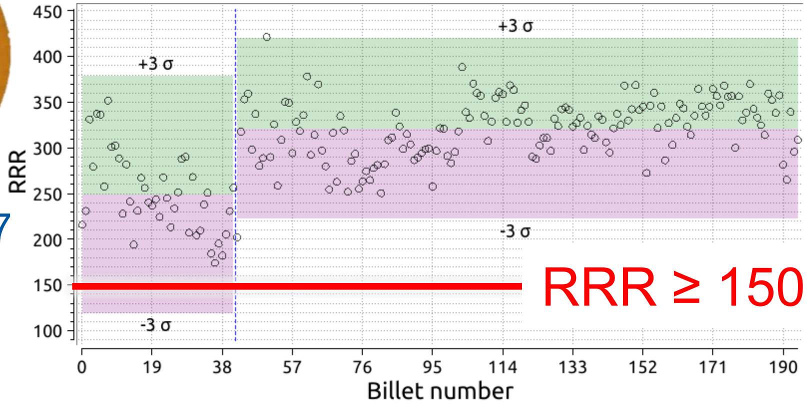
HL-LHC wires and cables



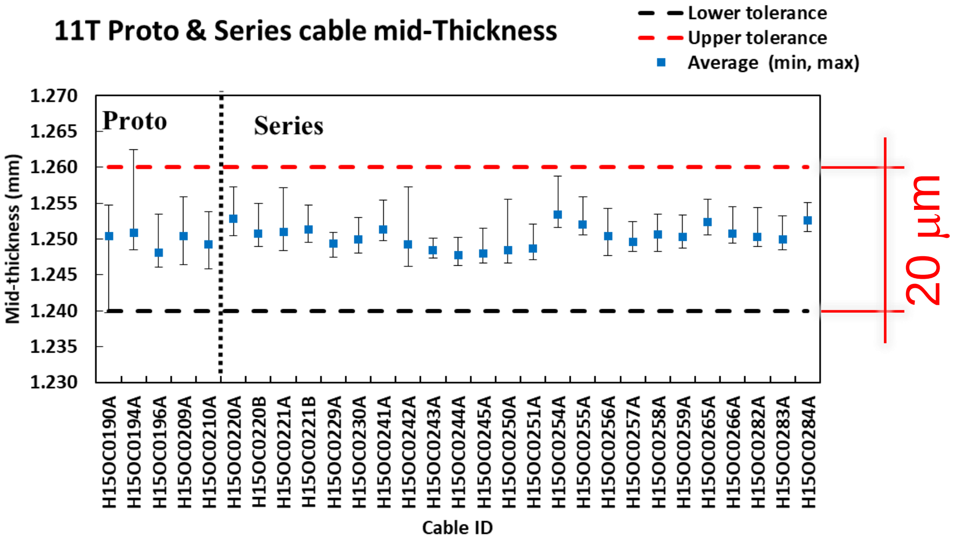
I_C(4.2 K, 15 T) ≥ 331 A



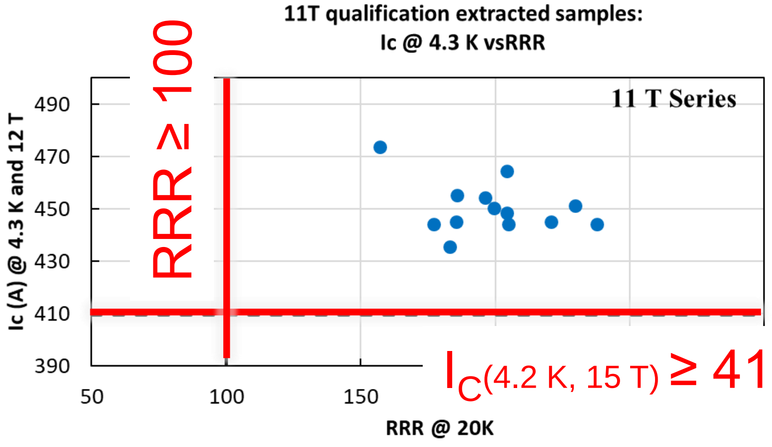
RRP 108/127



RRR ≥ 150



11T Proto & Series cable mid-Thickness

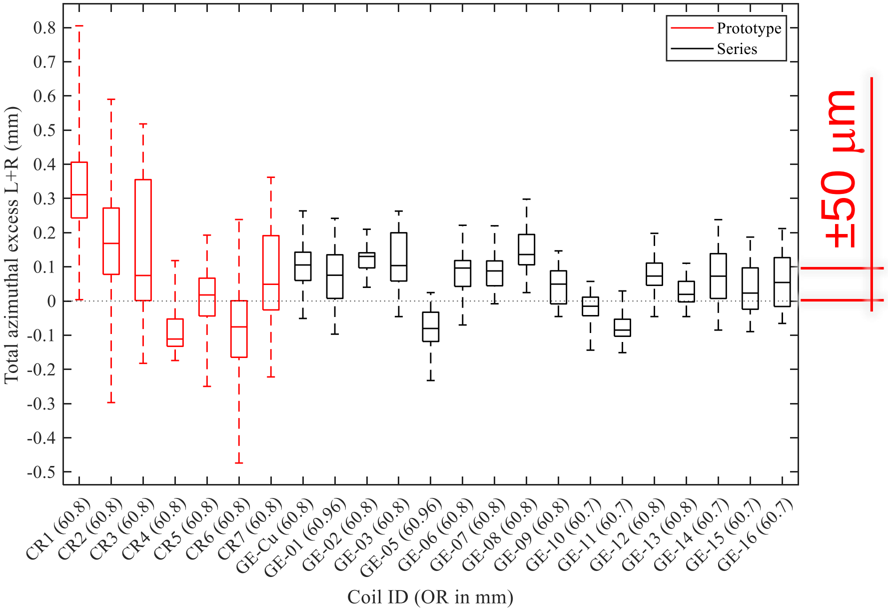


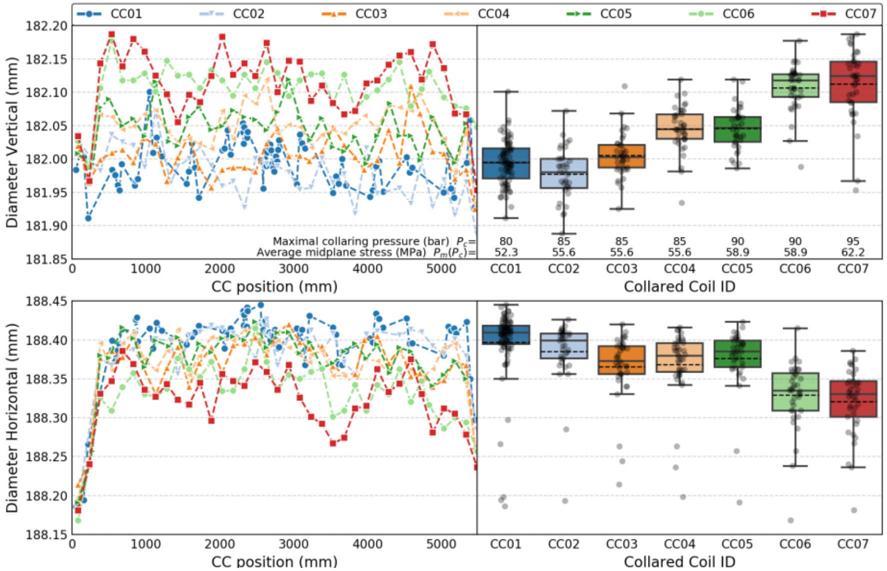
11T qualification extracted samples:
Ic @ 4.3 K vsRRR

