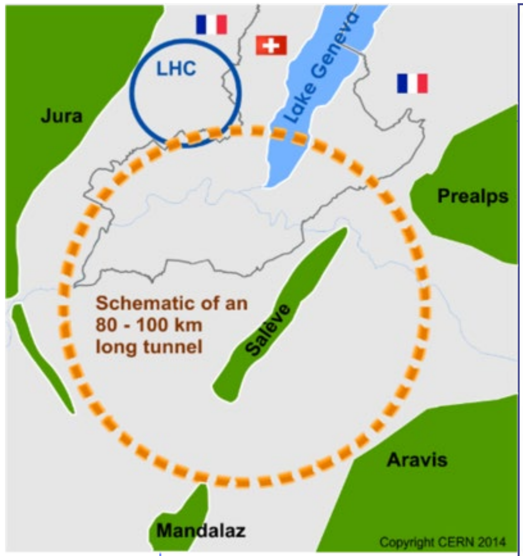
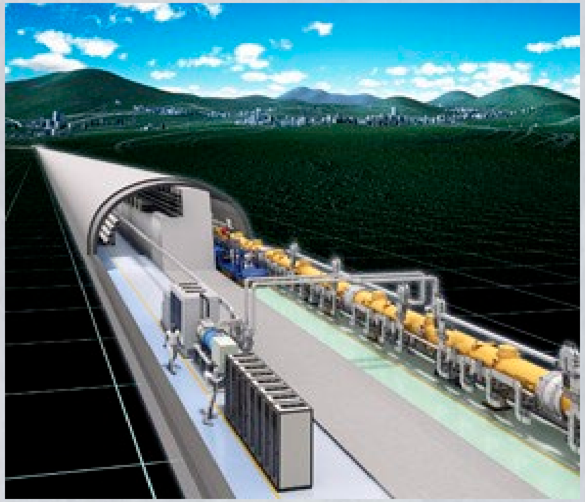
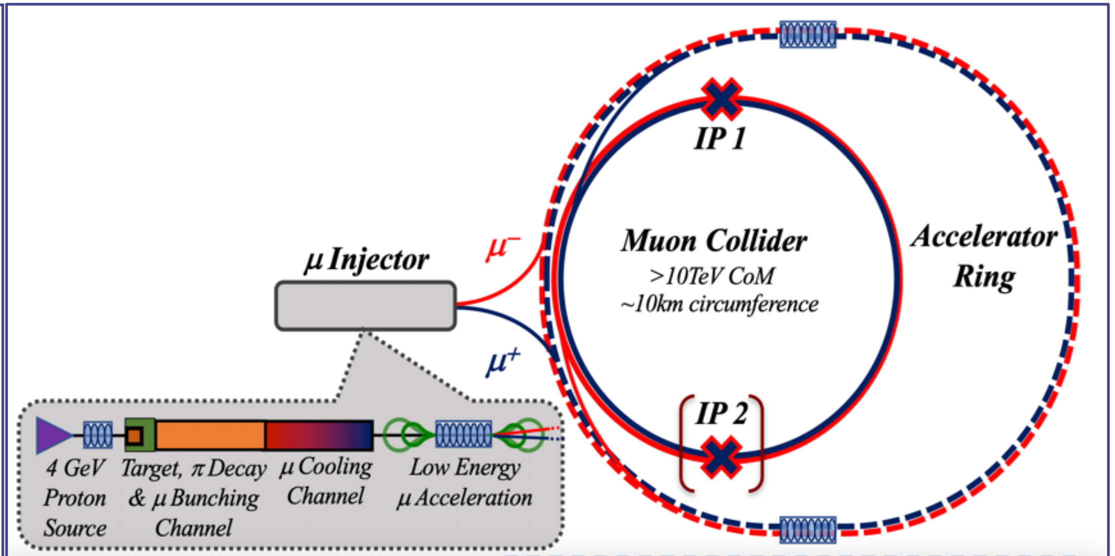


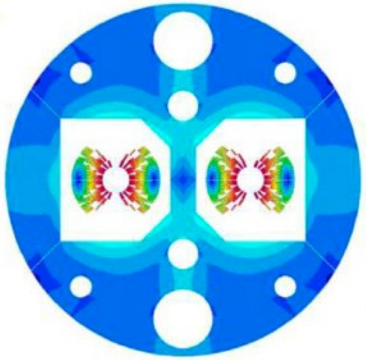


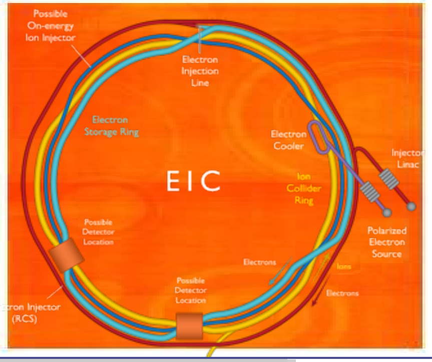


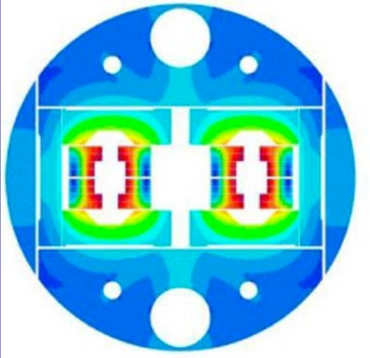
THE NEXT GENERATION OF SUPERCONDUCTING MAGNETS FOR FUTURE PARTICLE ACCELERATOR PROJECTS: LONG & SHORT-TERM ROADMAPS

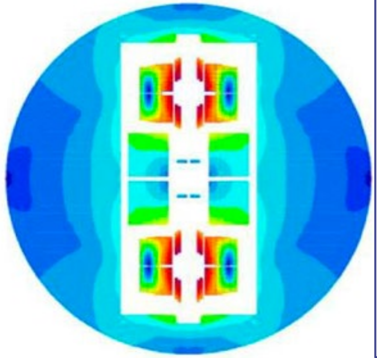
Luis García-Tabarés

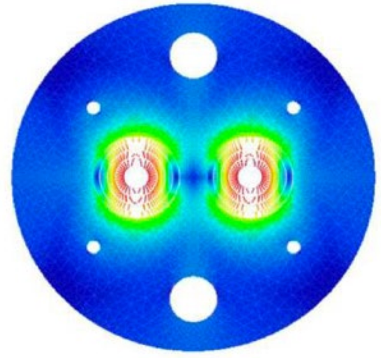
CIEMAT











SUPERCONDUCTING MAGNET
WORKSHOP
LASA, MILAN (IT) 17-18 NOVEMBER 2022

Introduction

SCOPE:

This presentation describes the present and future status of HEP accelerator magnet technology. After a short introduction to explain which is the role of the magnets are their future requirements, the talk summarizes the on-going and proposed future accelerator projects with a special attention to their magnet needs.

In parallel, a description of the State of the Art in High Field Magnet technology is first made, then an identification of the limits and challenges to be overcome and finally, a description of roadmaps and R&D Programmes for the next years and specifically the one recently developed by a Panel of Experts to the LDG

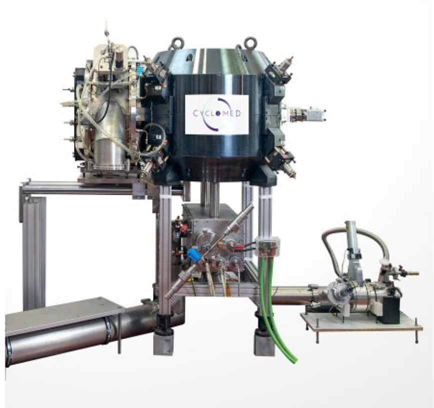
STRUCTURE:

- Introduction
- Basic Concepts of Magnets & SC Magnets for Accelerators
- The Next Generation of HEP Accelerators & the Magnets they Need
- State of the Art of Superconducting Magnets for HEP Accelerators
- Roadmap and Short & Long Term R&D Programmes for High Field SC Magnets
- Conclusions

