Shaping a new generation of high field magnets for future accelerators at CERN

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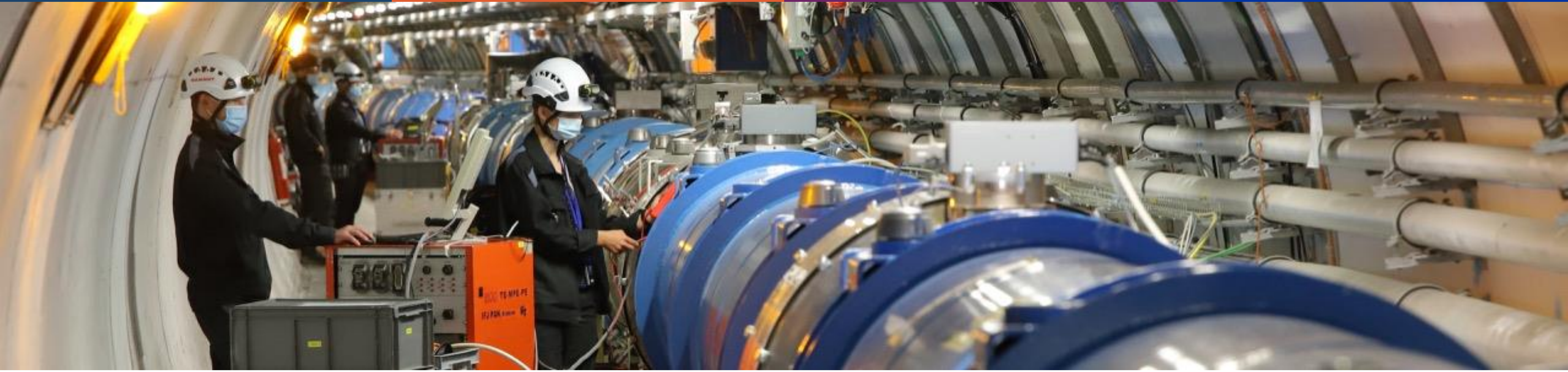
Outline

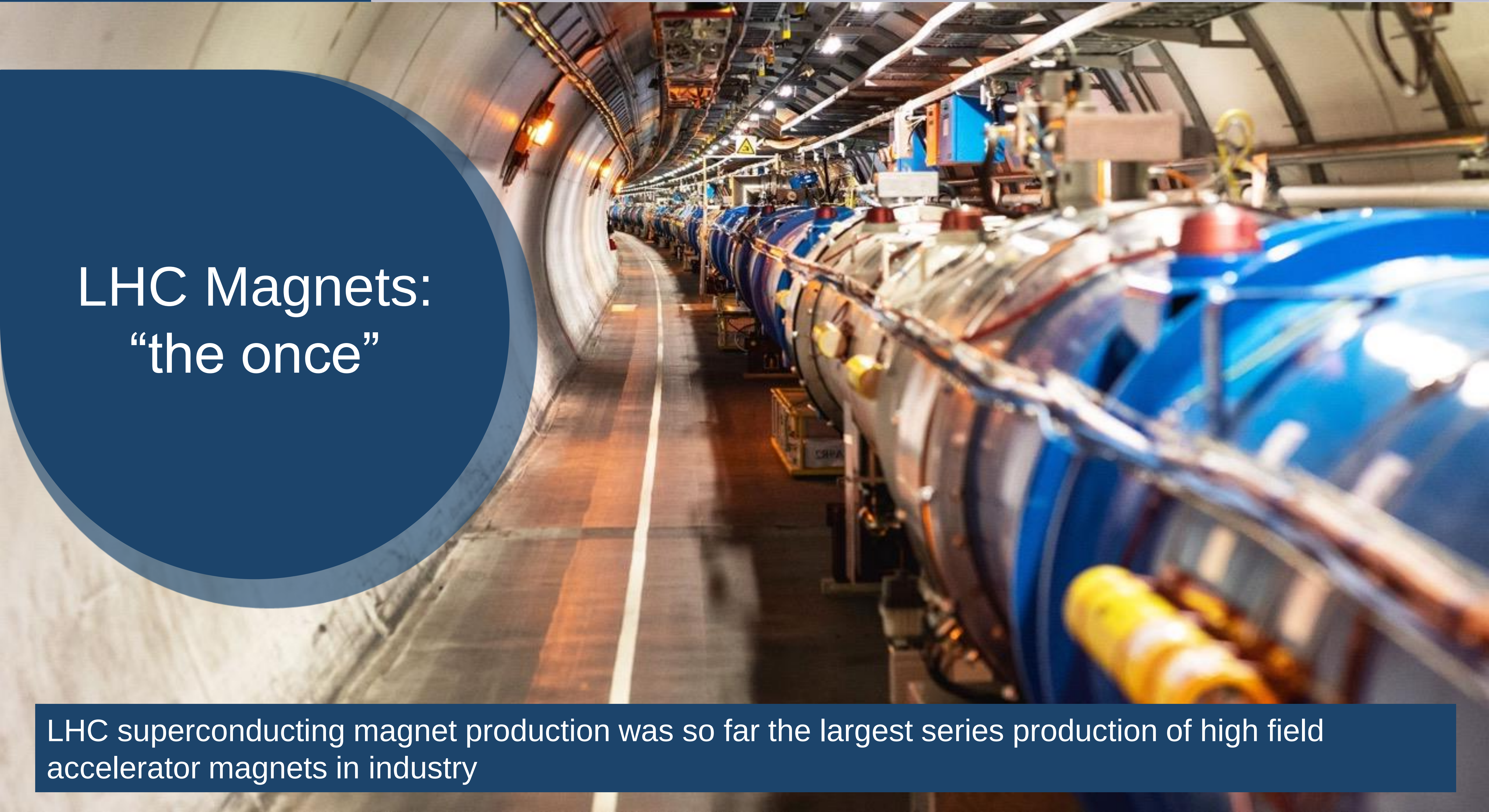
- LHC Magnets: “the once”
- HL-LHC Magnets: “the present”
- Post-LHC Magnets: “the future”
- Selected latest developments
- Final Remarks



Motto:

Pessimists do not move new challenges forward, optimists usually do it !!

LHC Magnets: “the once”

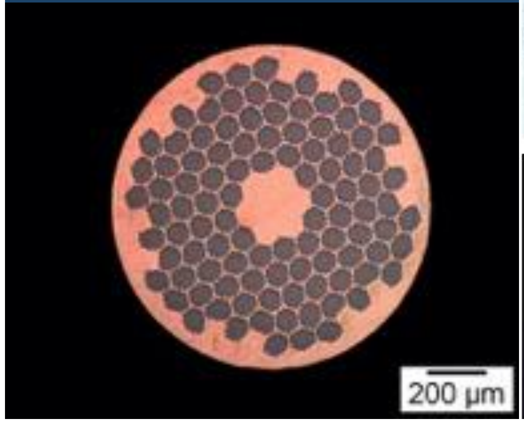


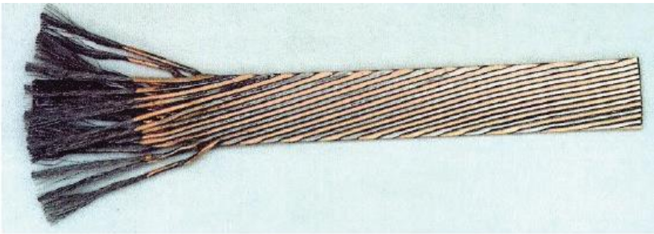
LHC superconducting magnet production was so far the largest series production of high field accelerator magnets in industry

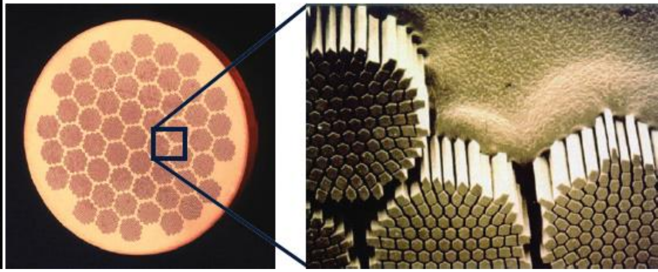
The success story of the LHC Nb-Ti cable production