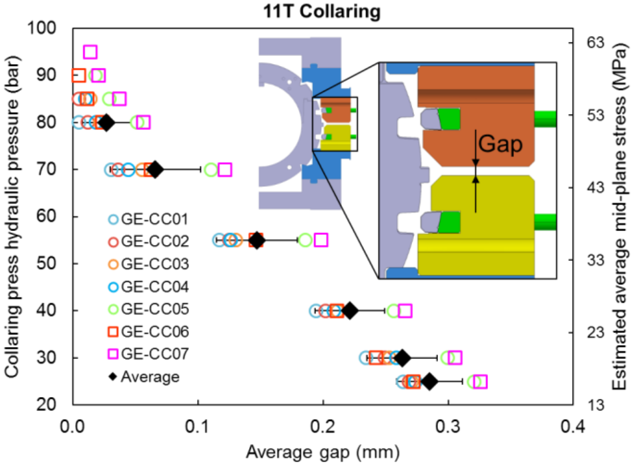
I_C(4.2 K, 15 T) ≥ 410 A

This is an industrial production !

11T collared coils

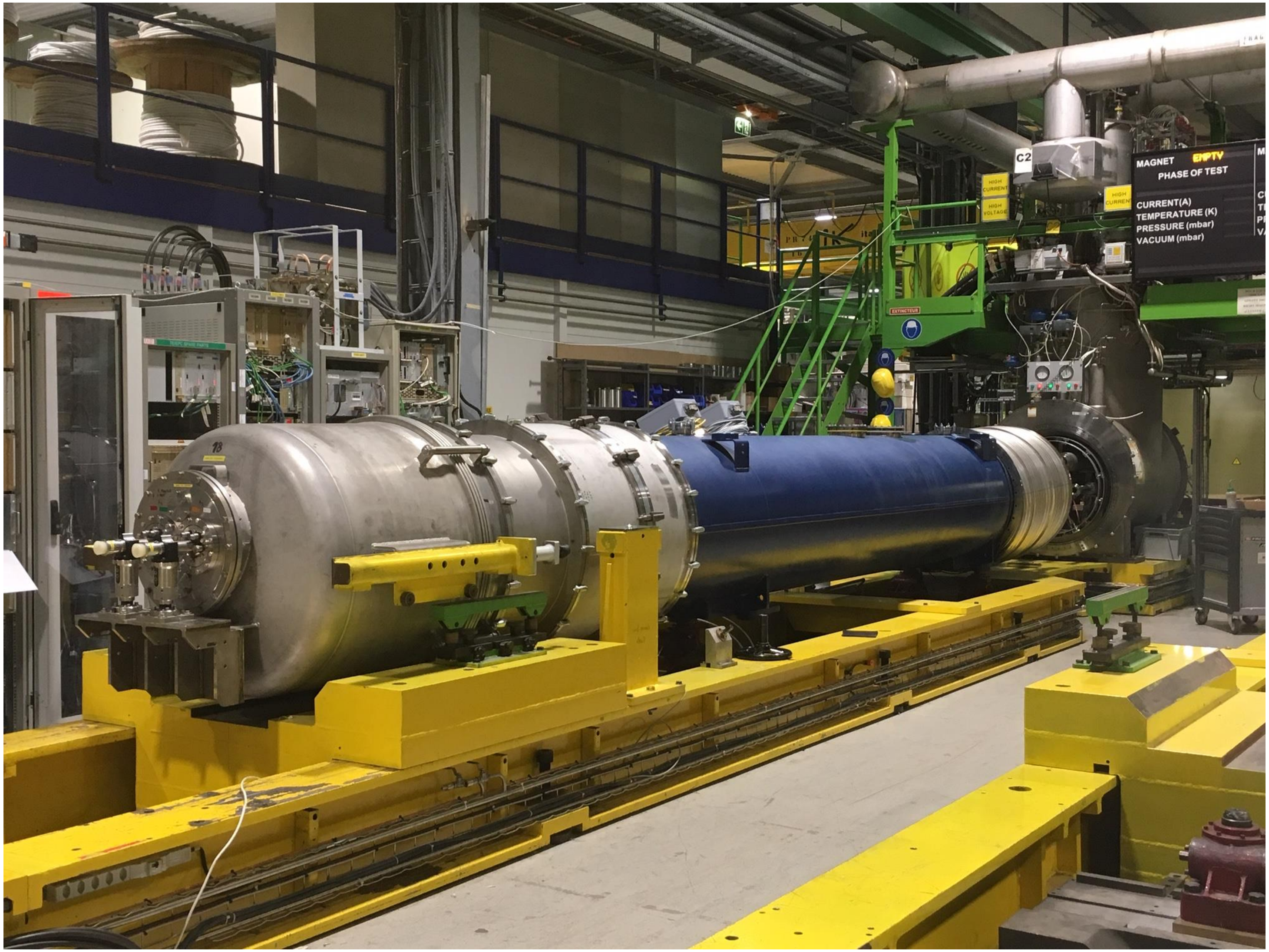




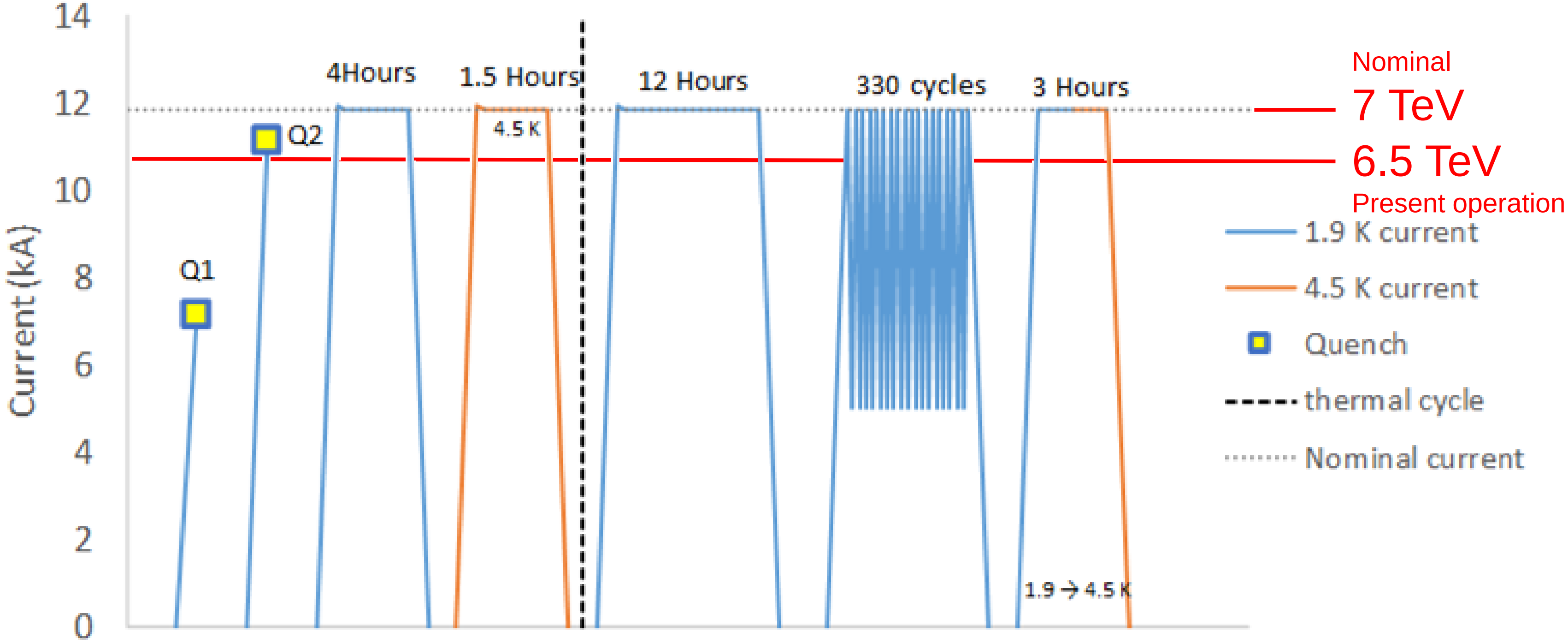


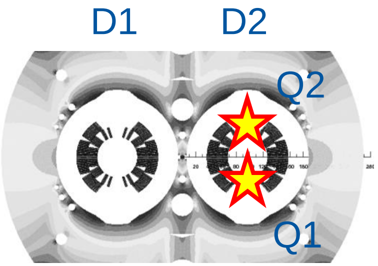
This is an industrial production !

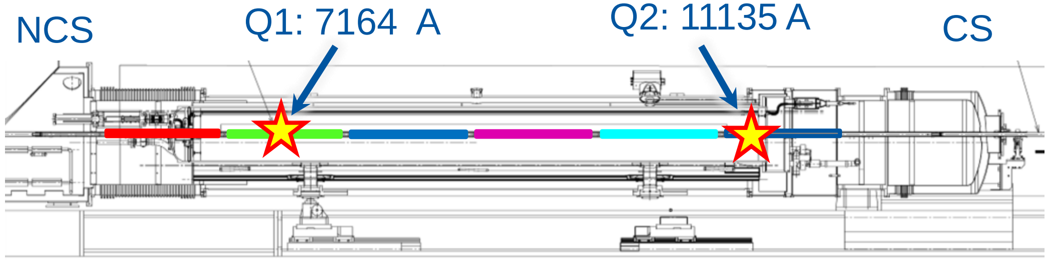
LMBHB0002