Relevant Applications of Superconductors

MEDICAL

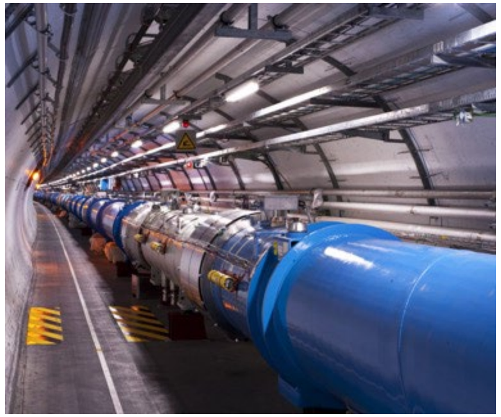
MRI



Accelerators

SCIENCE

NMR



HEP Accelerators

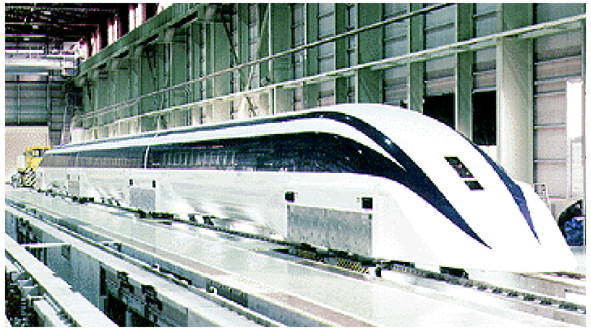
ENERGY

Fusion

Transmission

SMES

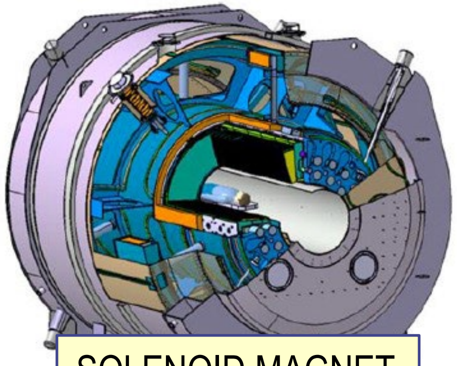
TRANSPORT



Maglev

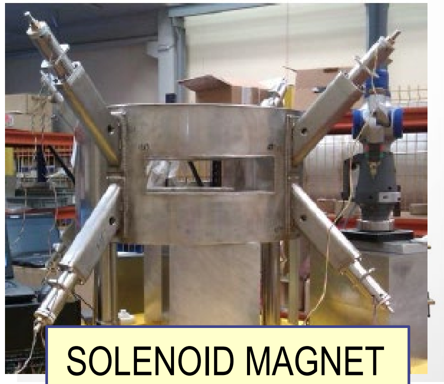
How These Applications are Implemented

MEDICAL



SOLENOID MAGNET

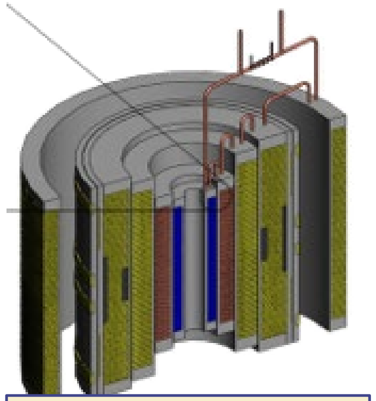
MRI



SOLENOID MAGNET

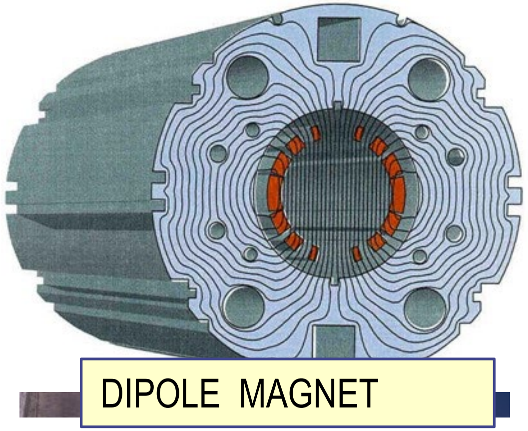
Accelerators

SCIENCE



SOLENOID MAGNET

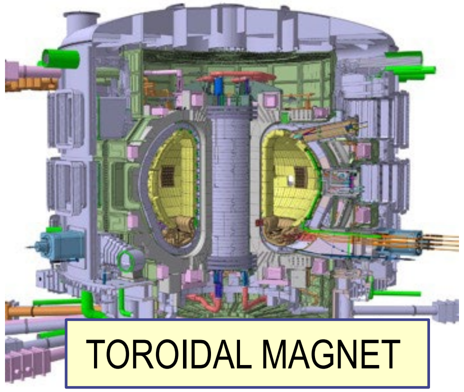
NMR



DIPOLE MAGNET

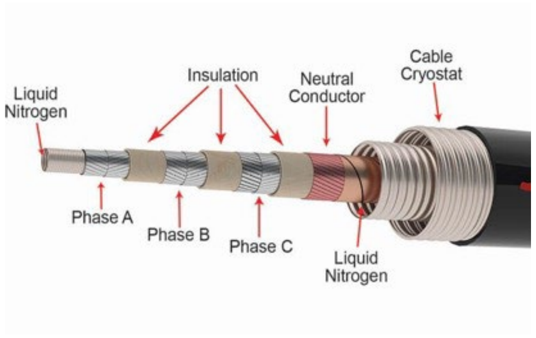
HEP Accelerators

ENERGY

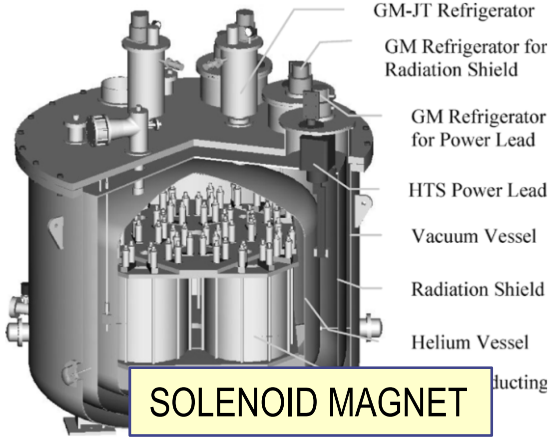


TOROIDAL MAGNET

Fusion



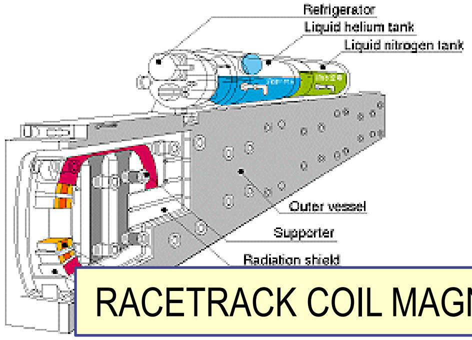
Transmission



SOLENOID MAGNET

SMES

TRANSPORT



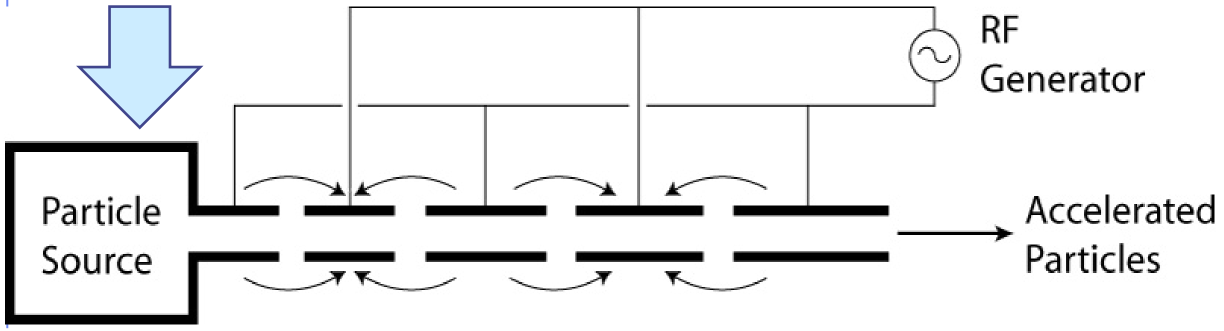
RACETRACK COIL MAGNET

Maglev

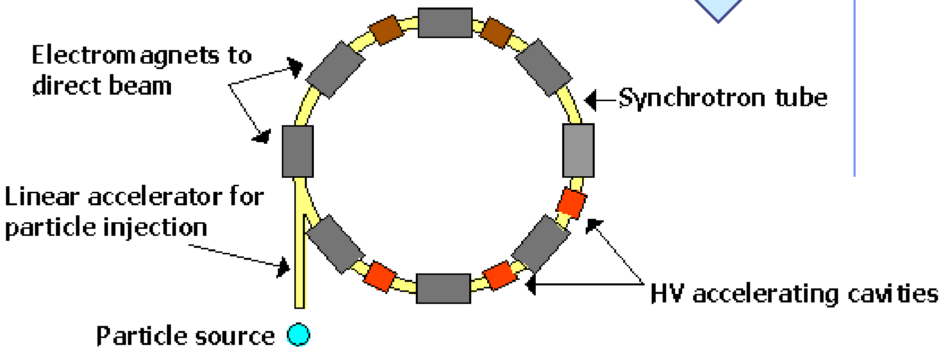
Some basic concepts on Particle Accelerator Magnets

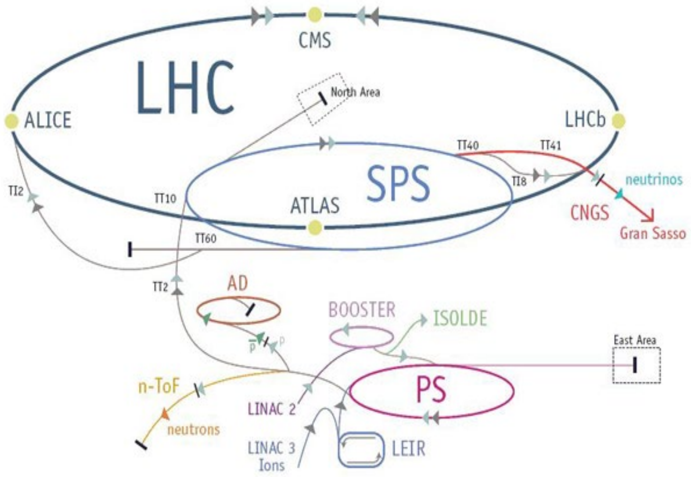
Two types of particle accelerators

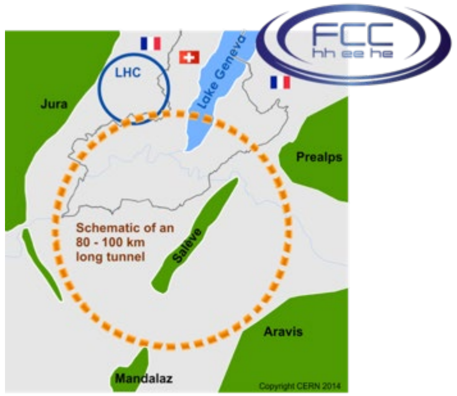
Linear Accelerators: Particles go through each accelerating element only once.



Circular Accelerators: Particles can go through each accelerating element many times.





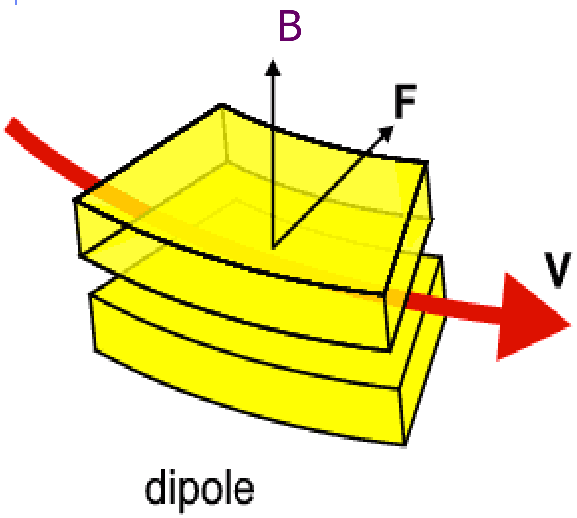


First Accelerators (≈ 1920) → Present Accelerators → Future Accelerators

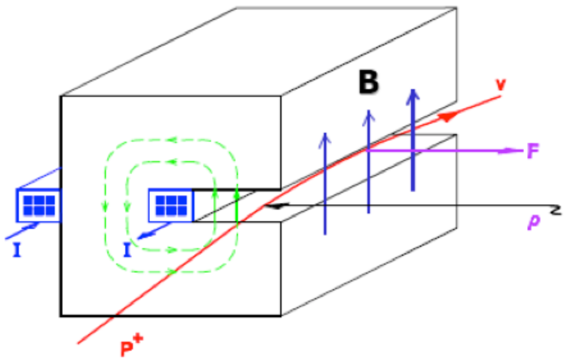
~ 100 keV X 100.000.000 ~ 10 TeV x 10 ~ 100 TeV

Circular Accelerators Need Bending Magnets

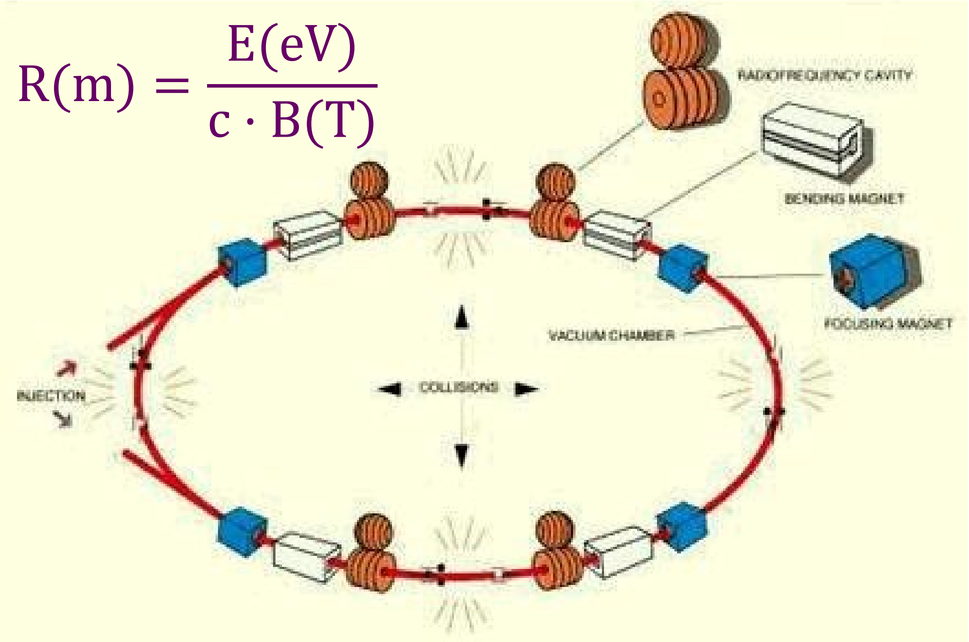
To bend the trajectory of the particle an external additional force must by applied to balance centrifugal force acting on the particle. Dipole magnets supply this force.