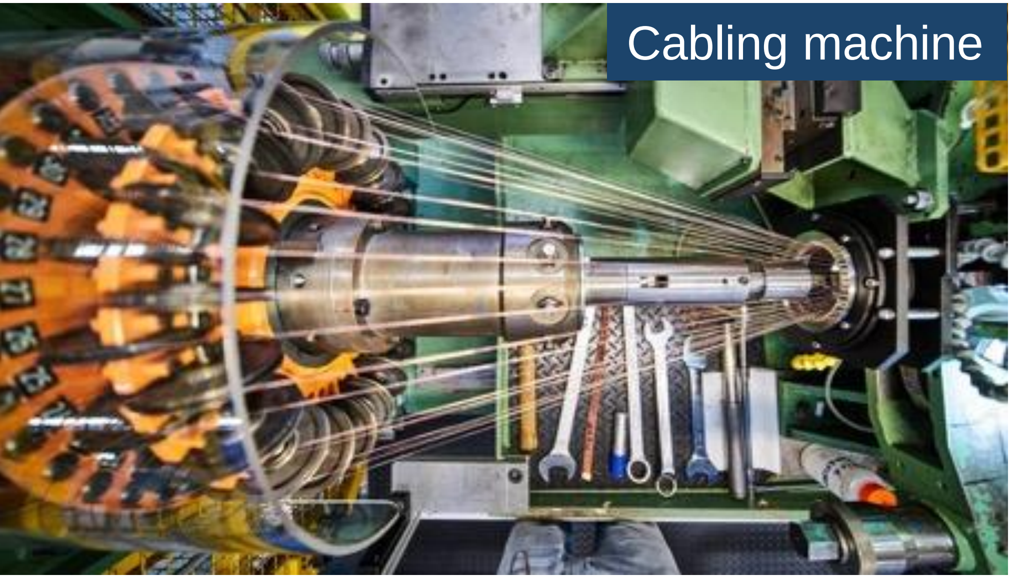
- Worldwide effort to produce the LHC Cu/Nb-Ti superconducting Rutherford cables
  - ~1200 tons of Nb-Ti alloy
  - ~250000 km of Nb-Ti strands
  - ~7600 km of Rutherford cables
- The LHC Nb-Ti wires and cables are up to the present time the state-of-the Nb-Ti superconductors

Nb-Ti LHC Type1

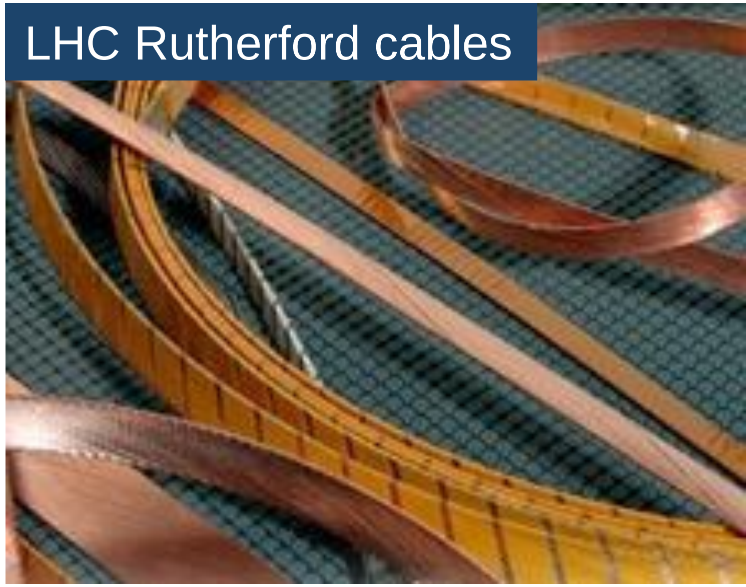







Cabling machine

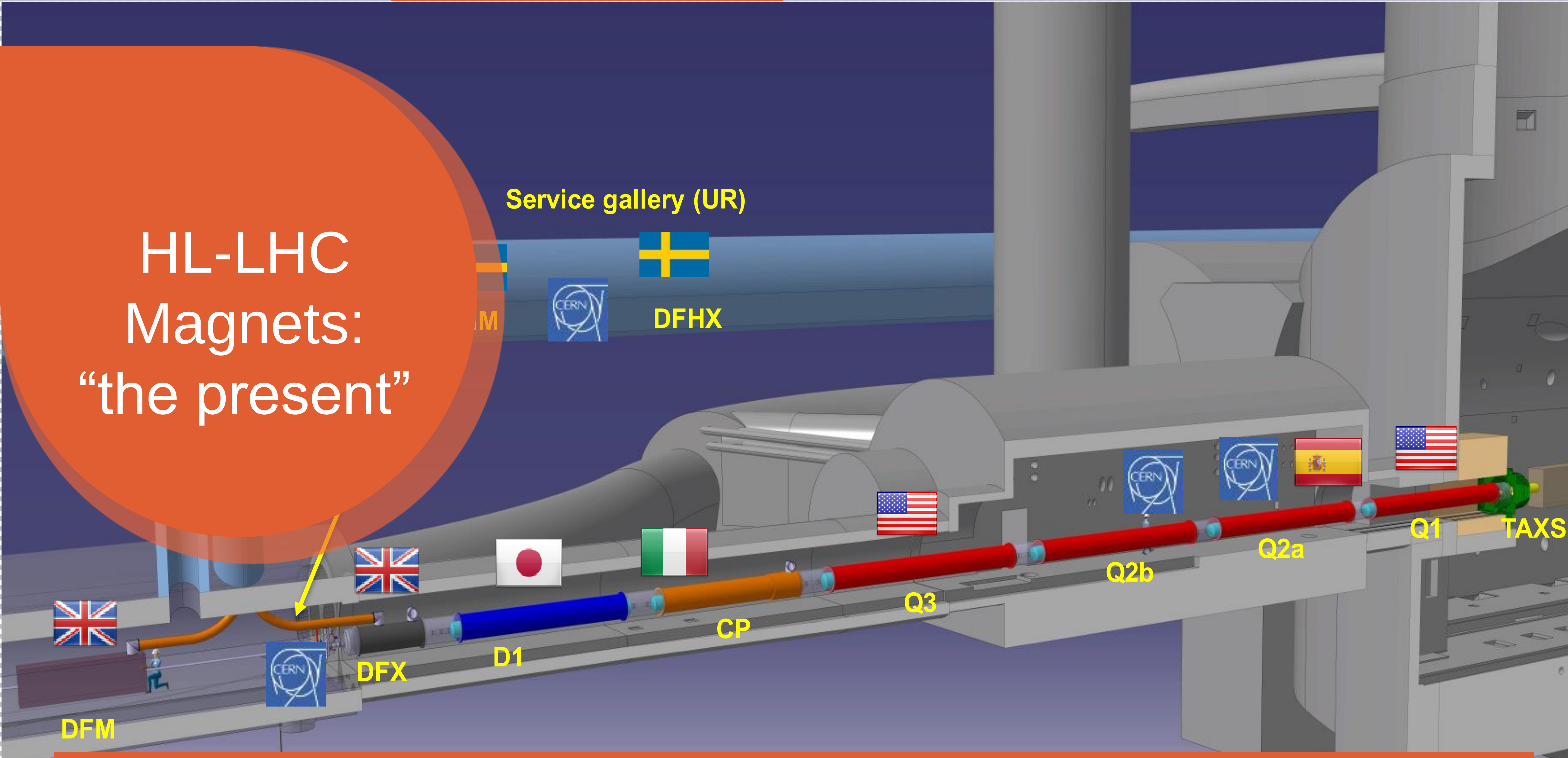

QC of NbTi strands


LHC Rutherford cables

The success story of the LHC magnet production

- LHC has required 12 years of focused R&D and industrialization (1989-2001) and 5 years for magnet production (2002-06) with high and consistent quality produced by industry. Largest series production of high-field accelerator magnets to date. Many lessons have been learned from this project, just to name a few:
  - Importance of appropriate strategy of cooperation with the industry, involving companies from the very beginning, starting with the 1m model magnets
  - Introduction of industrial prototyping and pre-series production as intermediate steps allowing for better cost and risk assessment and introduction of the risk cost sharing model
  - Splitting and awarding contracts to several companies for additional risk mitigation, including reduction of a vast "business bubble" to be managed by companies

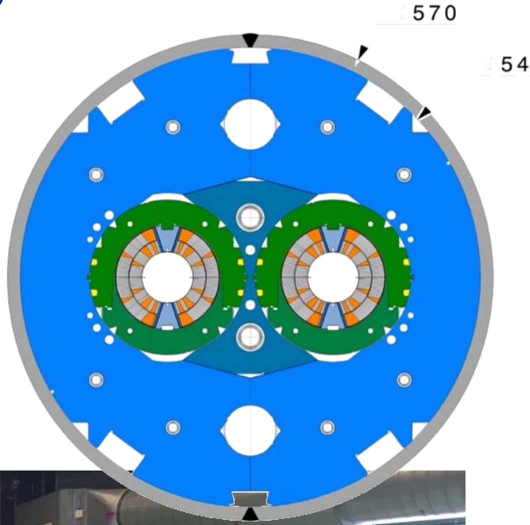
HL-LHC Magnets: “the present”



Particularity of the HL-LHC magnet work package is the variety of magnet families with a small number of magnets in each family → different model of cooperation with the industry

HL-LHC 11 Testa NB_3Sn Dipole Magnets

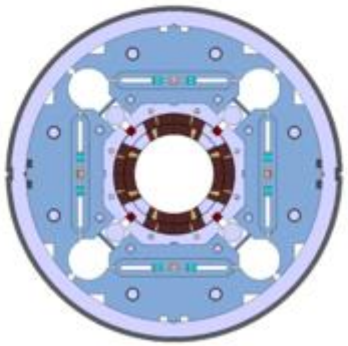
- New model of cooperation with the industry
  - Project scale for industry was relatively small.
  - To cut invest costs in tooling CERN decided to set up a workshop for in-house development and production.
  - As part of the fruitful cooperation with General Electric, 35 Nb_3Sn coils were produced, which will be used in the 11 T dipoles for HL-LHC.
  - The production of collared coils lasted for almost three years.
  - While it is doable for industry to work on-site for a magnet development and production, it is not a preferred solution.