C2
HIGH CURRENT
HIGH VOLTAGE
MAGNET EMPTY
PHASE OF TEST
CURRENT(A)
TEMPERATURE (K)
PRESSURE (mbar)
VACUUM (mbar)

LMBHB002 powering tests


MBHB-002 Summary of quenches, endurance tests and cyclic loading

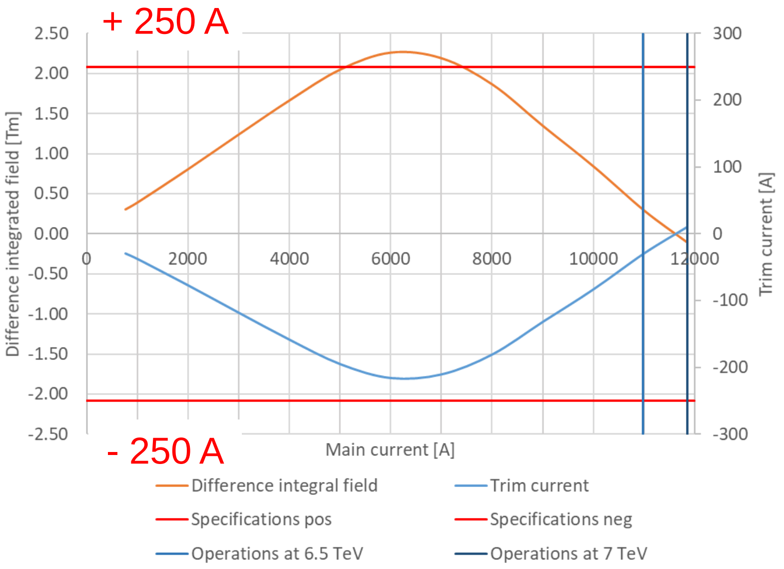




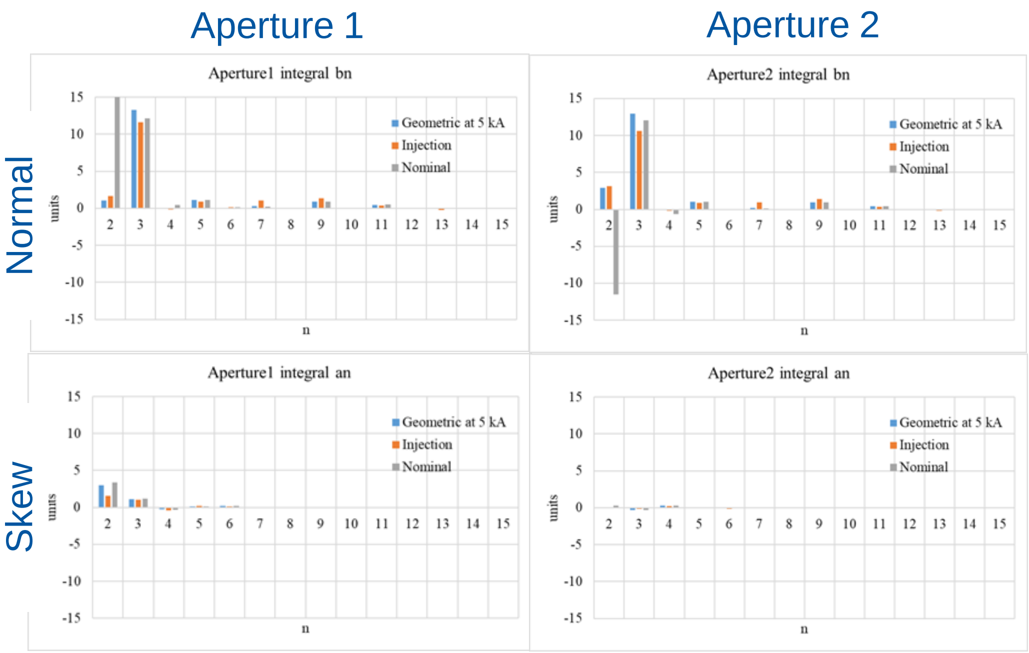
This is an accelerator worthy dipole !