$$R = \frac{p}{q \cdot B(T)}$$



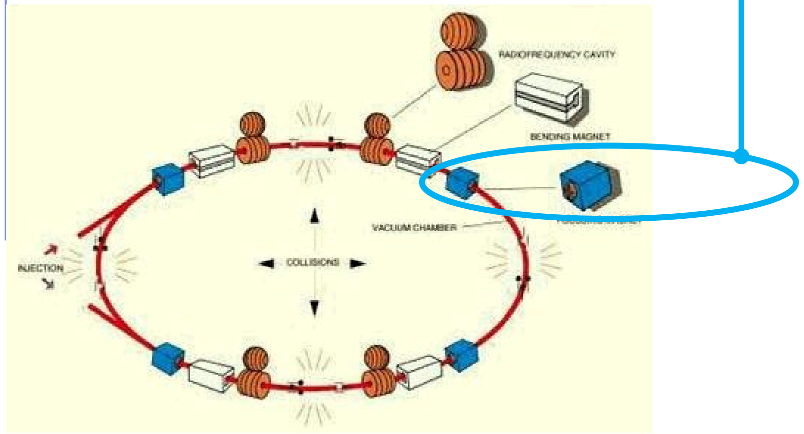
$$R(m) = \frac{E(eV)}{c \cdot B(T)}$$

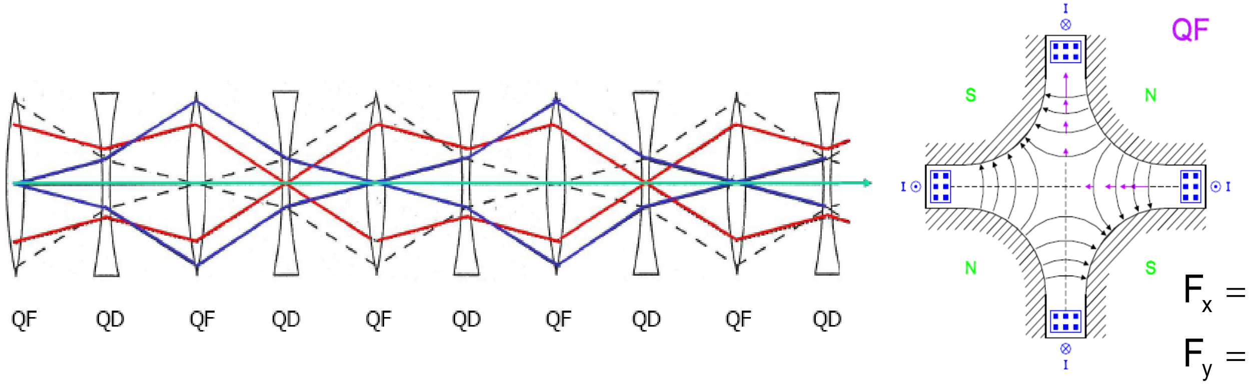


If we had used conventional magnets (1≈T) for the LHC (E≈7 TeV) its radius would have been around 23000 m and its circumference around 150 km.

All Types of Accelerators Need Additional Magnets

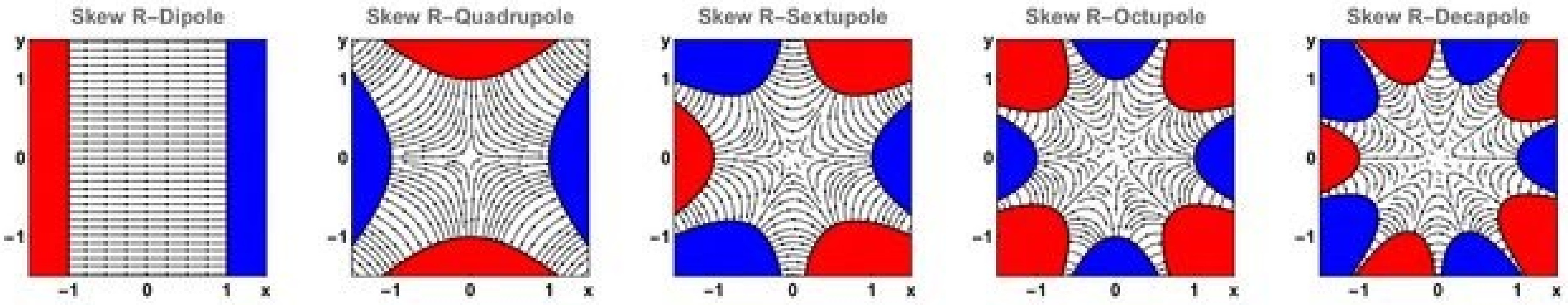
Even for the case of linear accelerators, particles need to be focused (keep them inside a certain envelope) and this requires additional magnets: **the quadrupoles.**





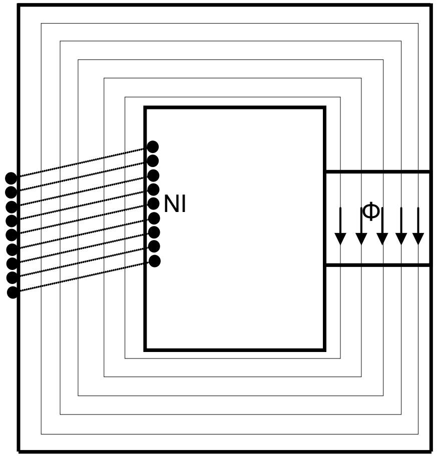
$$F_x = -k_q x$$
$$F_y = k_q y$$

Besides quadrupoles, higher multipolar magnets are required to correct chromaticity and non-linear effects in the beam. Sextupoles, Octupoles and Decapoles are also used in particle accelerators.



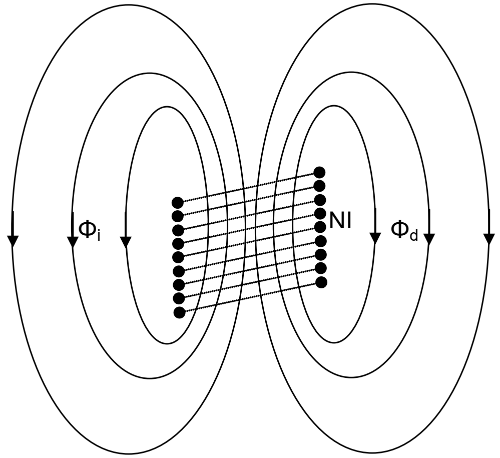
Modern Accelerators Need Very Strong Magnets

If we want to increase the accelerator energy with reasonable accelerator sizes (Tunnel Cross-Section & Length), we need to increase the magnetic field, but not the sizes of the magnet producing that field.



IRON-CORE MAGENT

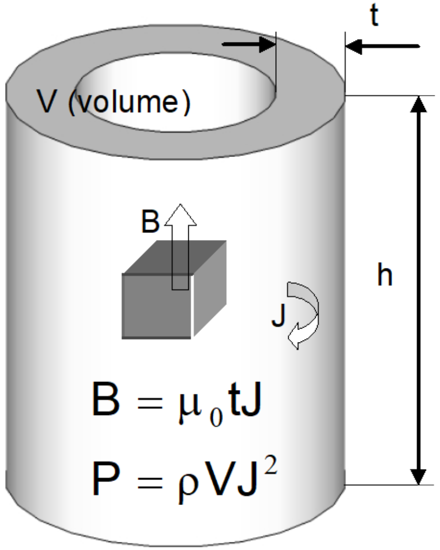
The field produced by a magnet increases with its current and decreases with the reluctance of the magnetic circuit. Iron helps to reduce the reluctance while it is not saturated.



AIR-CORE MAGENT

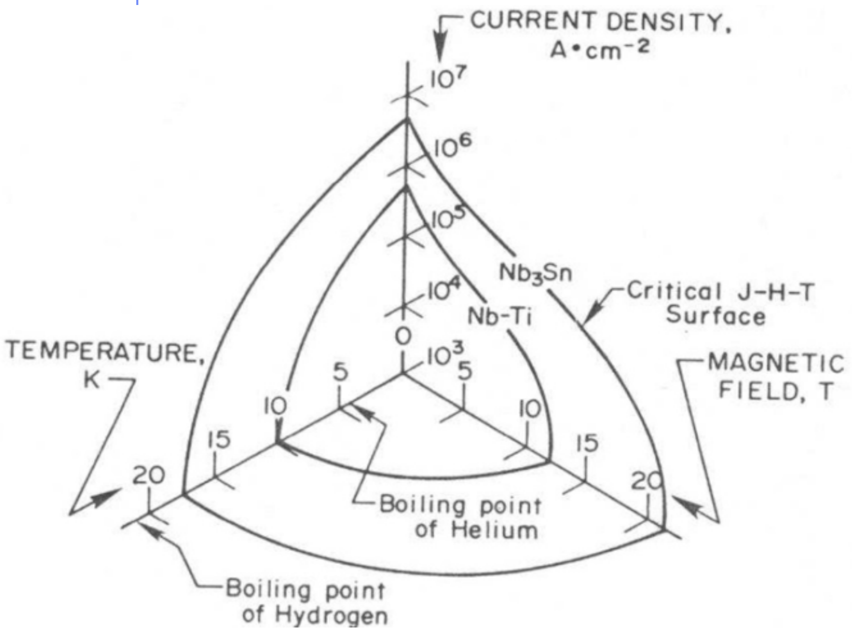
Trying to achieve very high fields with conventional magnets leads to "impossible" magnets.

10T solenoid > 8m in diameter + 20m in length + 70MW in power consumption.



The Solution: Using Superconducting Materials (I)

Since we need to augment the field and we can't reduce the reluctance, we have to increase the current, but we want to avoid losses and to limit the magnet sizes **> We need to increase the current density and the use of superconductors is mandatory.**



Presently, there are a limited number of usable superconducting materials, which are globally classified in two big groups:

* LTS (Low T_c Superconductors): They obey to the BCS theory and their T_c is below 40K. The 3 most important materials are NbTi, Nb_3Sn and MgB_2. They are arranged in the form of multifilamentary wires

* HTS (High T_c Superconductors): They are based on copper oxides, with critical temperatures above 77K. Their behaviour is not explained by the BCS theory. The 2 most important materials are the (RE)BCO and the BSCCO groups. They are arranged in the form of tapes.