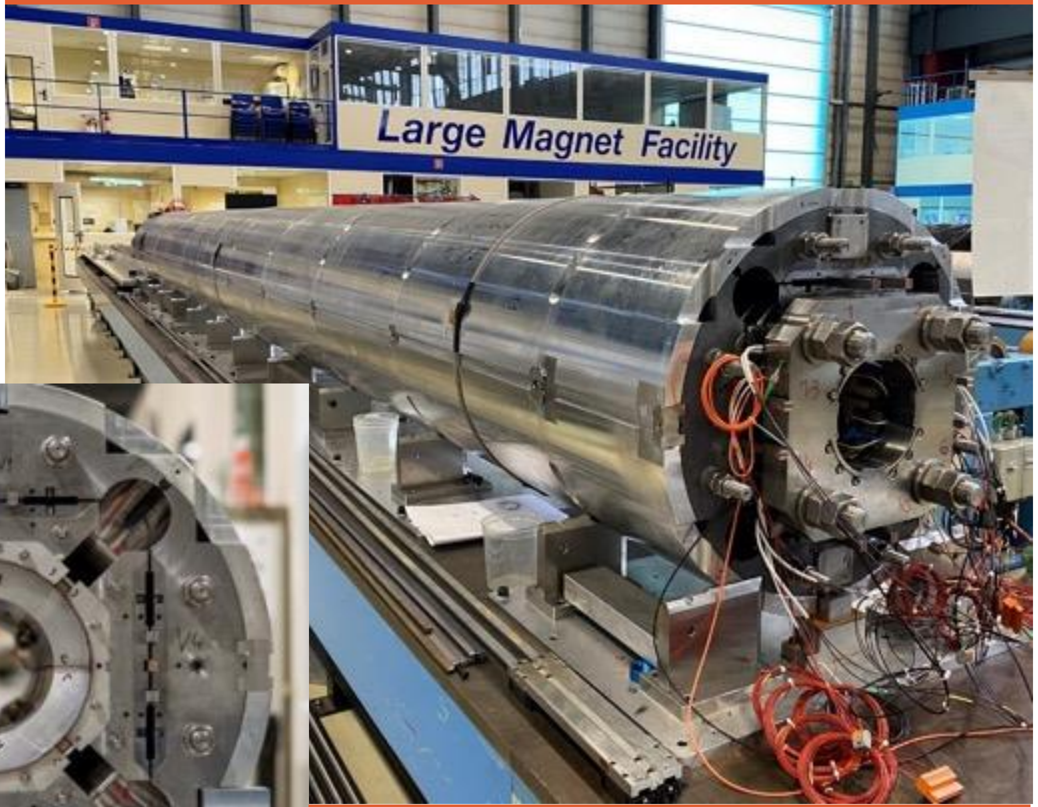
HL-LHC MQXF Nb_3Sn Quadrupole Magnets

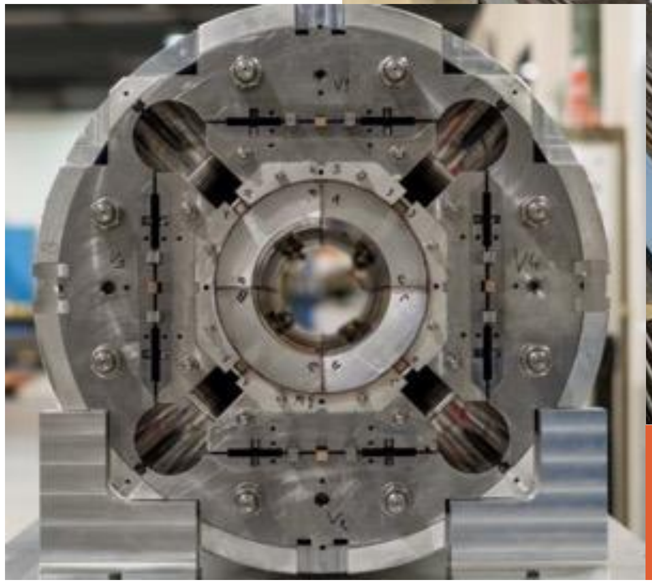
- The time constraints did not allowed for the industrialisation of these magnets.
  - Project scale, however bigger than that for 11T dipoles was still small for concerned industries.
  - CERN and US-AUP decided to use existing workshops for in-house production.
  - Production at CERN is managed by CERN staff with the fruitful share from the industrial partners who are responsible for the predefined missions within the production process.
  - CERN assumes the overall responsibility for the production. No sharing of risks.

  - Industrial partners, contributing to the production of the MQXFB magnets were already used to work on-site for other activities.



HL-LHC MQXFB Nb_3Sn Quadrupole

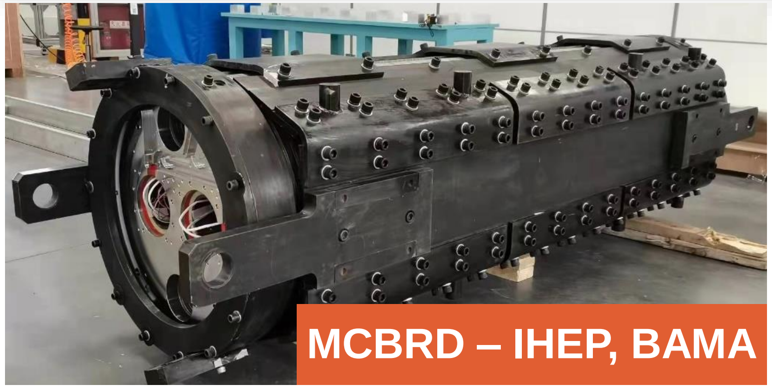




Field gradient 132.6 T/m
Bpeak = 11.4 T

HL-LHC Nb-Ti D1, D2 and Corrector Magnets

- HL-LHC D1, D2 and corrector magnets are using the Nb-Ti technology.
  - These magnets were developed by national laboratories INFN, CIEMAT, KEK and IHEP
  - INFN, CIEMAT, KEK and IHEP transferred the know how to national industries. Production is ongoing.



Main Direct CERN Contracts for HL-LHC WP3 (IR Magnets)

Equipment / Component	Supplier
Nb3Sn Wire	BRUKER
Cable insulation	C.G.P
Coil wedges	LUVATA Oy
Coil end spacers	GEVALCO
Ti Poles	GEVALCO
Quench Heaters	TRACKWISE
Material for collars	SANDVIK
Material for yokes and masters	AK Steel
Yoke and Loadpad laminations	MALVESTITI