LMBHB002 Field Quality

Transfer Function difference MB vs. MBH



Geometric Multipoles (@17 mm)



A trim current is injected in the 11 T dipole circuit to match LHC dipole transfer function (based on average of integral field measurements for the 2 apertures)

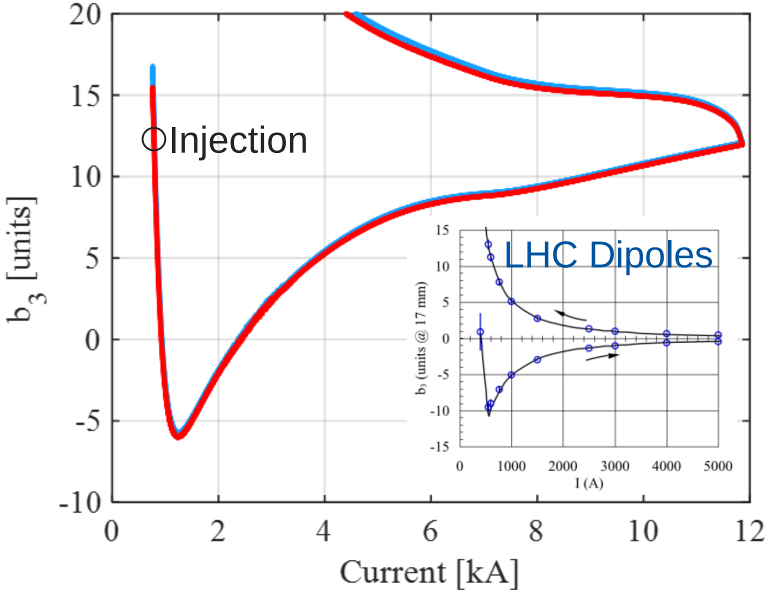
b_2 (normal quadrupole) arises from iron saturation and is as expected (~±14 u);

b_3 (normal sextupole) is a bit larger than expected (~7 u).

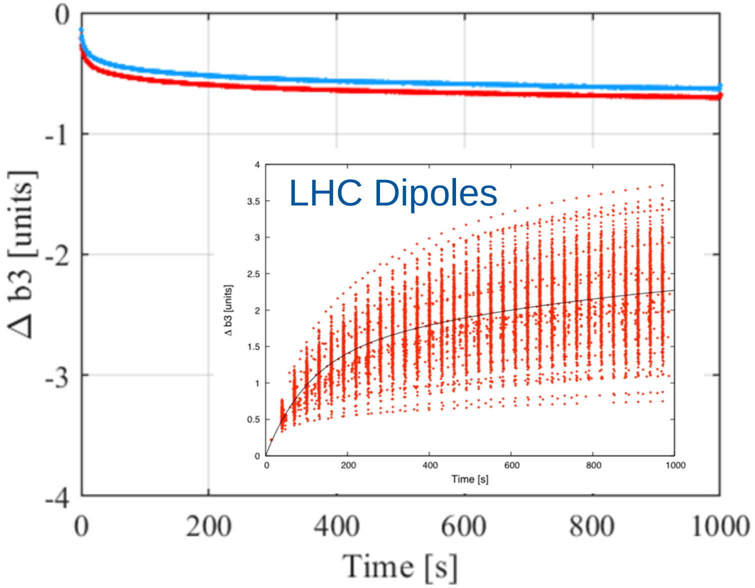
This is an accelerator worthy dipole !

LMBHB002 Field Quality

Persistent Magnetization Currents
(2^{nd} cycle, both apertures)



Time decay at Injection (760 A)



The injection current is on the "wrong side" of the peak of persistent current sextupole due to the inherent magnetic moment of the SC filaments (approximately 50 μm diameter), and ≈ 2.5 times larger than in the LHC Nb-Ti dipoles

b_3 time decay at injection is "reversed" due to the initial point, and relatively small when compared to the LHC Nb-Ti dipoles

This is an accelerator worthy dipole !

Ultimate Nb_3Sn HF dipole

- Objective: Explore conductor and magnet technology at the upper limit of Nb_3Sn (LTS) with a projected upper target of 16 T
- Scope: Produce accelerator-relevant short models as technology demonstrators, in connection with progression in basic R&D (conductor and cable, SMC, RMC, RMM,…)
- Time scale: 2020…2024

R&D themes: 1, 2, 3, 8

Value engineered HF dipole

- Objective: Develop cost-effective design features and robust manufacturing processes that apply to large scale production (10^3 magnets) of high-field accelerator magnets, *securing* the field range achieved with HL-LHC
- Scope: Study engineering processes and solutions. Demonstrate initially at small scale (e.g. SMC). Progress to scale increase, from models to long prototypes
- Time scale: 2020…2027

R&D themes: 1, 2, 3, 6, 8

HTS HF magnets

- Objective: Explore conductor and magnet technology at field beyond Nb_3Sn, using HTS, with a projected upper target of 20 T for dipoles (and equivalent for other magnets)
- Scope: Demonstrators are small coils and high-field inserts to be tested in background facilities, relatively small amount of HTS
- Time scale: 2020…2024

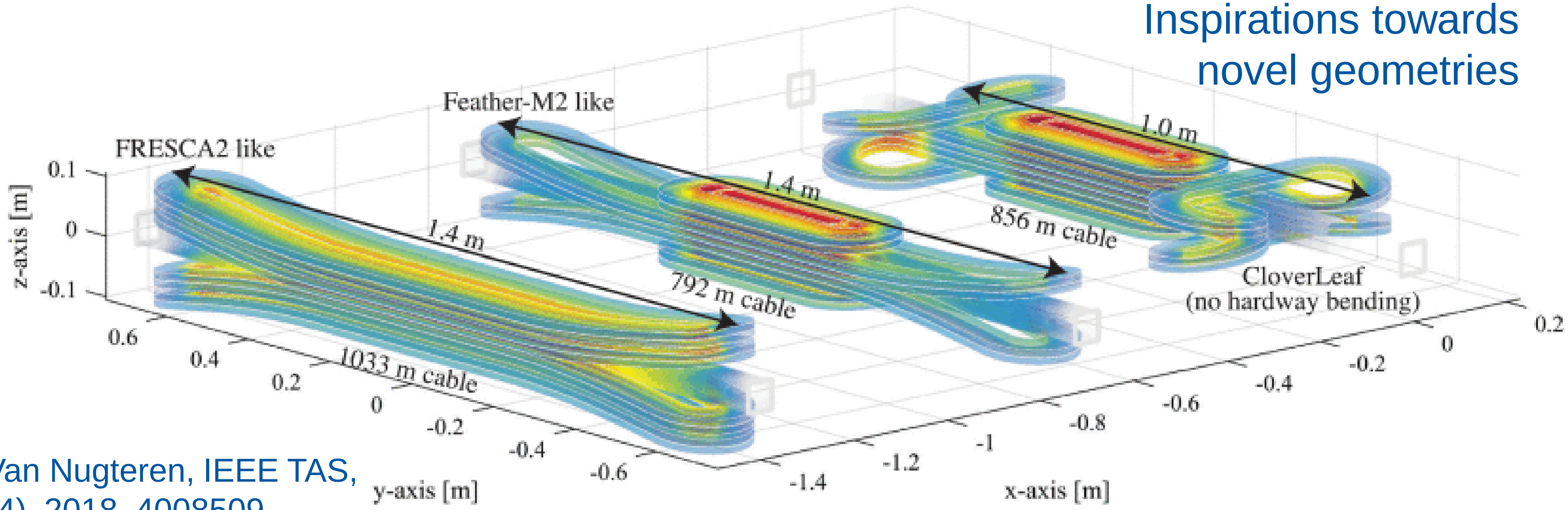
Very High Field Test Facility

- Objective: a new test bed, mostly dedicated to HTS cables and inserts, approaching operating conditions of very high-field accelerator magnets
  - $B_{bkg} \approx 15$ T
  - $I_{op} > 20$ kA
  - $T_{op} \approx 1.9$ K … 100 K
  - Large aperture (≈ 150 mm)
- Scope: conductor procurement and magnet construction, this project materializes the R&D on the ultimate Nb_3Sn dipole
- Time scale: 2021…2025