Once they are arranged in the form of conductors (wires, tapes or cables) their properties can be classified in three types:

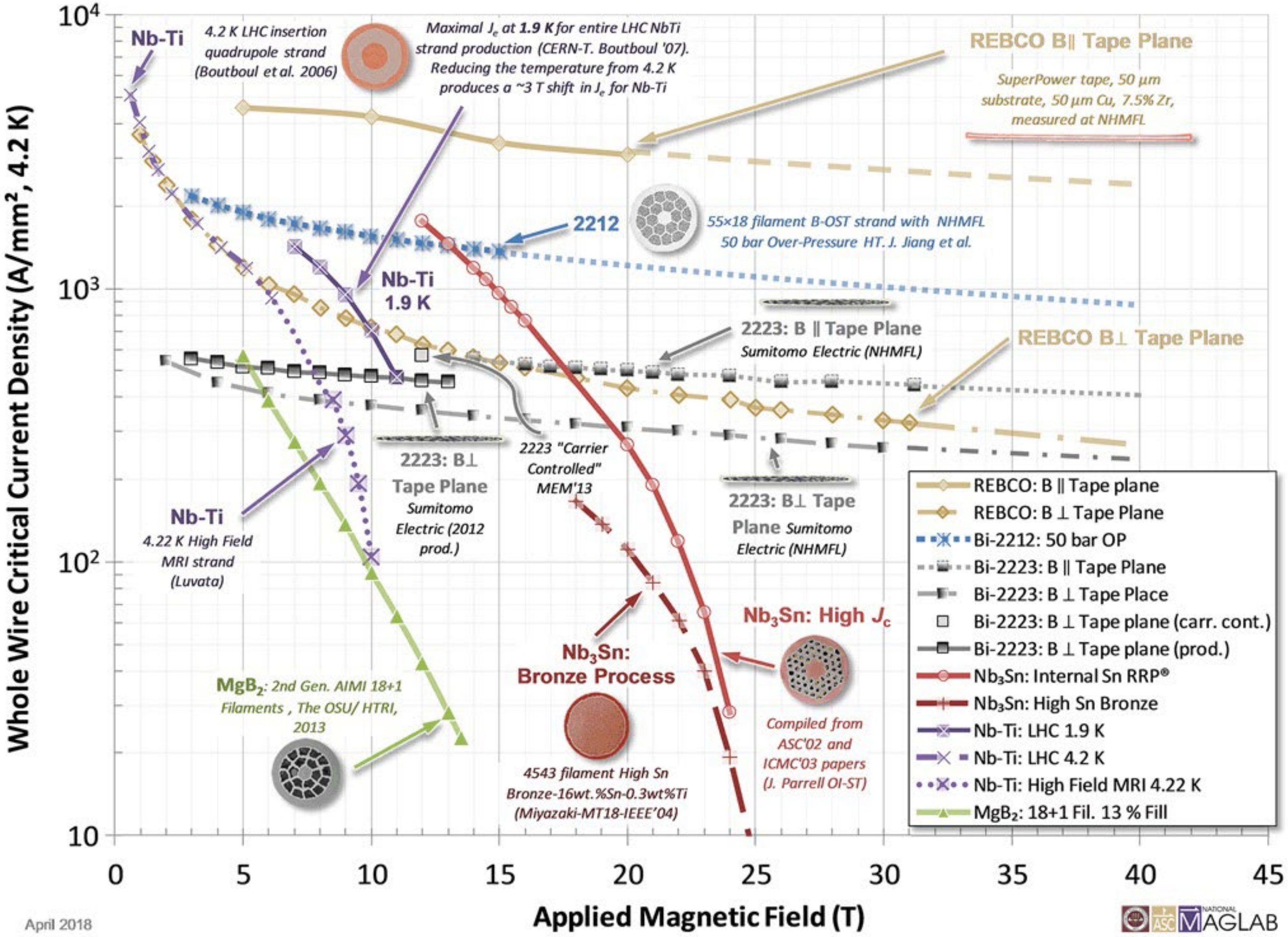
ELECTRICAL: Defined in terms of the critical J, T & B values

ELECTROMECHANICAL & THERMAL: Usually in terms of yield strength and stress induced J_c degradation including bending radius and thermal conductivity.

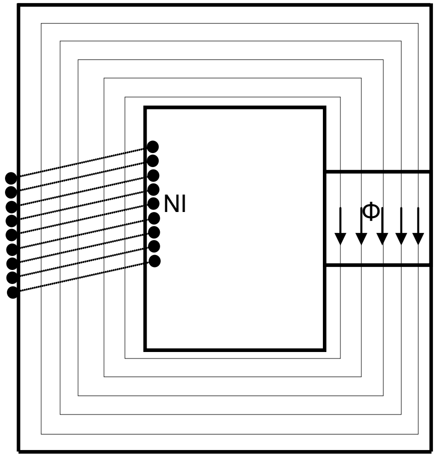
TECHNOLOGIAL: Which are more qualitative and related to their capability to fabricate magnets.

The Solution: Using Superconducting Materials (II)

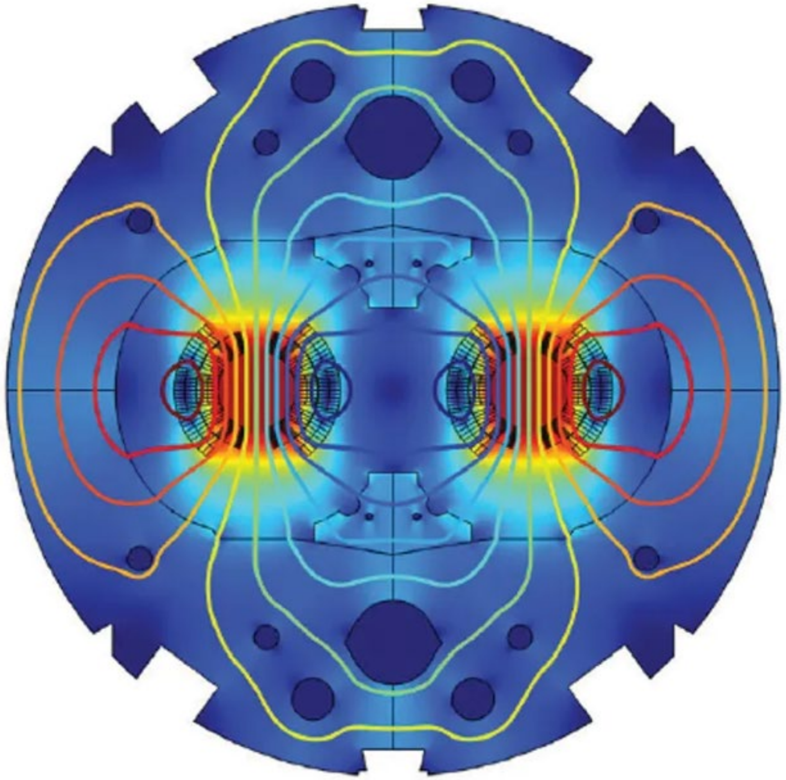
LTS & HTS electrical properties can be compared for a common low temperature (4.2K). Interesting features can be noticed such as the much sharper Jc drop with the field for LTS, the much smaller dependence of Jc with B, BUT also a much stronger anisotropy of Jc with the field orientation.



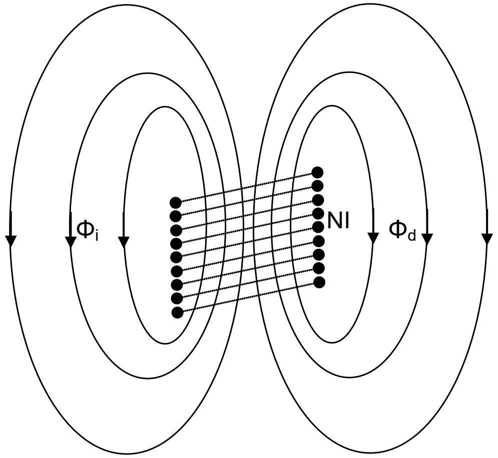
The Solution: Using Superconducting Magnets (I)



IRON-CORE MAGENT CONFIGURATION



SUPERCONDUCTING MAGNET CONFIGURATION



AIR-CORE MAGENT CONFIGURATION

In a Superconducting magnet, the field is basically imposed by the current and the conductor position, although, usually, some iron is used to close the magnetic circuit. Current density in the conductors can be three orders of magnitude bigger than for a resistive magnet. The price to pay: The magnet must work at cryogenic temperatures.

The Solution: Using Superconducting Magnets (II)

Superconducting dipole magnets for high energy hadron colliders: Tevatron (1983) (NbTi, warm-iron, small He plant, 4.5K), HERA (1991) (NbTi, Al collar, cold iron), RHIC (2000) (simple and economical design) and LHC (2008) (2K super fluid He, double bore) - courtesy of Dr. Alexander Zlobin, (Fermilab).

The Next Generation of HEP Accelerators and the Magnets they need

The ESPPU priorities for future particle physics accelerator facilities

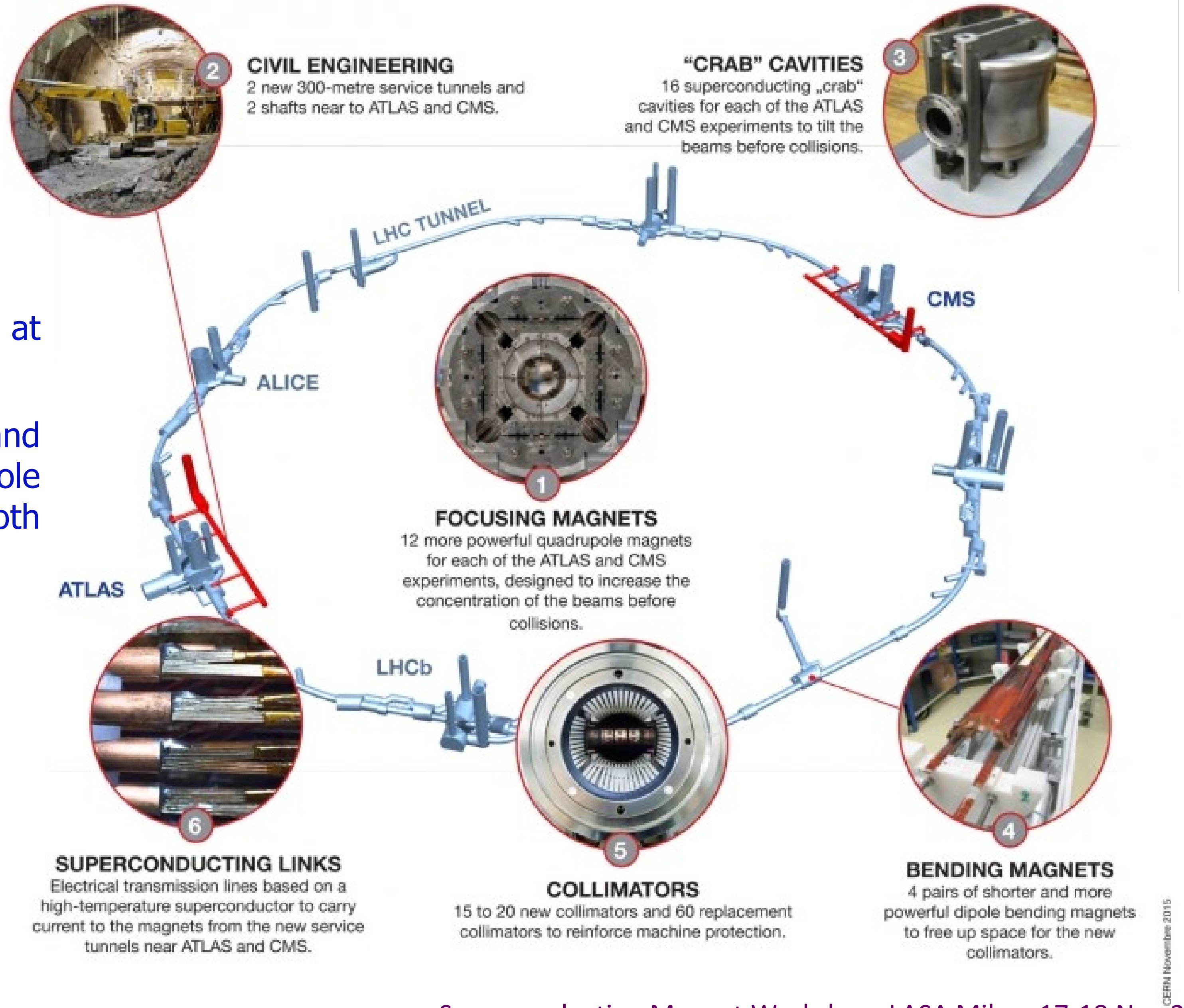
The 2020 update of the European Strategy for Particle Physics Update (ESPPU) outlined the current status and prospects in the field, and identified priorities for future particle physics accelerator facilities. In time order, these are: completion and commissioning of the CERN High Luminosity LHC (HL-LHC); a future electron-positron Higgs factory; and a future hadron collider at the highest achievable energy and luminosity.