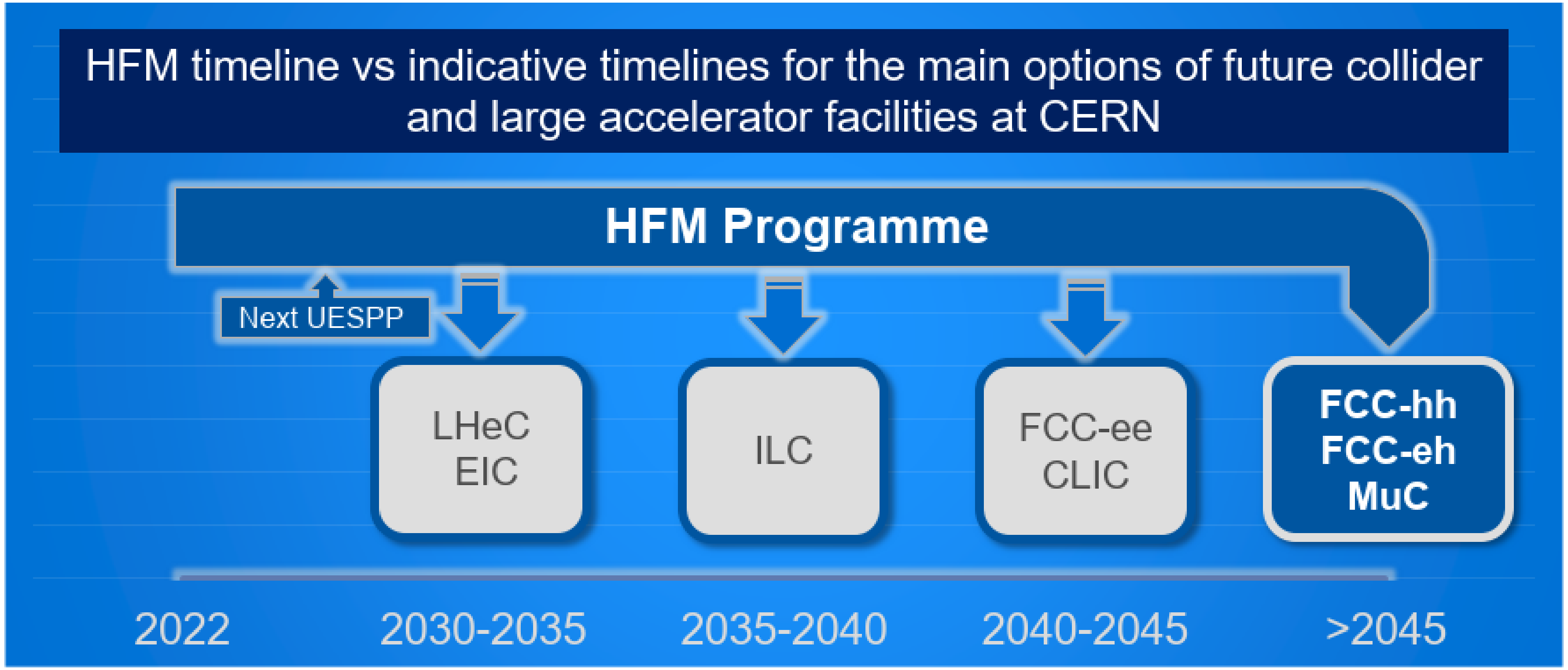
Equipment / Component	Supplier
Internal and External Master	VAN HALTEREN METAAL
Al Shells - Material	IMBACH & CIE
Al Shells machining Thick Yokes	FMI HIGHTECH SOLUTIONS
Shells - Material	Industeel
Shells -Production	AP Tela
End Covers	IMBACH & CIE
Cold Supports	OPTIMAL
Vacuum Vessels	BOESSENKOOL
Service Modules	INOX INDIA

Post-LHC Magnets: “the future”

The present vision to go significantly beyond what we can do in particle physics today is to study feasibility of future collider options: FCC-hh, FCC-ee, FCC-eh and MuC, all requiring high and ultra-high superconducting magnets.

High Field Magnet Programme Hosted at CERN

- HFM programme aims to look forward to a future of accelerator magnet technologies and builds, in particular on the past conceptual designs of FCC-hh magnets
- Fostering and profiting from collaborations with EU partners will be an essential part of the HFM programme as well as linking to ongoing worldwide efforts



HFM Programme – broad goals

The Accelerator R&D Roadmap at CERN identifies two main objectives for the HFM programme:

- The first is to demonstrate Nb_3Sn magnet technology for large-scale deployment. This will involve:
    - moving towards production scale through robust design, industrial manufacturing processes and cost reduction, taking as a reference the HL-LHC magnets, i.e., 12 T)
    - pushing the Nb_3Sn magnet technology to its practical limits in terms of ultimate performance (towards the 16 T target required by FCC_{h-h})
- The second objective is to demonstrate the suitability of high temperature superconductors (HTS) for accelerator magnet applications, providing a proof-of-principle of HTS magnet technology beyond the range of Nb_3Sn, with a target in excess of 20 T

R&D Strategy and Focus Areas (2022-2027)

Topic 1 Nb3Sn Conductors

- Present limitations linked to stress/strain sensitivity and degradation, to be overcome by
  - improved mechanical robustness
  - higher Jc (thus, increased margins)
- Development and industrialization of improved Nb_3Sn superconductors will require industrial partners
- Otherwise, magnet structures must be adapted to deal with performance limitations in more realistic ways than FCC-hh CDR (see topic 3)

Topic 2: 12 T Robust Nb_3Sn Magnets

- Implement all lessons learned from LARP + HL-LHC programs
- Demonstrate maturity of Nb_3Sn technologies
- Improve manufacturability and protection of coils against overstresses
- Collaboration of CERN as well as INFN with the industry is an integral part of this project
- Reaching 14+T with this robust technology will be aided by improved mechanical robustness of conductor (see Topic 1)

R&D Strategy and Focus Areas (2022-2027)

Topic 3: 14+T Feasibility Studies

- Multiple,exploratory magnet-development by EU laboratories.
- Approaches range from evolutionary, based on LARP/HL-LHC technology to departures from state-of-the-art.
- From evolutionary to revolutionary:
    - cos theta (see Topic 2) - block coil (reduced high-field coil stress) - common coil (simplification of coil-manufacturing) - stress managed version of either coil variant (drastically reduced coil stresses, at cost of lower efficiency)
- 1st priority: performance and (sufficient) robustness.
- 2nd priority: maximum robustness and reduced cost.

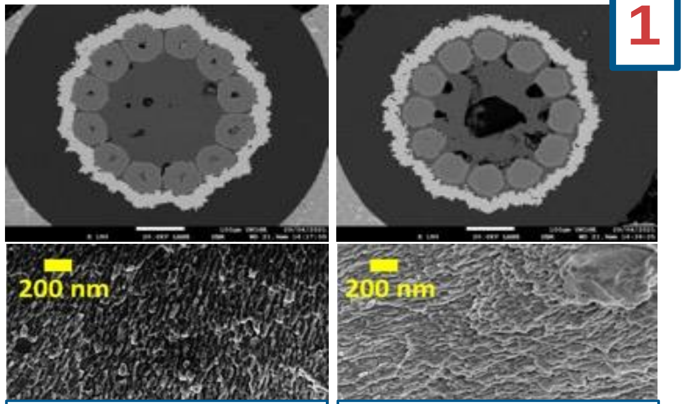
Topic 4: HTS Conductor and Magnet Technology

- Improve ReBCO conductor in view of accelerator requirements.
- Development of alternative HTS superconductors.
- Stand-alone demonstrator magnets.
- Subscale tests in background field and hybrid HFMs.

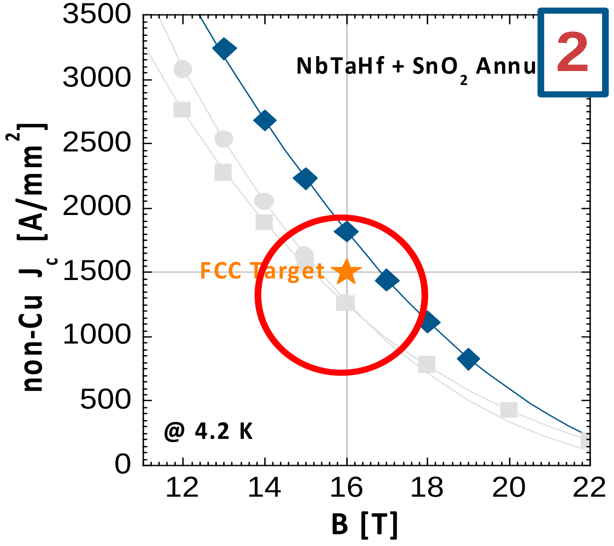
Selected developments:

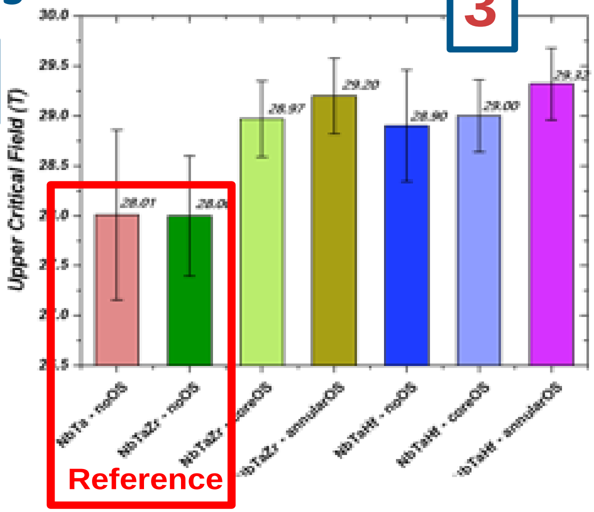
Latest Nb_3Sn Wire Development

Internal Oxidation in prototype multifilamentary wires



Average grain size ~ 47 nm	Average grain size ~ 45 nm





Larger billets under development

Pushing Nb_3Sn towards its ultimate performance

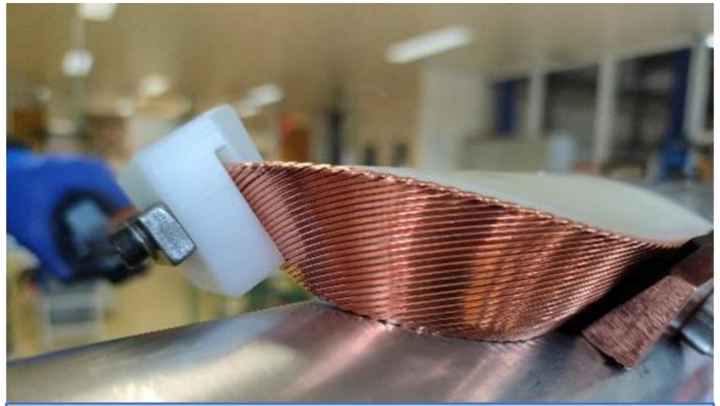
1. Refinement of the grain size: 100 nm → 50 nm
2. Large increase of the layer J_c → exceeding the FCC target
3. Enhancement of B_{c2} by > 1 T → improved in-field performance

Courtesy of C. Senatore

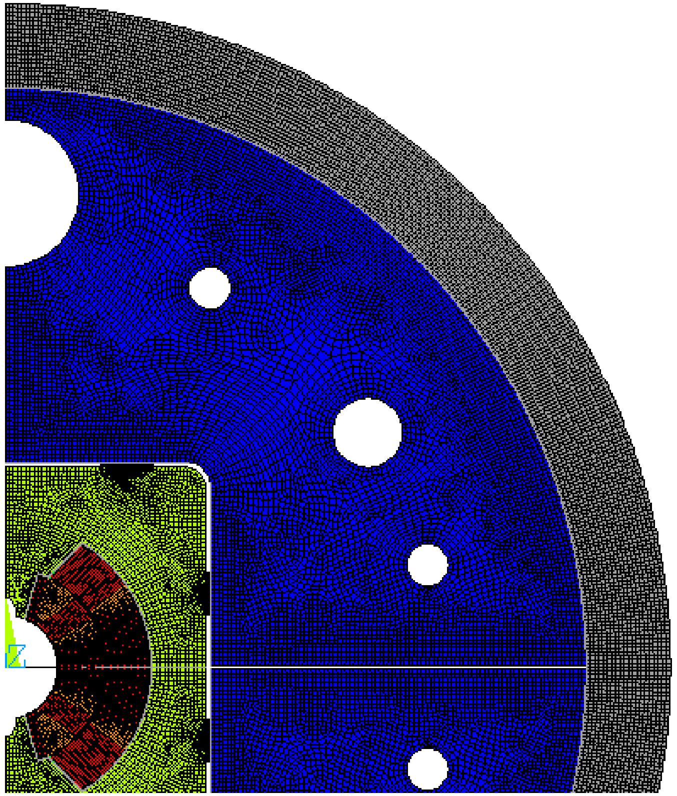
Selected developments: FalconD - single aperture, dipole model as part of the 12 T robust dipole development

- The collaboration between INFN and CERN with industrial partner contribution for the design and constructions of a single aperture high field dipole as part of the HFM “12 T robust dipole” development programme

- Systematic winding tests have started
- Three generations of FalconD end spacers were developed
- The Preliminary Design Review was successfully completed in August 2022



FalconD winding test, End spacers iteration 2. In some of the winding tests the cable is not insulated to have a better visibility of the strand position and deformation. The white plastic element is part of the tool that help to keep the strand in position during the bend.

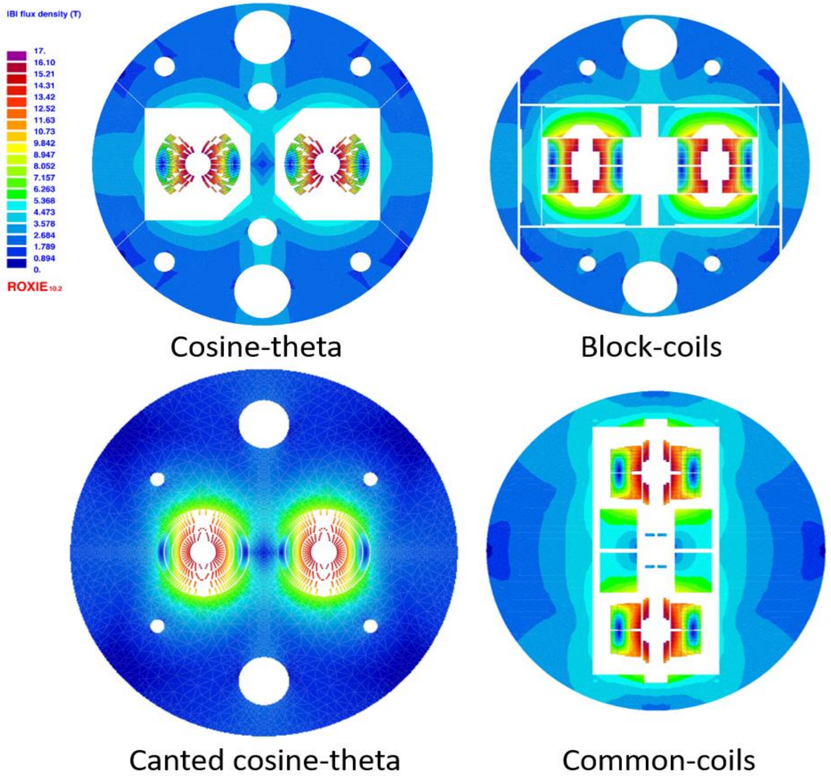


FEM model of the FalconD single aperture bladders and keys, 12 T dipole.

Courtesy of S. Farinon and D. Perini

Selected developments: Conceptual design of FCC-hh dipole magnets

- Exploratory phase of the 16 T Nb_3Sn FCC-hh main dipole design requiring developments beyond the state-of-the-art of both the Nb_3Sn conductors and magnet technologies
- Involved partners: CEA, CIEMAT, INFN, PSI and CERN



Property	Unit	Value
Wire		
Critical current density at 16 T and 1.9 K	A/mm^2	1500
Strand diameter HF conductor	mm	1.1
Strand diameter LF conductor	mm	0.7
Filament size HF conductor	µm	20
Filament size LF conductor	µm	20
Cu/nonCu HF conductor		0.8:1
Cu/nonCu LF conductor		2.1:1
Cable		
Number of strands HF cable		22
Number of strands LF cable		38
Width of HF cable	mm	13.2
Width of LF cable	mm	14.0
Keystone angle of HF/LF cable	degrees	0.5
Average thickness of HF cable	mm	1.950
Average thickness of LF cable	mm	1.265

FCC-ee: Challenge of the power consumption of conventional magnets vs superconducting counterparts

The FCC-ee baseline at the Conceptual Design Report:

- The FCC-ee is a conventional (warm) accelerator, much like LEP (CERN, 1989-2002) containing among others **2900** quadrupole and **6336** sextupole magnets, all normal conducting
- The total power loss in all (warm) magnet systems is ~80MW at the top energy of the collider

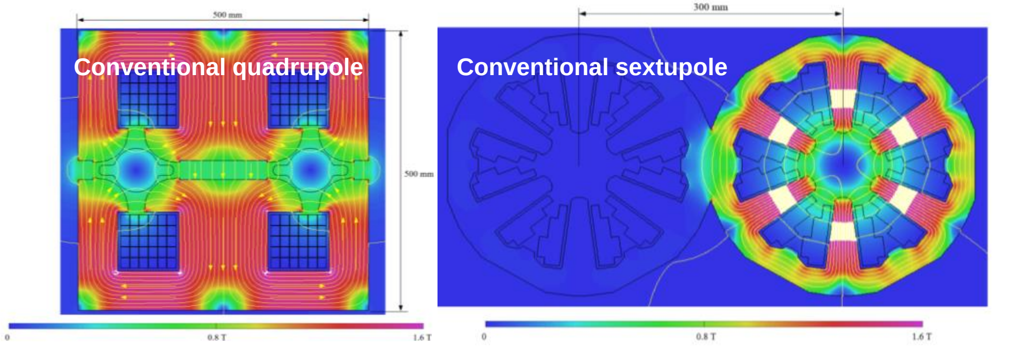


Figure 3.3: Cross-section of the FCC-ee main quadrupole, for a 10 T/m gradient.

gure 3.6: Cross-section of the FCC-ee main sextupole magnet. The position of the sextupole for the other beam is outlined on the left.