R&D themes: 2, 3, 5, 8

The HTS models

- Specific issues (e.g. winding geometry, field quality, …) may require to realize small magnets with aperture and intermediate field (range of 5 to 10 T)
- Given the charting nature of this R&D, it is important to approach problems gradually, especially in terms of force and energy density
- This is best achieved testing at variable temperature



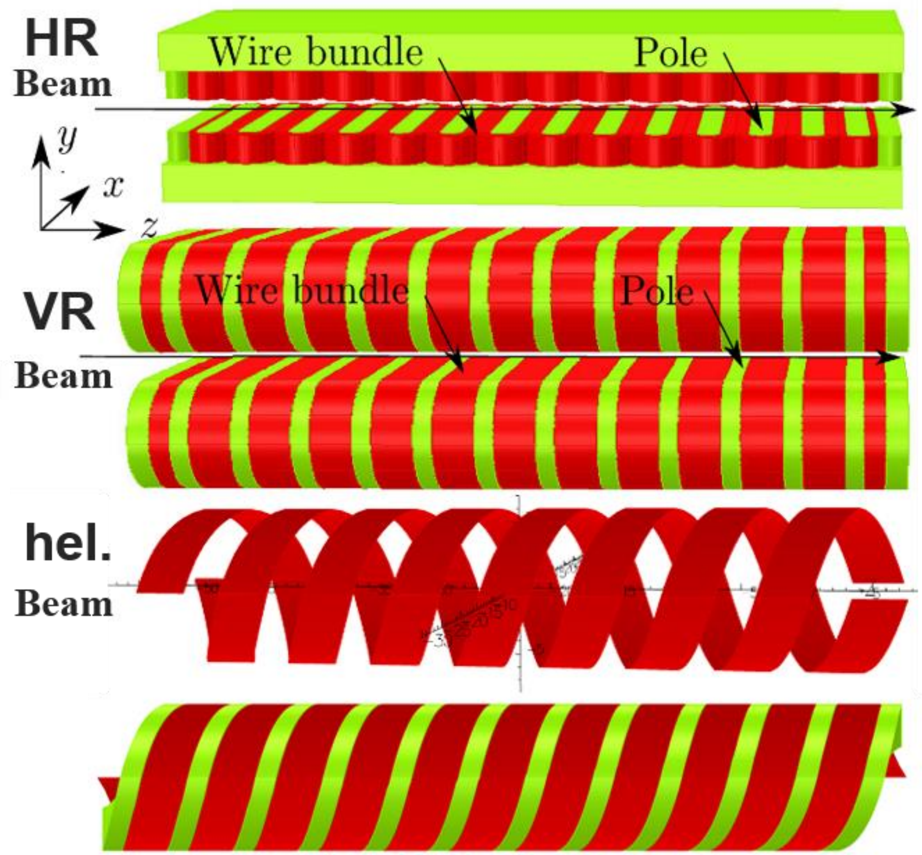
Inspirations towards novel geometries

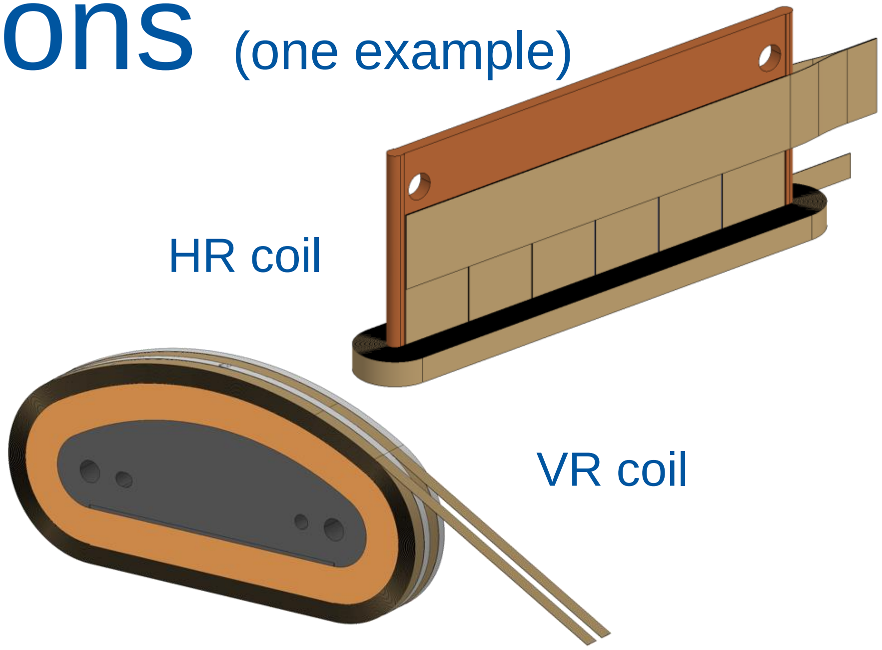
J. Van Nugteren, IEEE TAS, 28(4), 2018, 4008509

HTS wiggler/undulator

- Objective: design and prototype a HTS wiggler/undulator with a combination of field/period/gap that cannot be achieved by LTS
- Scope: design a wiggler/undulator demonstrator for a test in a beam line (synchrotron light source or free electron laser). This project materializes the R&D on the HTS dipole
- Time scale: 2019…2024

The demonstrations (one example)

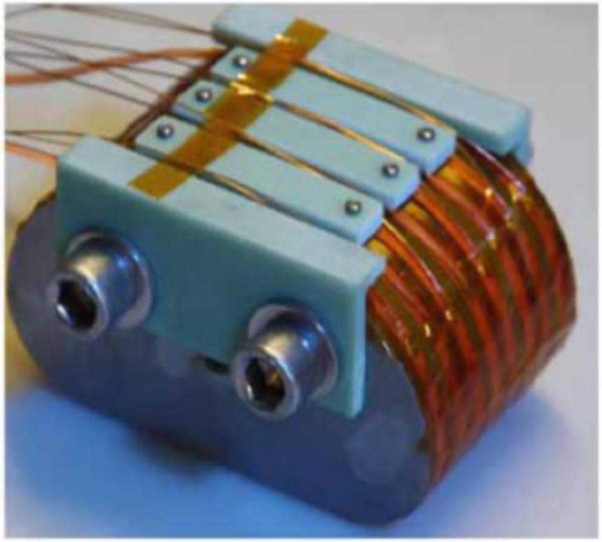




HR coil

VR coil

HTSCU H2020 Proposal
$B_{gap} \approx 3$ T
Gap ≈ 15 mm



C. Boffo
IDMAX10

This is the right scale for a beam test !

R&D Plan Overview – 1

1. Nb_3Sn Conductors

- Bring multiple suppliers to HL-LHC performances (2022), aim at stable production and reduced cost w/r to HL-LHC;

- Support development towards 1500 A/mm^2 at 4.2 K and 16 T (2024), including through SC Open Laboratory initiative;

- Initiate and support parallel R&D efforts on cabling and cabling degradation (2022-2024).

2. Nb_3Sn Magnet Technology

- Consolidate technology development program and carry out value engineering effort to bring Nb_3Sn accelerator magnet technology to full maturity and enable industrialization (2020-2024);

- Build model dipoles at increasing performances (up to 16 T) devoted at exploring design variants (2020-2024);

- Build a sequence of model dipoles aiming at optimization and proof of reproducibility (2024-2027).