Next SC magnets for future accelerators: The HL-LHC (1)

THE HIGH LUMINOSITY LHC

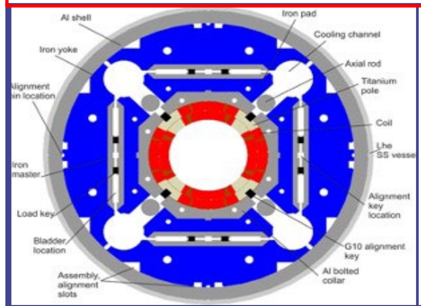
It is an upgrade of the LHC aiming at increasing its luminosity by a factor of 5.

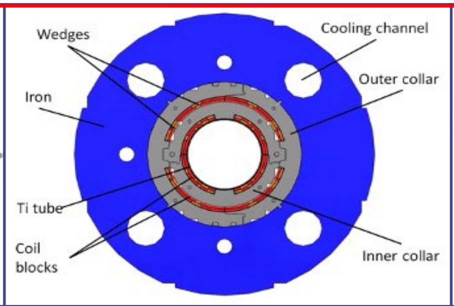
It includes different types of new and challenging magnets like the 11T Dipole magnet or the 130T/m Quadrupole, both using the Nb_3Sn technology.

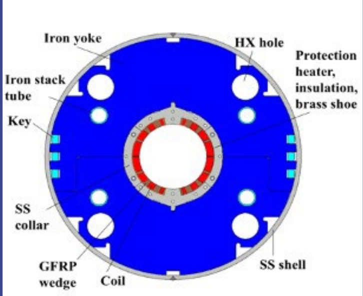


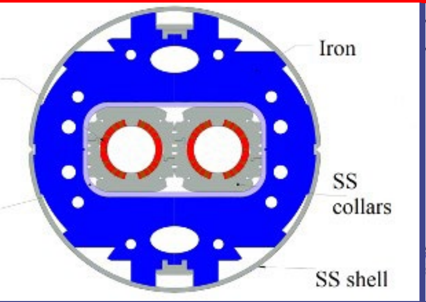
Next SC magnets for future accelerators: The HL-LHC (2)

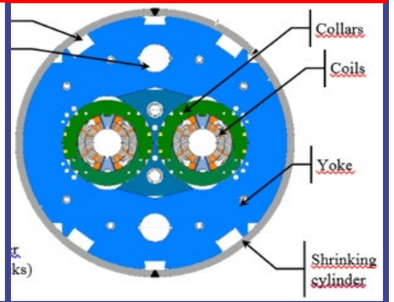
WP3 (Insertion Regions) | WP11





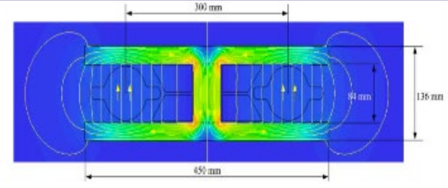
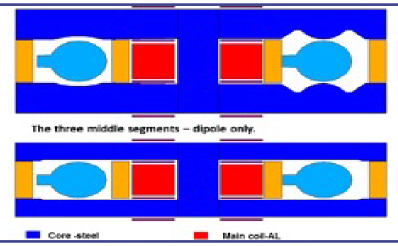
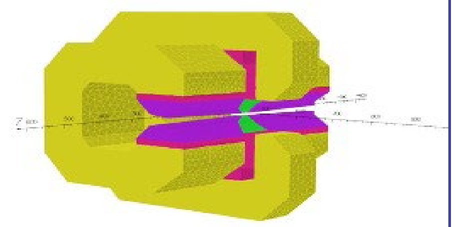
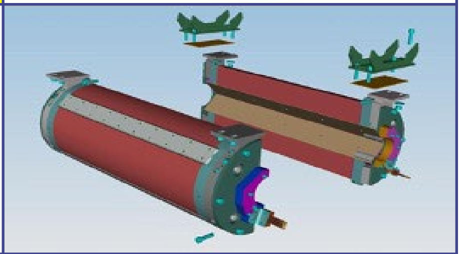
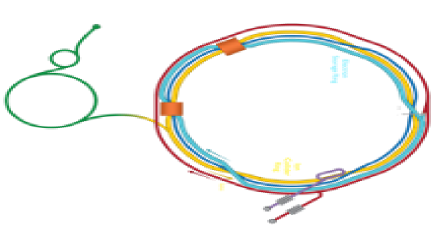




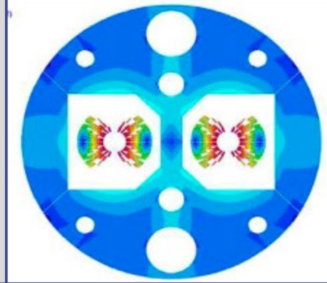
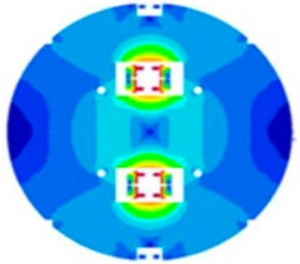
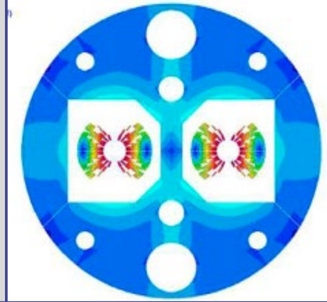
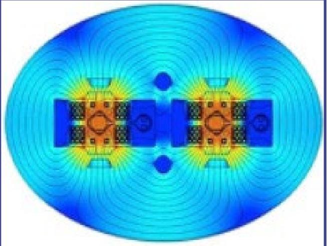


	MQXFA / MQXFB		MCBXFB/MCBXFA		MBXF (D1)	MBRD	MBH (11T)
Aperture (mm)	150		150		150	105	60
Material – Cu/NCu	Nb_3Sn (1.20)		Nb-Ti (1.75)		Nb-Ti (1.95)	Nb-Ti (1.95)	Nb_3Sn (1.15)
Field (T)			2.10/2.15	2.10/2.15	5.60	4.50	11.23
Gradient (T/m)	132.6						
Magnetic length (m)	4.20	7.15	1.2	2.2	6.26	7.78	5.31
Peak Field (T/m)	11.4		4.13		6.58	5.26	11.59
Temperature (K)	1.9		1.9		1.9	1.9	1.9
Current (A)	16230		1580/1430		12110	12328	11850
J overall (A/mm^2)	462		305/275		452	478	594
Load Line %	77		51		77	68	81
Stored energy (kJ)	4.91	8.37	0.077/0.143	0.134/0.239	2.13	2.26	5.13
Midplane stress (MPa)	108		40		91	51	134

Future Proposals for electron Colliders

Name	Type	Energy	Length	Magnets	
FCC-ee	Electron-Positron Non SC CIRCULAR Collider International collaboration hosted by CERN	<365 GeV	100 km	* 100 mT resistive magnets	
CEPC	Electron-Positron Non SC CIRCULAR Collider A Chinese Academy of Science proposal	120 GeV	100 km	* 70 mT resistive magnets -Solenoidal SC magnets -Sextupolar SC magnets	
CLIC	Electron-Positron Non SC LINEAR Collider collaboration hosted by CERN	3 TeV	11- 50 km		
ILC	Electron-Positron SC-RF LINEAR Collider international Collaboration (GDE)	250 GeV	31 km	Around 13000 magnets (2300 being SC)	
EIC	Electron-Ion CIRCULAR Collider based on the upgrade of the RHIC at BNL	20-140 GeV		Conventional water-cooled iron dominated magnets + SC NbTI magnets @4.2K	

Future Proposals for hadron Colliders

Name	Type	Energy	Length	Main Magnets	
FCC-hh	Hadron Circular SC Collider. International collaboration hosted by CERN	100 TeV	100 km	* 16 T @ 1.9K magnets based on a next generation of Nb_3Sn cable	
SPPC	Hadron Circular SC Collider. A Chinese Academy of Science design study	75-150TeV	100 km	* 12 T magnets based on Iron Based SC * 24T magnets based on IBS & HTS	
HE-LHC	Hadron Circular SC Collider. International collaboration hosted by CERN	30 TeV	27 km	* 16 T @ 1.9K magnets based on a next generation of Nb_3Sn cable	
Collider in the Sea	Hadron Circular SC Collider. Installed at sea in neutral buoyancy at 100m depth. A USA design study	500 TeV	1900 km	* 3.2 T magnets based on a cheap design using Nb-Ti technology	

Future Proposals for muon Colliders

Muon Colliders has emerged in the past years as promising candidates to provide unique opportunities for particle physics applications. Since its mass is 207 higher than that of electron, synchrotron radiation intensity is much smaller.
Although the idea is old (1969), now is becoming to be seriously considered with the creation of the International Muon Collider Collaboration (IMCC). **Solenoids are required for muon production & dipoles & quadrupoles for storage & focus**

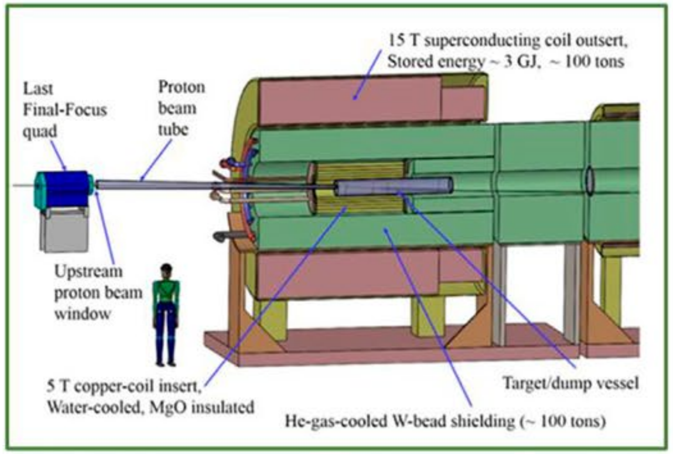
Solenoids for muon production

* Hybrid solenoid Outer Nb_3SN (15T)+Inner Resistive (5T) 300 mm aperture.