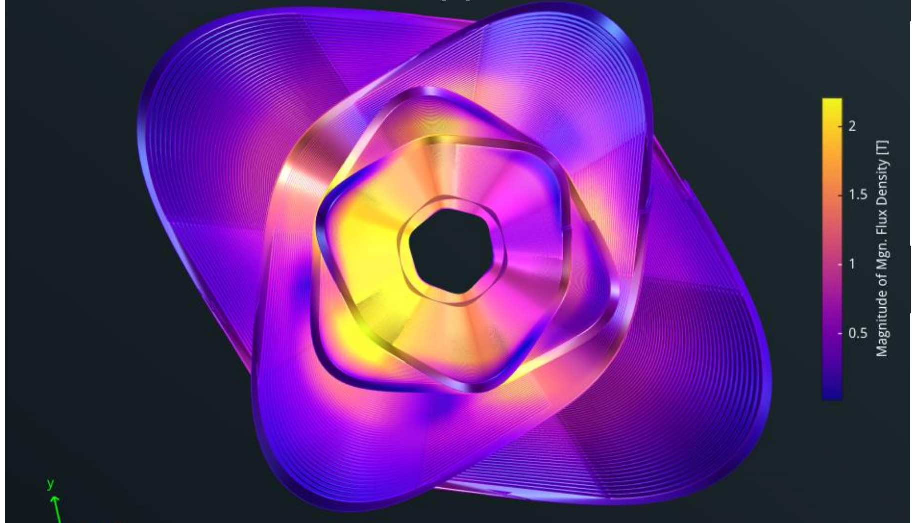
Can we do better? Yes! Make the magnets superconducting

- The energy is basically spent cooling the magnets. **Potential power reduction for these systems: ~90%**

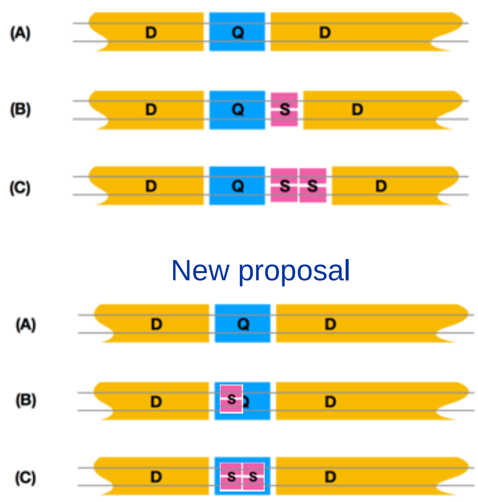
Also, we can "nest" the magnets, so that they take less space

- More pace available for bending magnets, so performance of the accelerator also increases

Nested superconducting CCT quadrupole-sextupole magnet, seen from the centre of the beam pipe



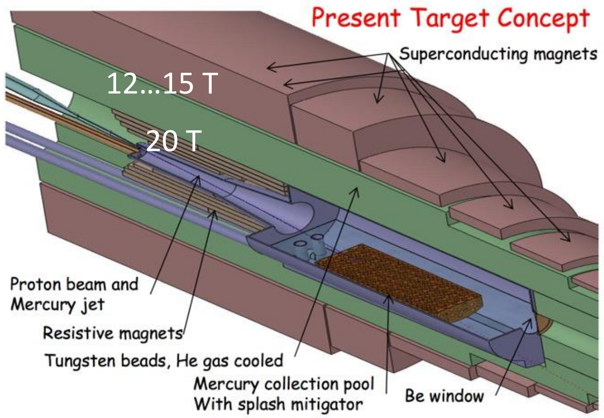
Potential power reduction : ~90%



Courtesy of M. Koratzinos

Muon Collider Magnets: Feasibility Studies

Conceptual design of capture solenoid (target area)



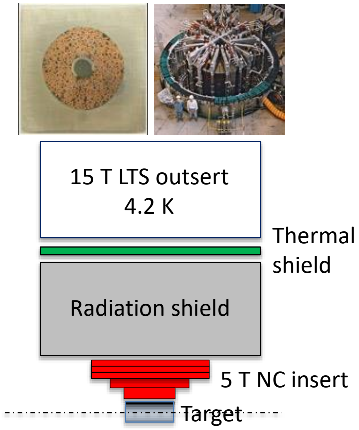
- Hybrid solenoid
  - SC outsert (14 T, 2.4 m)
    - Technology: Nb-Ti outer coil + Nb_3Sn inner coil
    - Heat load: 5 kW
    - **Power: 2 MW**
    - Stored energy: 1.2 GJ
    - **Cost: o(100M)**
  - NC insert (6 T, 150 mm)
    - Technology: hollow copper conductor, inorganic insulation
    - Heat load: 100 kW
    - **Power: 10 MW**

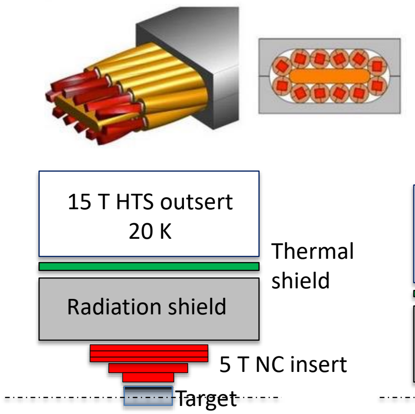
Capture field: 20 T, 150 mm

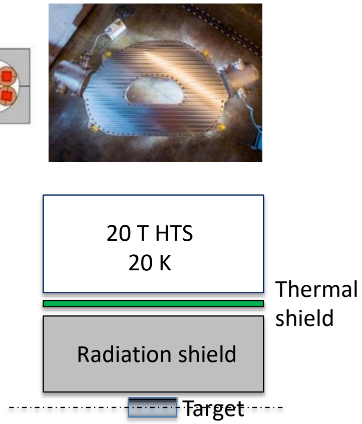
Highly integrated design

Although this is a single system, cost and power requirements are significant

Capture solenoid options







Based on existing technology (ITER CS Nb_3Sn CICC)
- Large bore solenoid has large stored energy, mass and cost
- Cryogenic efficiency for heat removal is low at 4.2 K
- Resistive insert has large consumption

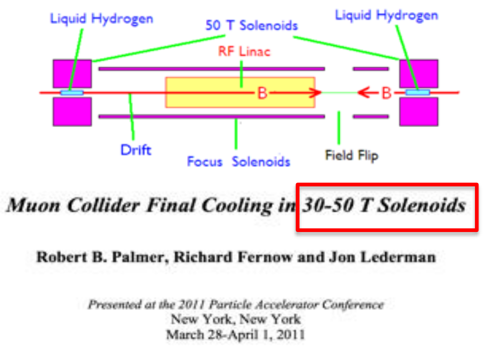
HTS internally cooled magnet wound with cable developed for fusion (CFS/MIT)
- Solenoid bore can be reduced by reducing shielding (e.g. accept a factor 2 in heating ?)
- Improved cryogenic efficiency (a factor 5 better Carnot)

All-HTS internally cooled magnet, no resistive insert
- Minimal solenoid bore radius
- Reduced power consumption
- Large field on SC cable

Courtesy of L. Bottura

Muon Collider Magnets: Feasibility Studies

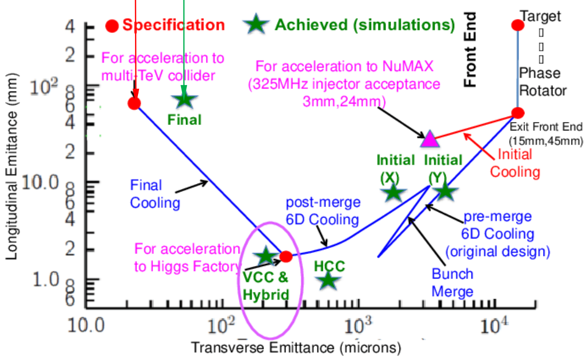
Cooling solenoids



40…60 T required

30 T assumed in MAP

A field of 40 T (minimum), up to 60 T (target), over a bore of 50 mm is required to meet the specification on the transverse emittance at the exit of the cooling stage