3. Nb_3Sn Accelerator Magnet

- Introduce engineering solutions for risk- and cost-reduction, robust production on a large scale, and *secure* the field range achieved with HL-LHC (11 T to 12 T; 2020-2024)

- Initiate construction of long prototypes (2024-2027)

R&D Plan Overview – 2

4. Non-LTS Conductors and HTS Coil/Magnet Technology

- Review and consolidate engineering specifications for HTS development (2020) and support development of non-LTS conductors;
- define and initiate HTS technology development program (2020);
- explore potential of HTS through small coils and inserts aiming at boosting field (3 T to 7 T) in a background magnet (13 T to 15 T) (2020-2025).

5. Special HEP Magnets and Know-How Valorisation

- special magnets for future HEP projects: *e.g.*, FCC e-e, CLIC, wigglers, spectrometers;
- valorize Nb_3Sn know-how by supporting other high-field applications: *e.g.*, 14 T MRI;
- valorise development of Medium Temperature Superconductors (MgB_2 or HTS) by exploring new potential applications: *e.g.*, large super-ferric magnets (2020-2030);
- valorize SC magnet know-how by supporting new medical applications and HTS undulators;
- networking with magnet community and industry.

R&D Plan Overview – 3

6. Infrastructures

- maintenance/upgrade of large manufacturing and test infrastructures.

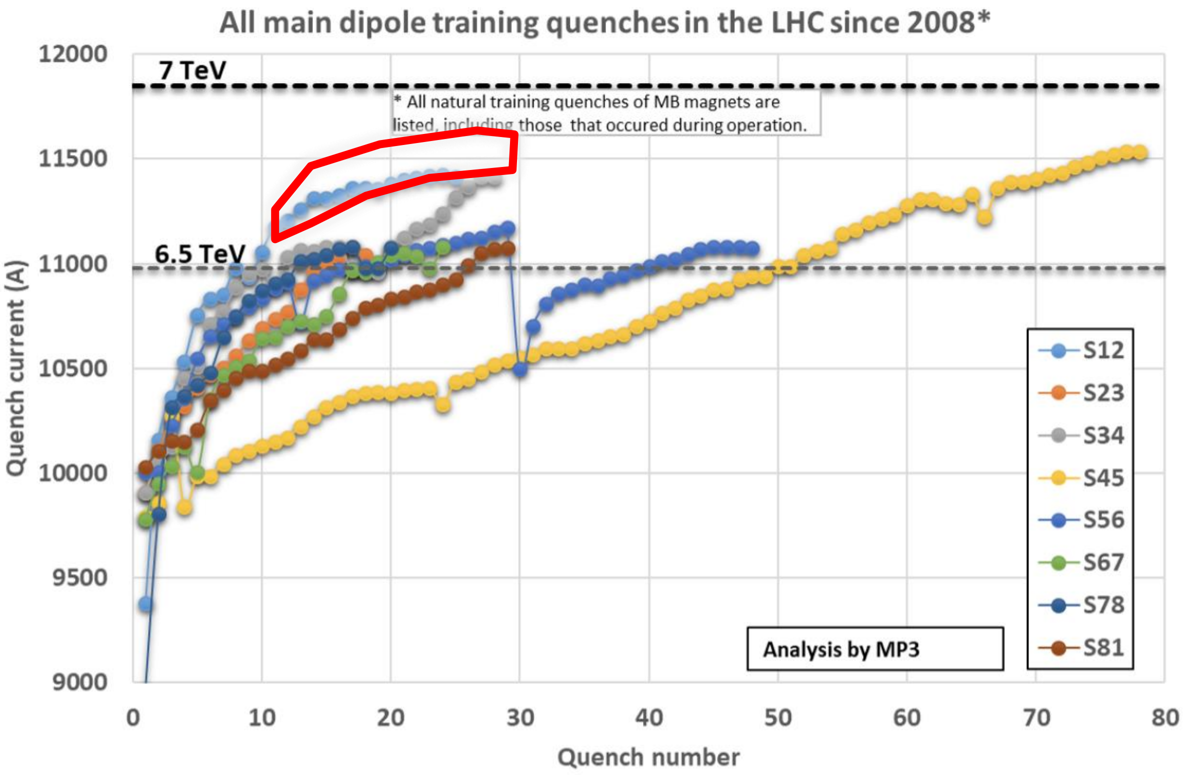
7. Instruments, design & analysis software tools and databases

- develop/upgrade specific instruments for qualification, quality control and testing;
- maintain/consolidate/develop suites of software tools and databases used for design, analysis, data acquisition, data storage and production follow up.

8. Polymers & radiation hard materials and cryostat components

- develop and qualify polymers and radiation hard materials for magnets and other applications at CERN;
- develop and qualify designs and materials for seals, feedthroughs and multilayer insulation.

On training – example of LHC



All main dipole training quenches in the LHC since 2008*

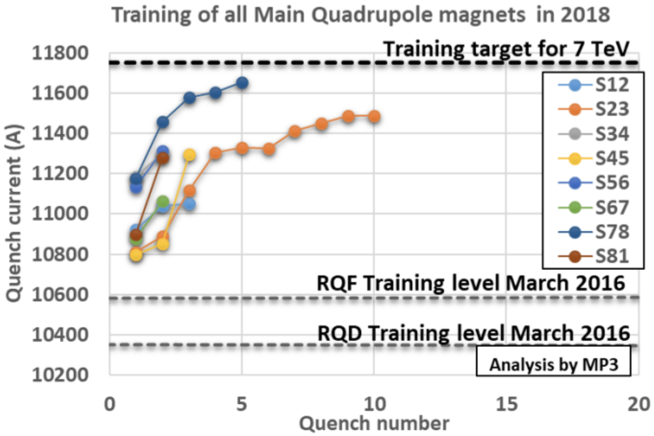
* All natural training quenches of MB magnets are listed, including those that occured during operation.

Analysis by MP3

Sector 12 training (end 2018)

- Series 1000: 8 quenches
- Series 2000: 2 quenches
- Series 3000: 5 quenches

Quadrupole training is ”faster” relatively rapidly the current corresponding to 7 TeV