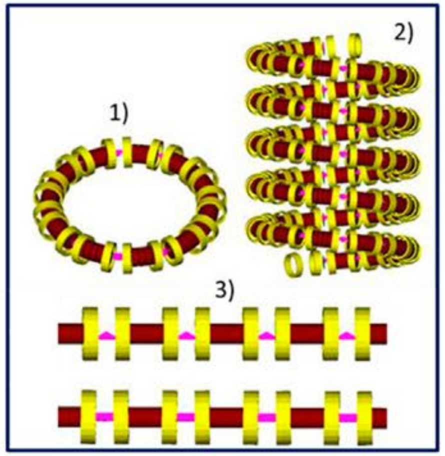
* 2T to 20 T Nb-Ti & Nb_3Sn solenoids

* 50 to 60 T LTS + HTS solenoids based on the 32T hybrid magnet

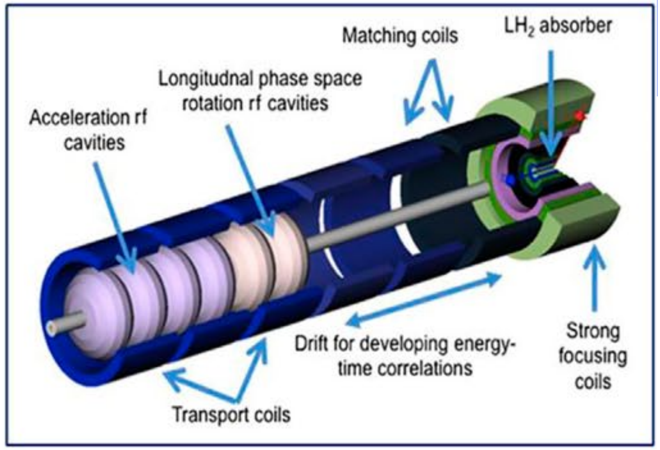
A MUON PRODUCTION



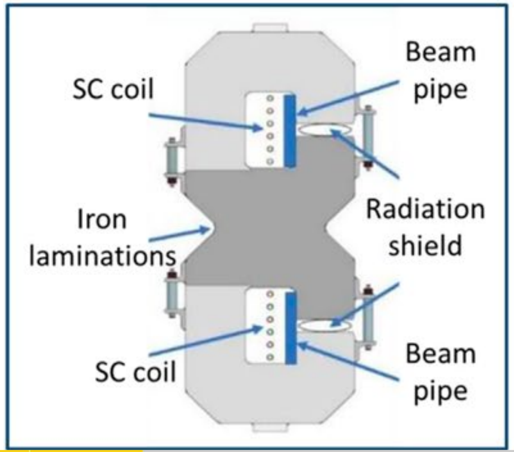
B MUON COOLING



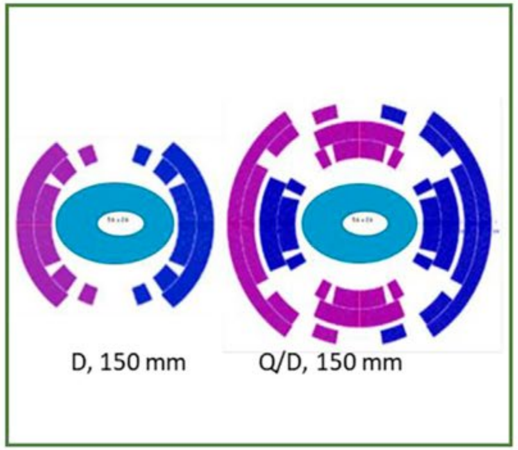
C FINAL MUON COOLING



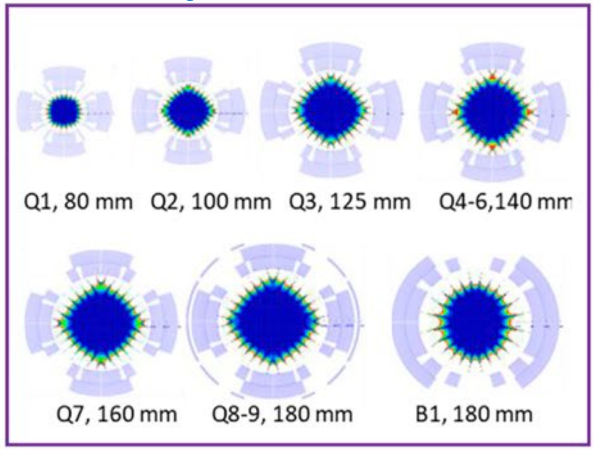
A SUPERFERRIC DIPOLES BASED ON HTS



B DIPOLES DIPOLE&QUADRUPOLE



C DIPOLE & QUADRUPOLES FOR THE IR



Magnets for muon storage & focus

* Superferric fast-cycling HTS dipoles

* Combined function 10.5T & 150 mm bore dipoles

* 250 T/m 80 to 180 mm aperture quads

* Possibility of Hybrid LTS+HTS 20 T magnet for a 10 TeV MC version

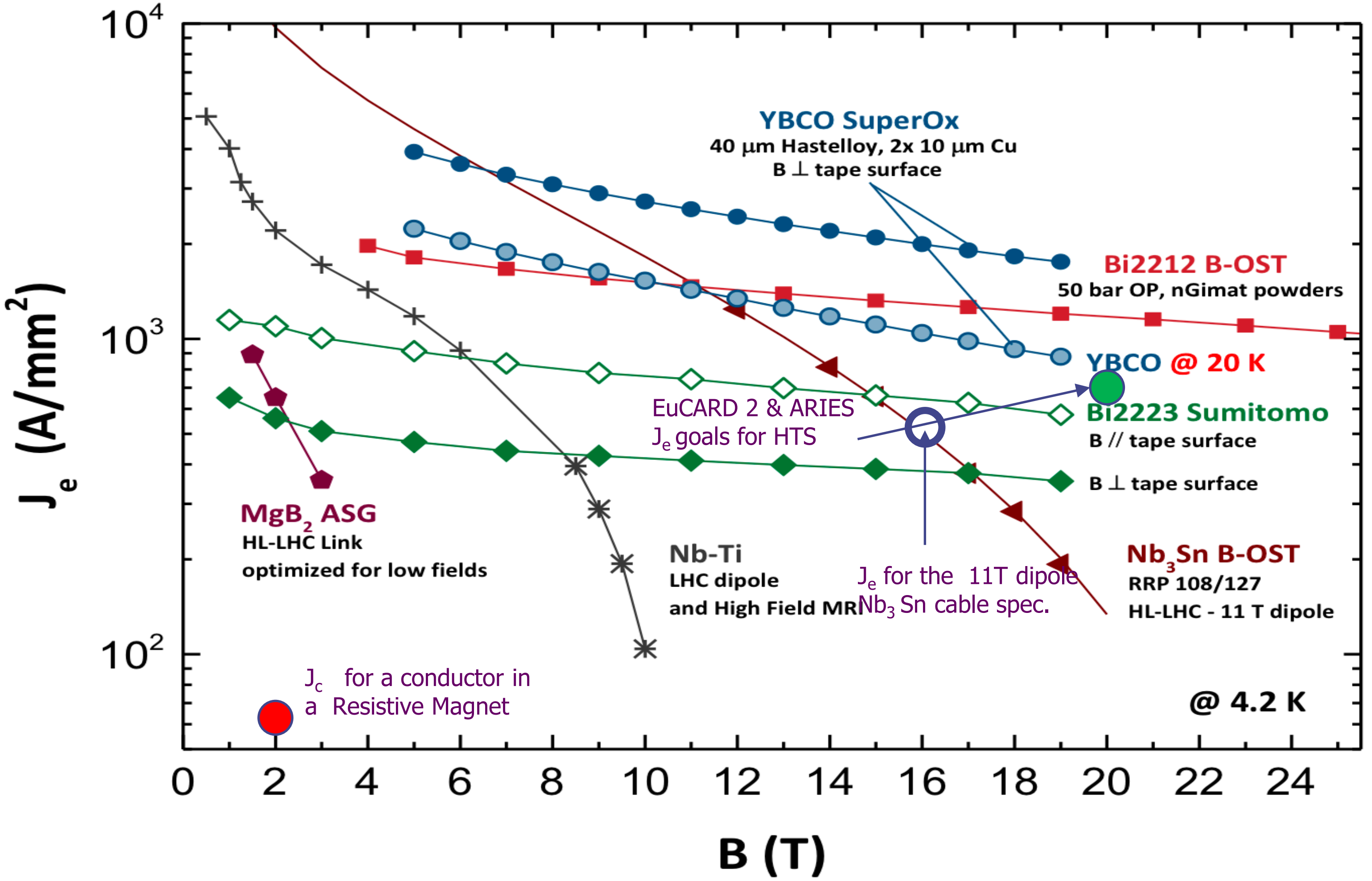
State of the Art of Superconducting Magnets for HEP Accelerators

Electrical Properties of Industrial Superconductors

This figure represents the J_e-B curve for the top performance present industrial superconductors

It includes:

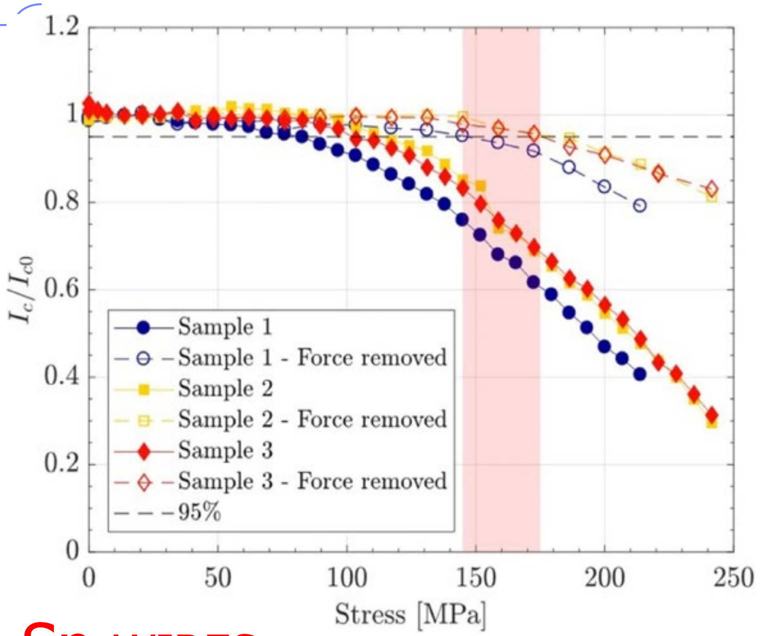
- Je for a resistive conductor
- Je for the present generation of Nb_3Sn wire (11T dipole) @16T
- Required goal for Je in HTS in the EuCARD program



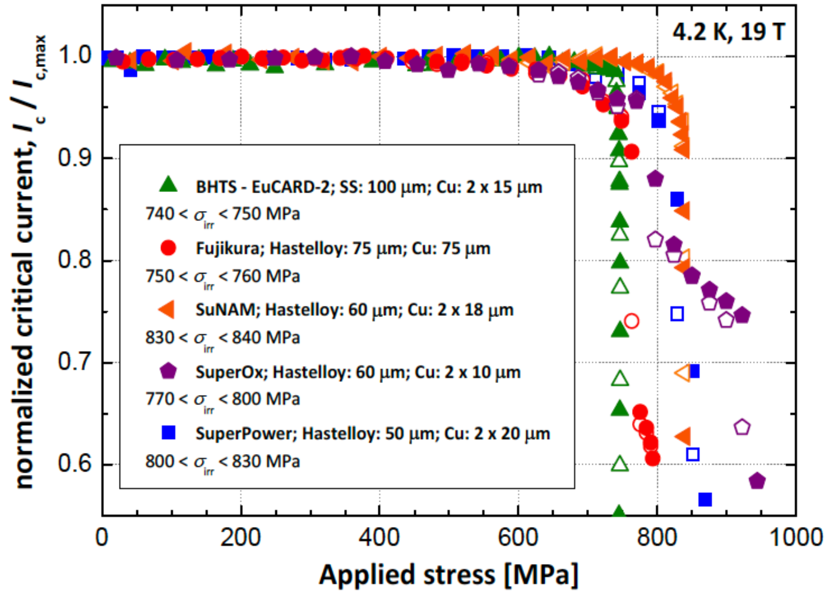
SOURCE: P. VEDRIN et. Al. European Strategy for Particle Physics. Accelerator R&D Roadmap

Electromechanical & Thermal Properties of Industrial Superconductors

SOURCE: L.ROSSI & C. SENATORE HTS Conductor & Magnet Accelerator Development in Europe



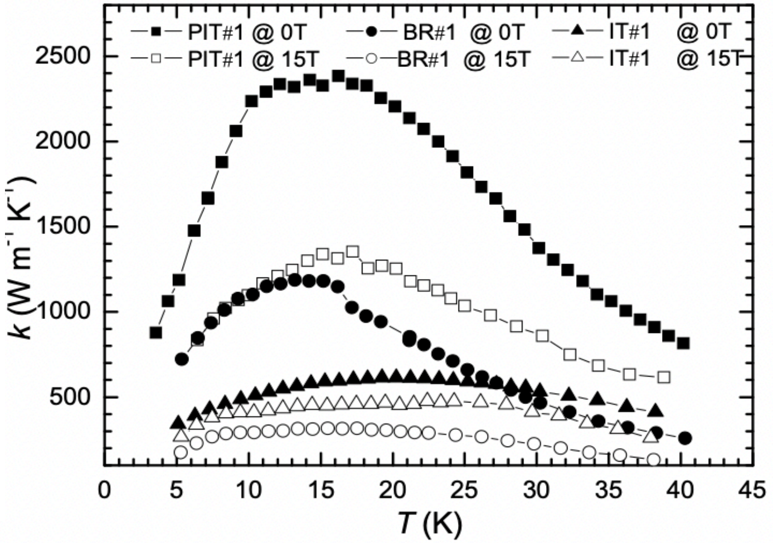
Apart from Electrical properties, Electromechanical & Thermal properties of the SC wires are also essential to define the performance of the magnet affecting its design and performance.