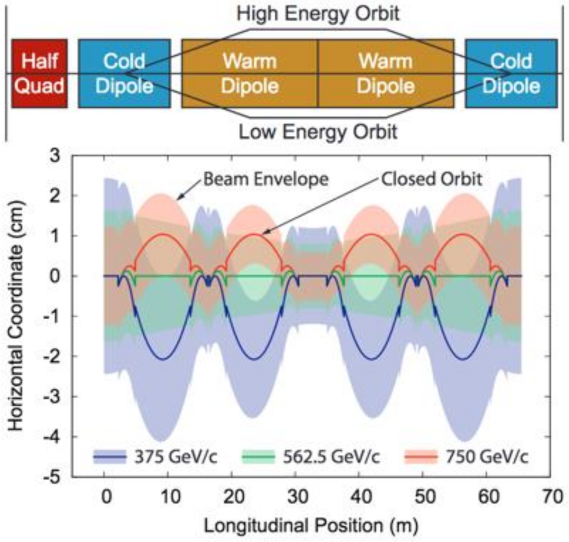


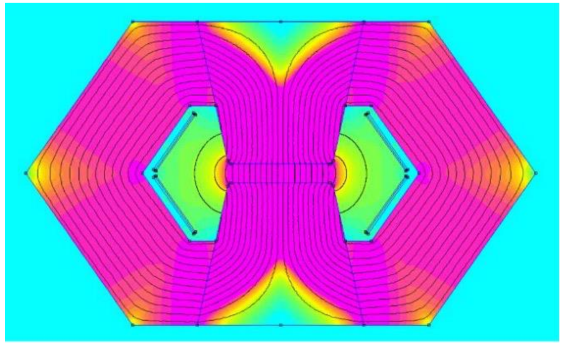
Target 40 to 60 T with 50 mm bore and ≈ 300 mm length

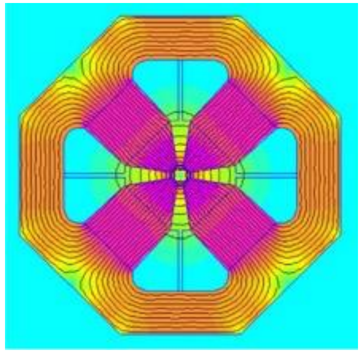
Stress level is at the limits of materials

Many solenoids are required for the complete cooling channel

Accelerator magnets



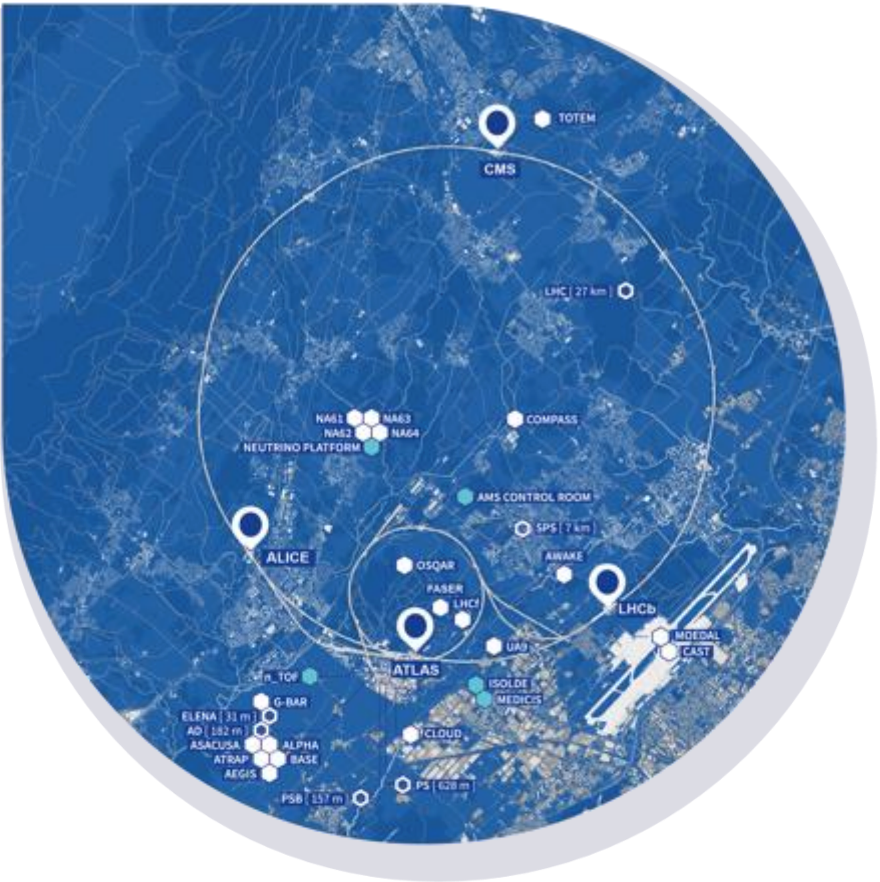




Combination of DC SC (10 T) and AC resistive (1.5…2 T) magnets. The resistive magnets are ramped in 0.4 ms (400 Hz)

Courtesy of L. Bottura

Final remarks

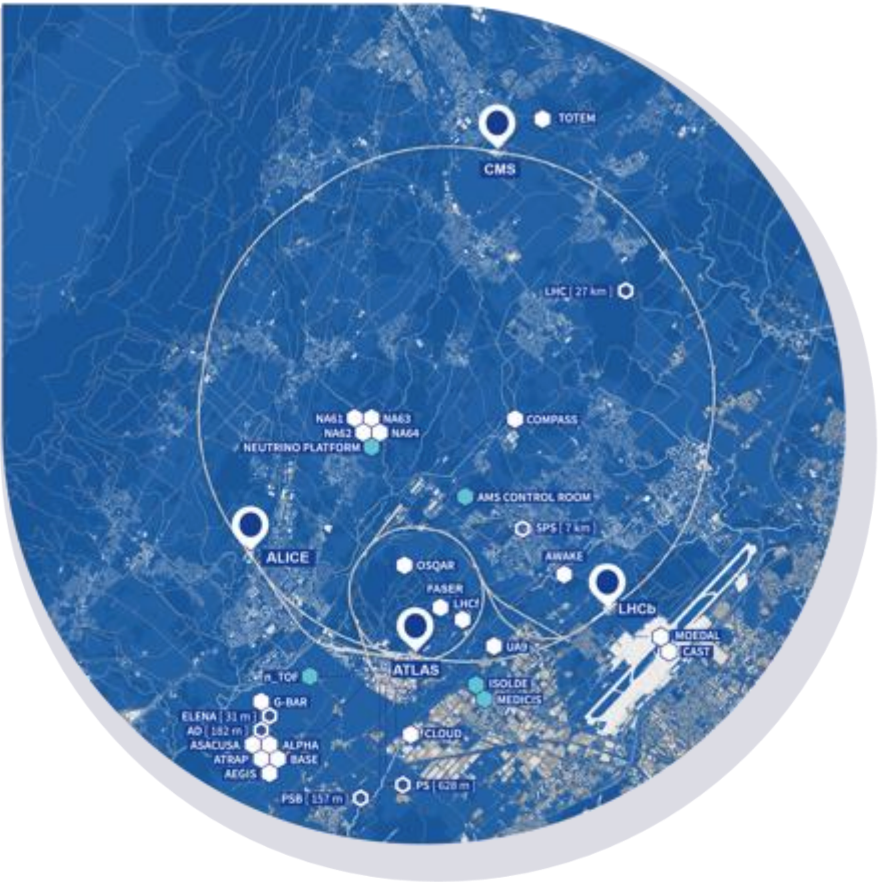


CERN has a large share in the development of accelerator technologies, in particular those designed for the high field magnets

CERN has a long tradition of collaboration with the industry, technology transfer, industrialisation, prototyping and series production

As shown by the example of LHC, targeted research and development of new superconducting magnets require many years before the start of series production, but during this period it is both desirable and a necessity to cooperate with industry partners

Acknowledgement



I am grateful for sharing some of the materials for this presentation to my following colleagues:

A. Ballarino, L. Bottura, A. Devred, M. Koratzinos, D. Perini, F. Savary, C. Senatore and E. Todesco

Spare slides

Detector magnet projects for existing & future colliders, non-colliders and space experiments

→ Many future superconducting detector magnet projects, with strong demand for suitable conductor types, especially aluminum-stabilized Nb-Ti/Cu conductor technology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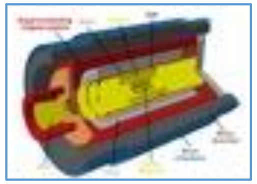
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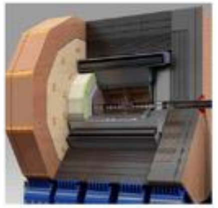
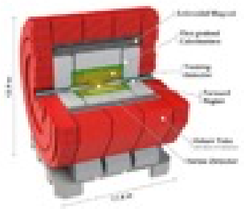