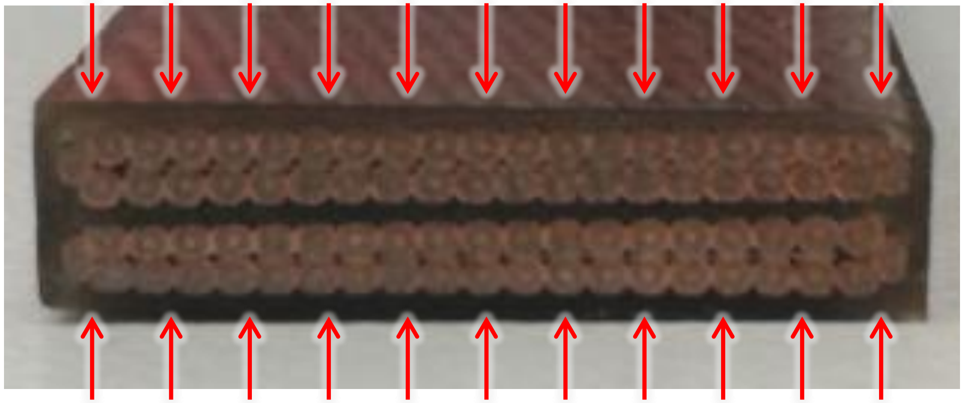


Training of all Main Quadrupole magnets in 2018

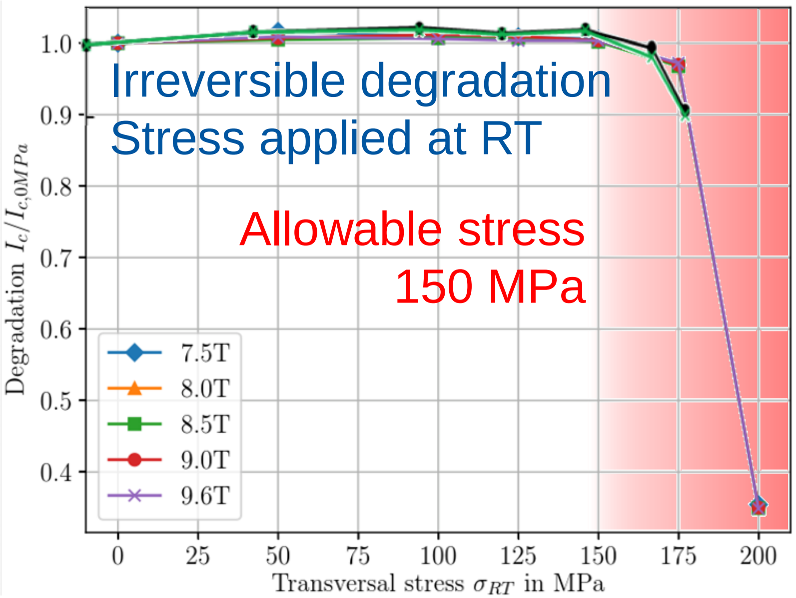
Analysis by MP3

Surprising ! previous statistics indicated a faster sector training. Still, no limits to 7 TeV, but time will be needed for training !