SOURCE: L.ROSSI & C. SENATORE HTS Magnet & Accelerator Conductor Development in Europe

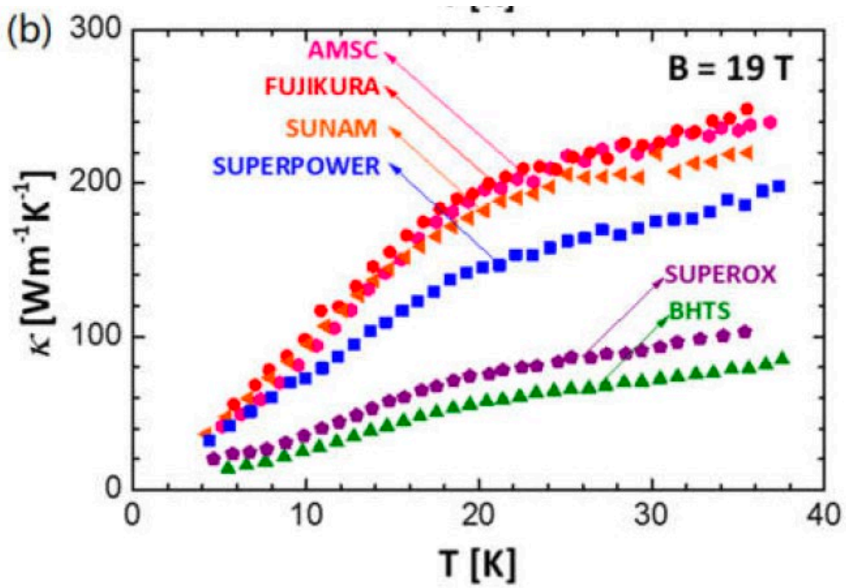
Nb_3Sn WIRES

SOURCE: M. BONURA & C. SENATORE Thermal Conductivity of Industrial Nb_3Sn Wires Fabricated by Various Techniques



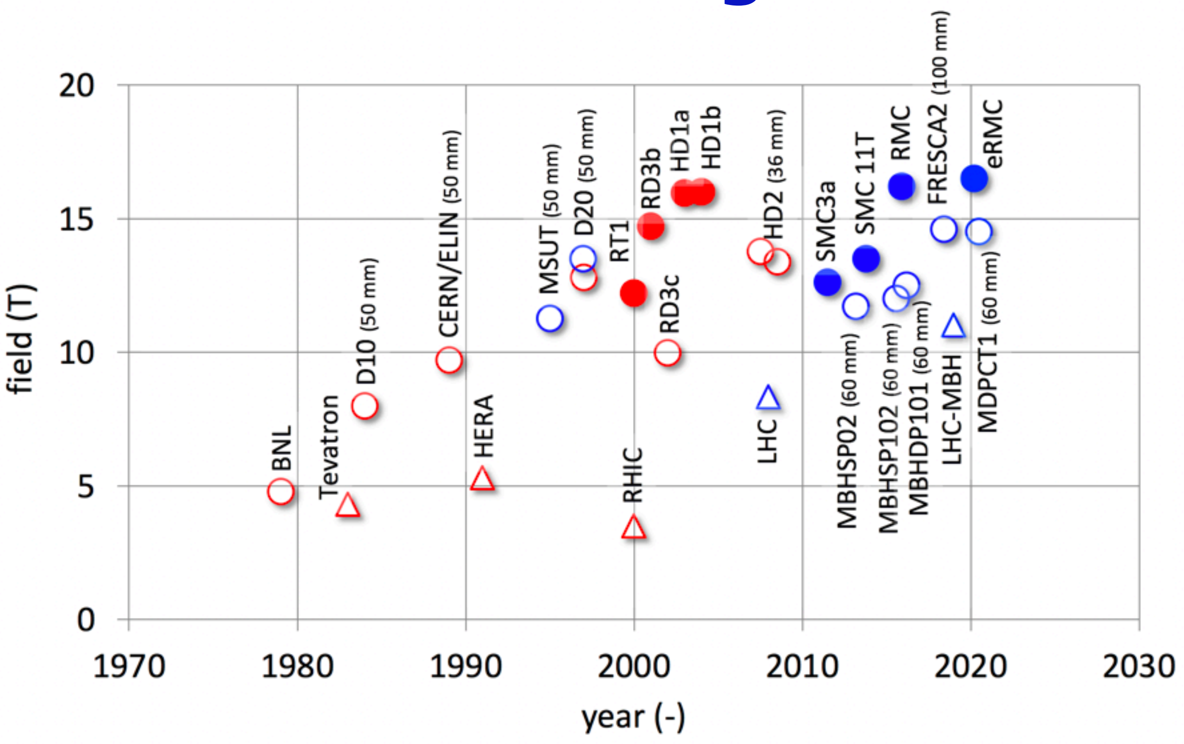
In general, stress degradation is more severe in Nb_3Sn and this requires to limit the stresses develop in the superconductor. On the contrary, thermal conductivity is much lower in HTS reducing the quench propagation velocity.

HTS TAPES

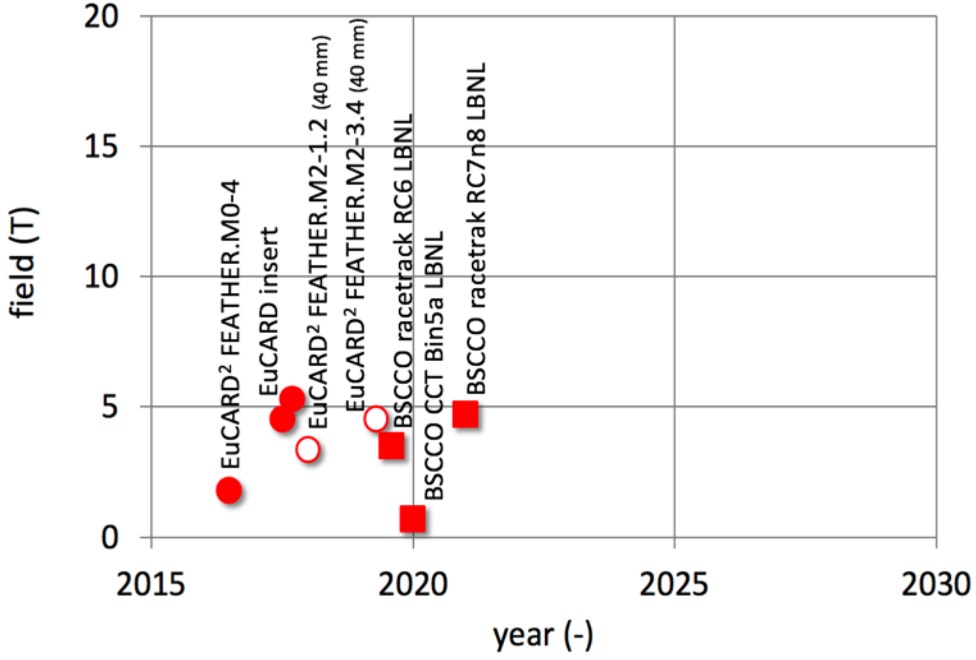


SOURCE: L.ROSSI & C. SENATORE HTS Magnet & Accelerator Conductor Development in Europe

Highest Fields attained so far (1)



SOURCE: L.BOTTURA, S.PRESTEMON, L.ROSSI & A.ZOBLIN Superconducting Magnets & Technologies for Future Colliders



Nb_3Sn MAGNETS

Fields attained with Nb3Sn dipole magnets of various configurations and dimensions, either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature. Solid symbols are short demonstrators, i.e. ‘racetracks’ with no bore, while open symbols are short models and long magnets with bore. For comparison, superconducting collider dipole magnets past and present are shown as triangles.

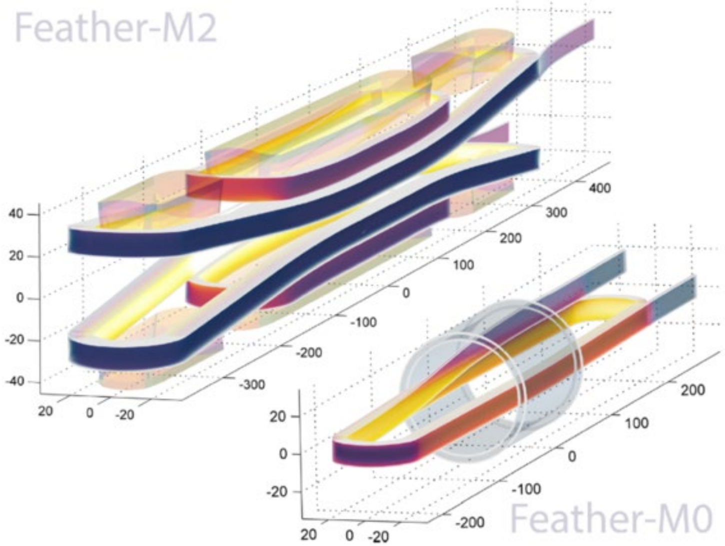
HTS MAGNETS

Fields attained with HTS short demonstrator magnets of various configurations, producing a dipole field. All tests performed in liquid helium (4.2 K). Solid symbols are racetrack magnets with no bore, while open symbols are magnets with bore. Round symbols are magnets built with REBCO, square symbols with BSCCO.

Highest Fields attained so far (2): Two examples

Nb$_3$Sn
Technology

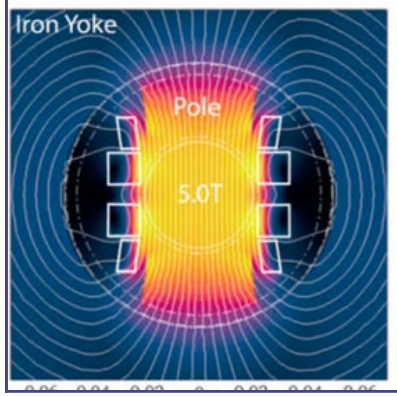
FRESCA2: A CEA-CERN Collaboration started in 2009 in the frame of EuCARD. Based on Nb$_3$Sn @ 1.9K. It reached 13,3 T in 2017 and 14.6 T in 2018 after a modification in the magnet prestressing



HTS
Technology

THE FEATHER PROGRAM: It is a 40mm aperture magnet producing a 5T field in a background field of 13 T (Produced by FRESCA2). Working at 10 kA and capable of producing Accelerator Field quality. It was done in the framework of EuCARD2 and uses Roebel REBCO-based cable