ILC-ILD


ILC-SiD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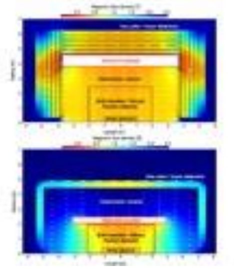
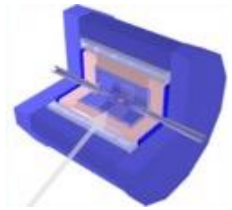

FCC-ee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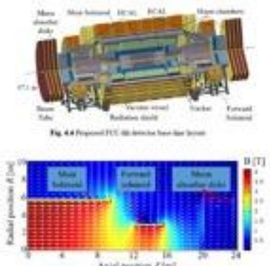
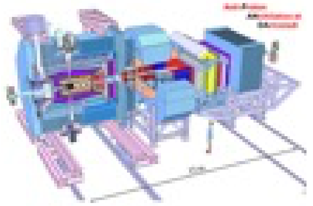

FCC-hh

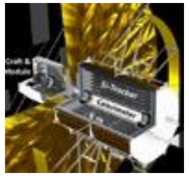

PANDA

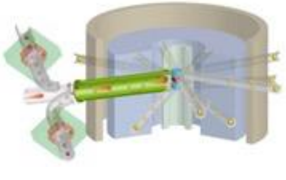

Mu2e


Comet


BabyIAXO

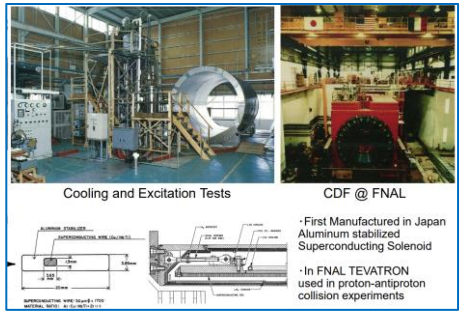

MadMax

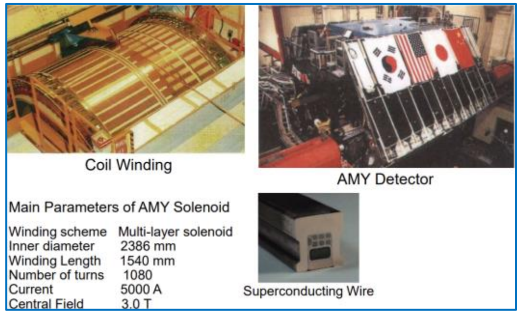

AMS100

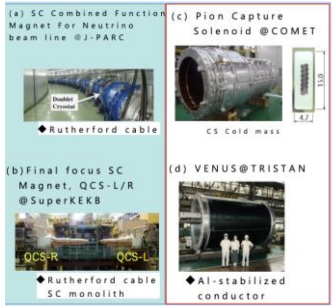

J-Parc MLF

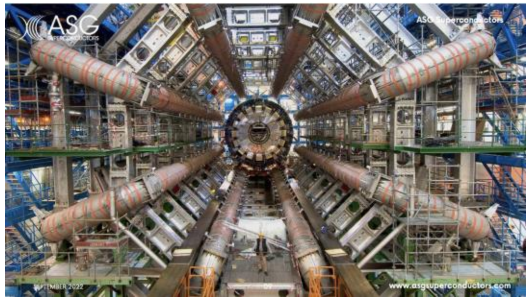
Courtesy of M. Mentink

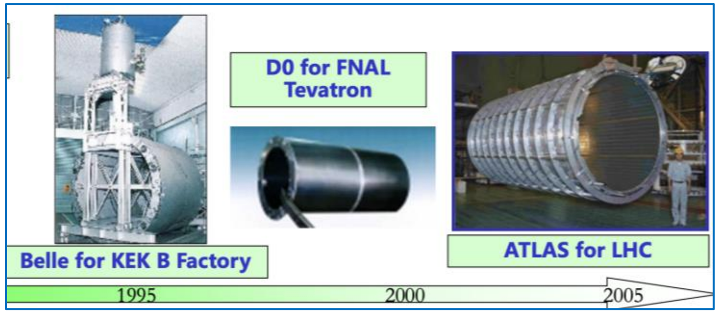
Industrial expertise for superconducting detector magnet fabrication

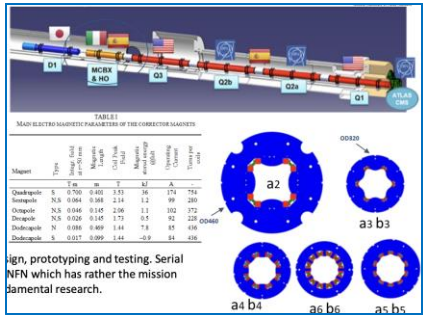


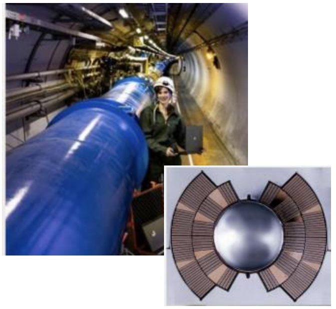










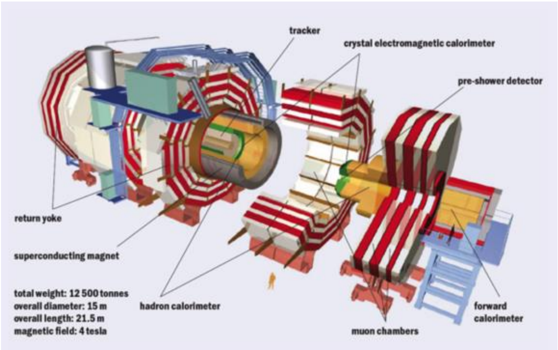


Production capabilities of superconducting detector magnets in industry:

Presentations by Hitachi (Jp), Mitsubishi (Jp), Toshiba (Jp), Bilfinger Noell (Ge), ASG (It), Saes-Rial (It), and Sigma-Phi (Fr)

Some examples of prior magnet production are shown above

Strong industrial expertise and capabilities for building superconducting detector magnets are available in industry, provided that the needed conductor is available



Courtesy of M. Mentink

Aluminum-stabilized Nb-Ti/Cu conductor, industrial availability

Industrial production capabilities of aluminum-stabilized Nb-Ti/Cu conductor (presentations by leading companies):

Significant industrial availability of Nb-Ti/Cu strand production

Significant industrial availability of Rutherford cable production for sufficiently large projects

Pure and nickel-doped aluminum is available in industry

There is no industrial availability of the co-extrusion process anymore, needed to bond the aluminum to the Rutherford cable. It is currently a topic of R&D at IHEP and Wuxi Tuly Electric (Ch), foreseen for the CEPC and Emus projects.

As demonstrated in the CMS conductor, aluminum-alloy reinforcements can be welded onto pure aluminum through E-beam welding (Techmeta, Fr) to mechanically reinforce the conductor, and other approaches such as stir-friction welding are a topic of interest for future research

Pre-processing equipment

Extrusion machine

On-going aluminum-stabilized Nb-Ti/Cu conductor R&D. Courtesy: Wuxi Tuly Electric (Ch)

Previous experience: E-beam welding on aluminum-alloy reinforcements onto aluminum-stabilized Nb-Ti/Cu conductor for CMS. Courtesy: Techmeta (Fr)

Courtesy of M. Mentink

Going forward

Outlook:

- Al-stabilized superconductor/magnet technology needs to be resumed,
- Industrial cooperation to be anticipated and strongly encouraged, in particular,
  - "Co-extrusion technology" of Al-stabilizer and NbTi/Cu-conductor to be resumed and widely available, and
  - "Hybrid-structure technology" by using electron beam welding (EBW) or by other approaches, to maximize the performance of Al-stabilized SC (Ni or Cu/Mg doped) combined with ultimately high-strength Al-alloy structure.
- **Laboratory's leading effort will be very important to advance the technology to be openly transferred to the industry.**

Remarks:

- It will be **also important** to investigate/seek for backup solutions such as soldering technology of NbTi/Cu conductor with Cu stabilizer, Cu-coated Al-stabilizer, and/or conductor technology developed for fusion applications (Cable-in-Conduit-Conductor, HTS).
- Al-stabilized HTS can provide important potential in specific detector magnet applications.

Courtesy of M. Mentink