On Nb_3Sn limits



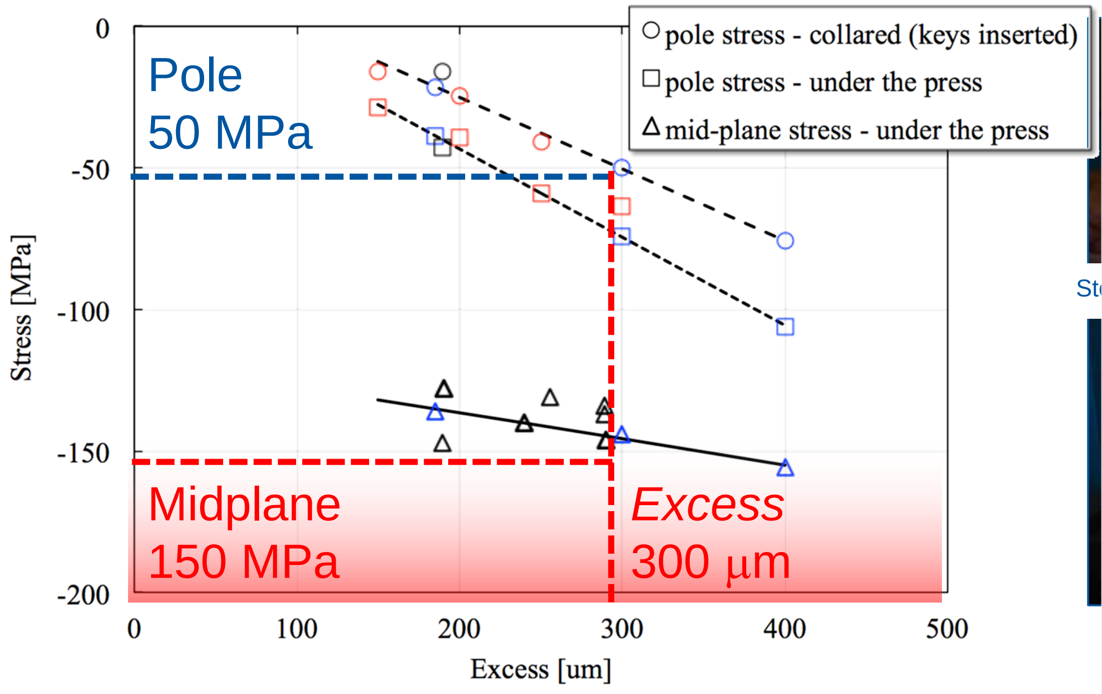
Nb_3Sn is brittle and extremely fragile

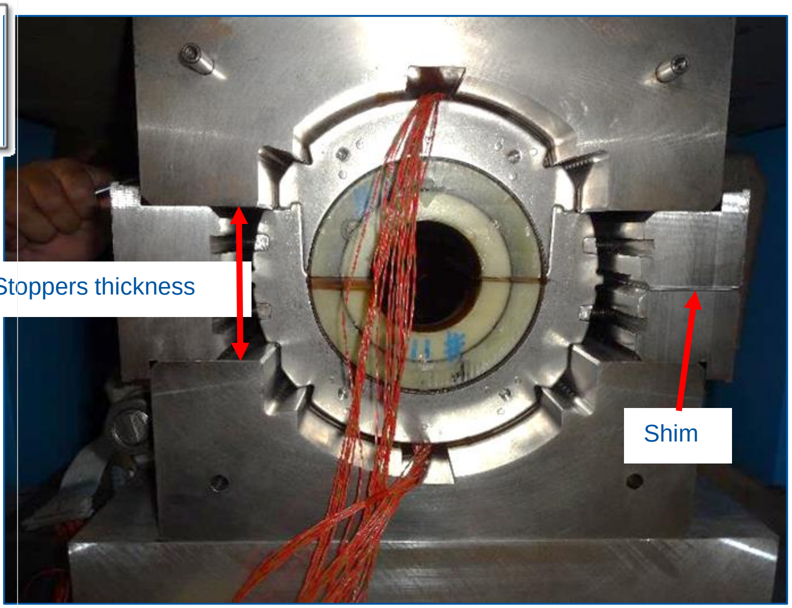


Irreversible degradation
Stress applied at RT

Allowable stress
150 MPa

On collaring – 11T

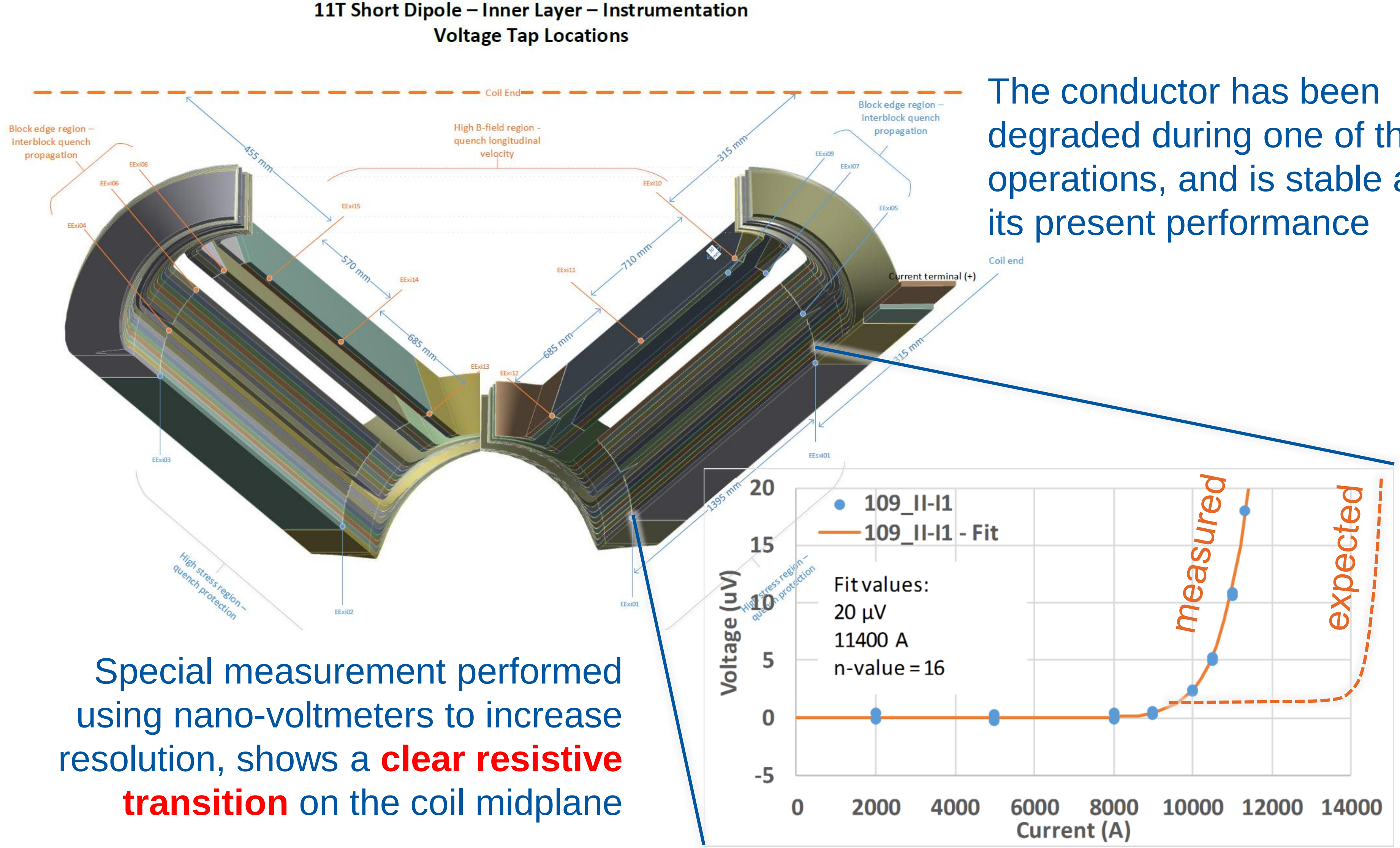




- A maximum excess of 300 μm is allowed
- This target has been applied for the collaring operations of SP107, SP109, and GE02/GE03

On conductor limits in magnets

The conductor has been degraded during one of the operations, and is stable at its present performance

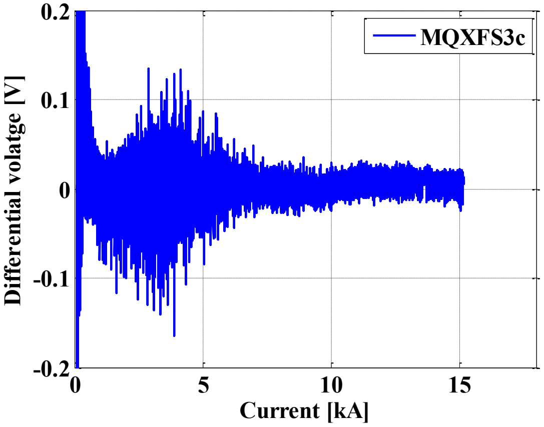


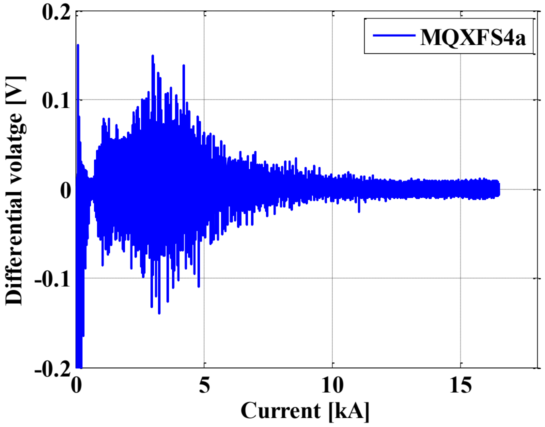
11T Short Dipole – Inner Layer – Instrumentation
Voltage Tap Locations

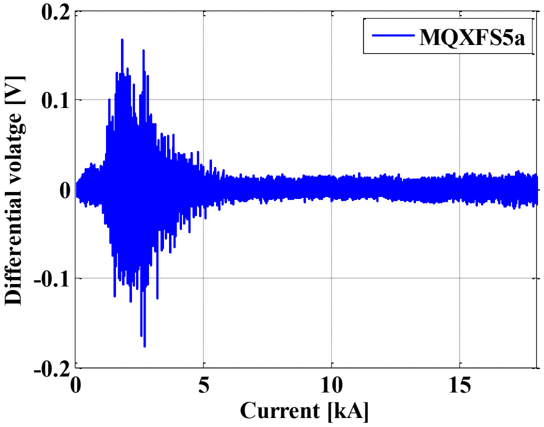
Special measurement performed using nano-voltmeters to increase resolution, shows a **clear resistive transition** on the coil midplane

Flux jumps in Nb_3Sn magnets

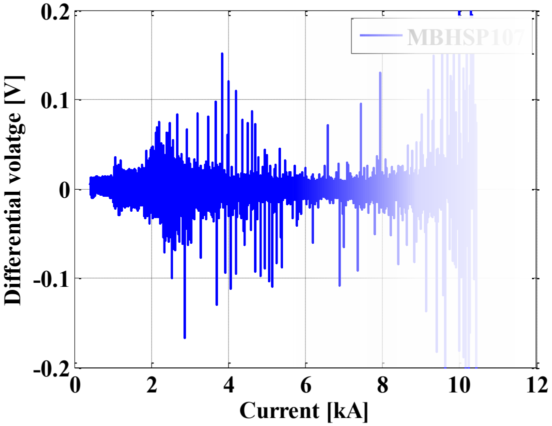
MQXFS (1.5 m)

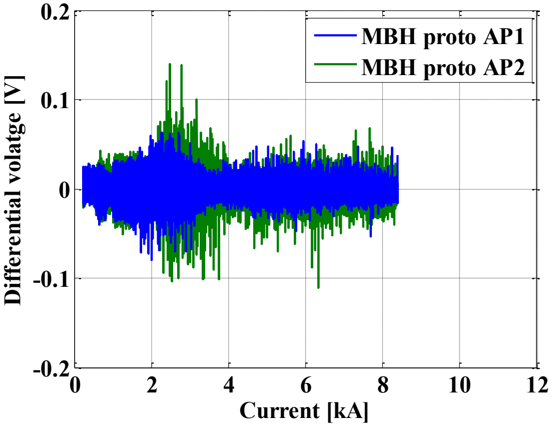






MBH 11 T (1.8 m and 5 m)





Similar behavior on Nb_3Sn magnets tested at CERN to date

- Amplitude <150 mV
- Mainly at low or intermediate field
- From the data collected up to now we see same amplitude on MBH full-length proto