We still need to improve and overcome problems

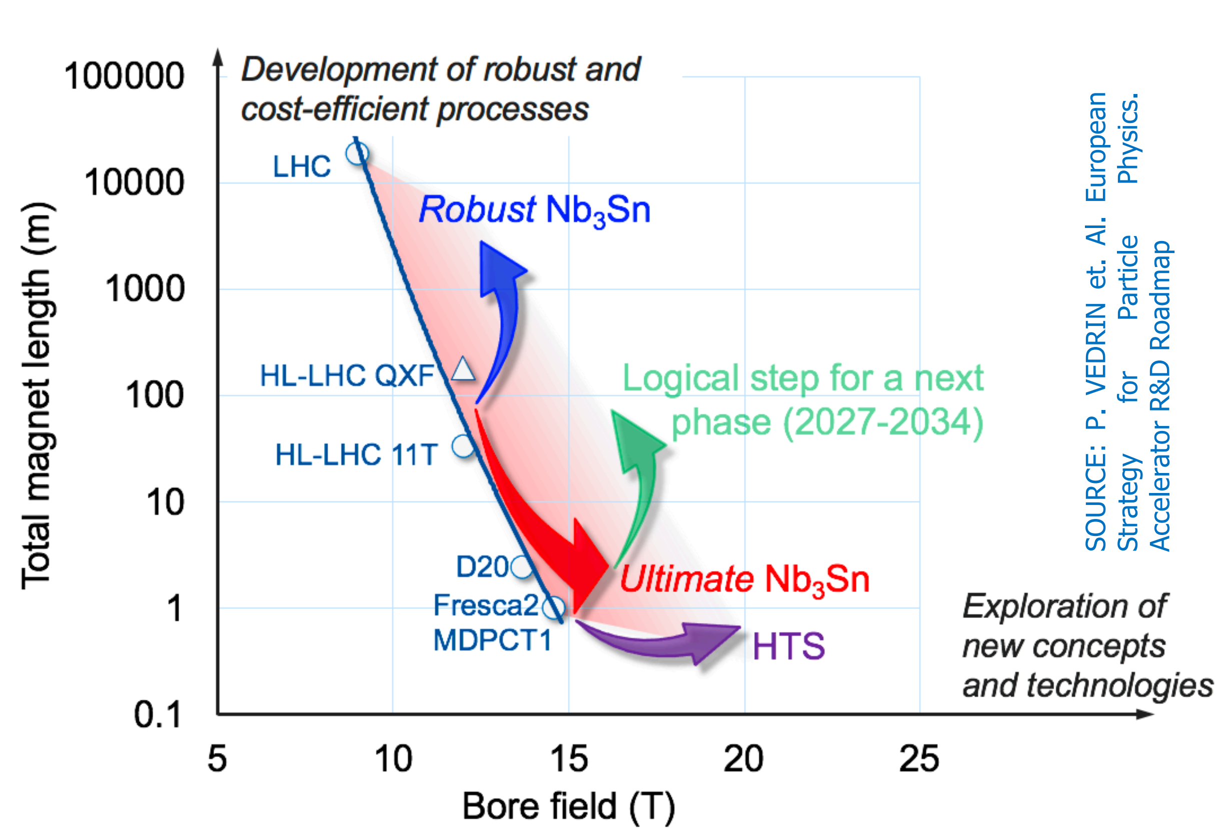
ISSUES	Nb_3Sn	HTS
WIRES & CABLES 	• **COST** (It is foreseen that SC cost for the FCC magnets will be 50% of the total cost). Mainly driven by HEP magnets > difficult to reduce • **INSULATION** (Able to withstand reaction required temperatures)	• **COST** push down bellow 100 \$/m: Driven by other applications >easy to reduce • **UNIT LENGTH SIZE** Going beyond 200 m • **LIMITED DEFECT DENSITY** • **INTERNAL RESISTANCE BETWEEN REBCO LAYER & CU** (R< $5 \cdot 10^{-12}$ Ωm^{-2})
MAGNETS 	• **COST** (Reduction of wire amount, Manufacturing automation increase, Novel preloading systems) • **LOW ENTHALPY** (1/100 less than HTS magnets) **AND SENSITIVITY TO SMALL HEAT DEPOSITIONS GENERATED** by: 1) Epoxy Craking 2) Stick-Slip coil movements 3) Epoxy metal debonding • **RELATIVELY LOW TOLERANCE TO MECHANICAL LOADS** (Beyond 150 MPa irreversible filament damage may occur) • **HIGH SENSITIVITY TO ASSEMBLY TOLERANCES** (Pre-loading levels are in the range of 100 Mpa) • **SENSITIVITY TO CYCLIC LOADS** (including thermal cycles and repeated quenching. It includes insulation degradation)	• **COST** (reduction of wire amount is mandatory and manufacturing automation increase) • **CABLE CONFIGURATION** (Roebel, Single tape, Double tape…) • **ADAPTABILITY TO ANY COIL GEOMETRY** (Cos ϑ, Block Coil, Flat Coil…) • **SPLICING** (Joints of unit lengths) **& LOSSES** • **DELAMINATION UNDER HIGH FIELDS** • **HANDLING THE STORED ENERGY** (E/m as the 2.5 power of B) • **QUENCH PROPAGATION VELOCITY** (one order of magnitude lower than for LTS magnets) • **QUENCH DETECTION SYSTEM** (Derived from the low propagation velocity)

Roadmaps and Short & Long Terms R&D Programmes for High Field SC Magnets

Overview of the HEP Accelerator Magnet Programmes

Country / Region	HEP Accelerator Magnet Programs
United States	• HL-LHC Accelerator Upgrade Project (US contribution of > 750 M$) • US Magnet Development Program: Performance limits of Nb_3Sn Magnets, HTS magnet >5T and hybrid operation >16T, Magnet Design & Optimization, Improving performances of Nb_3Sn & HTS wires & tapes • LARP (LHC Accelerator Research Program, a 15 year long programme) • LEAF (A program to demonstrate muon and hadron collider magnets to be developed from 2025-2035 aprox.)
Europe	• CARE, EuCARD, EuCARD2, ARIES ,iFAST & CERN-HFM Programme • LDG Roadmap for HFM HEP Accelerators (to be commented later)
Japan	• KEK R&D on NbTi, Nb_3Sn and HTS conductors & magnets along more than 40 years • Activities for the future, concentrated on: High precision 3D magnet technology, radiation-hard HTS magnets, HFM for future colliders.
China	• Research on IBS superconductors & magnets • The IHEP is working on 1) Superior performance HTS 2) High Current density /Low price HTS cables 3) Novel Stress management & Quench protection for HFM

The High Field Magnets (HFM) R&D Programme for 2021-2027



In 2021 CERN´s Council endorsed the Laboratory Directors Group (LDG) the development of an Accelerator R&D Roadmap which was executed by different Panels of Experts. One of these panels was devoted to Magnets for the next generation of HEP accelerators.

GOALS OF THE PROGRAMME

1. DEMONSTRATE Nb_3Sn MAGNET TECHNOLOGY FOR LARGE SCALE DEPLOYMENT

1.a) Quantify & demonstrate Nb_3Sn ultimate field

Conductor development and fabrication of model magnets aimed at achieving next generation ultimate field (16T)

2.b) Develop Nb_3Sn magnet technology for Collider-Scale production.

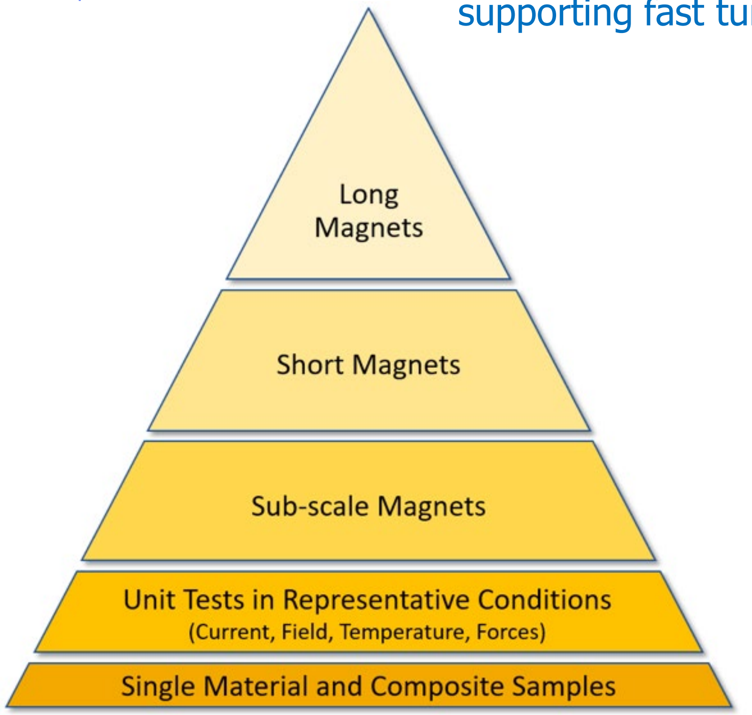
Fabrication of few tens of magnets able to achieve today´s ultimate field (>12T) with better performance tan present Nb_3Sn magnets (HL-LHC) . Fabrication processes adapted to an industrial production of thousands of magnets.

2. DEMONSTRATE THE SUITABILITY OF HTS FOR ACCELERATOR MAGNET APPLICATIONS

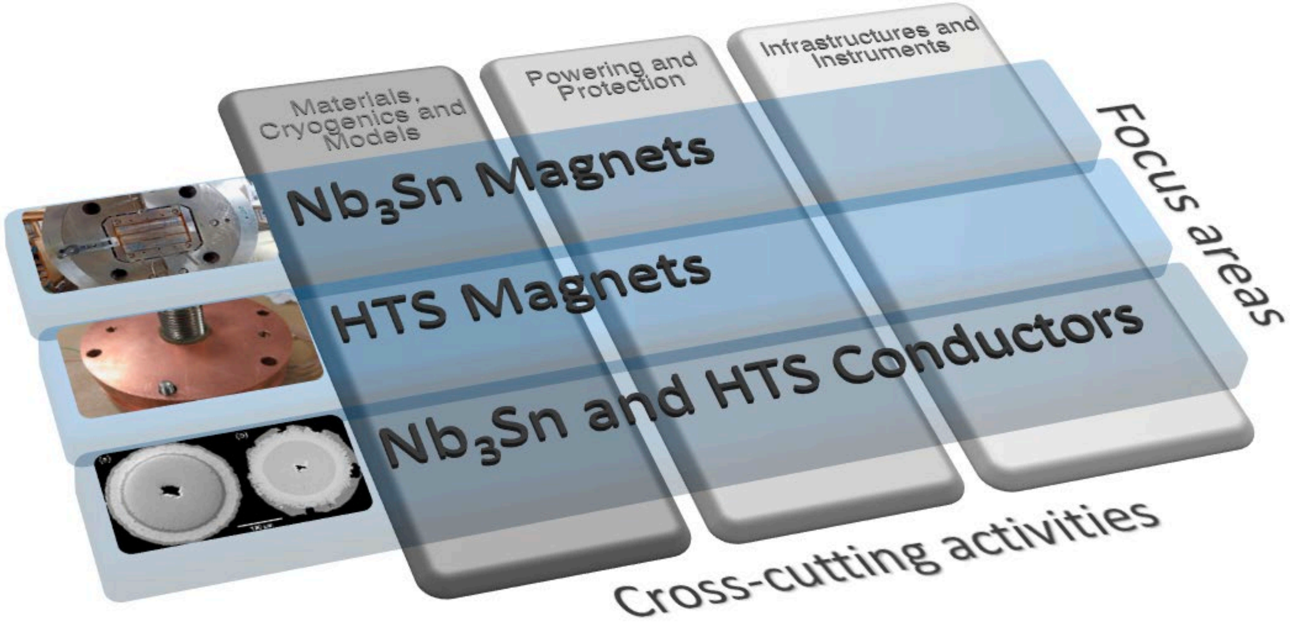
Probing a proof of concept of HTS magnet technology beyond the reach of Nb_3Sn. A suitable target dipole field could be 20T HTS to be considered for specific applications where not only high field is required but also higher operating temperature.

Innovation through a fast-turnaround R&D Programme

The Innovation Pyramid Concept, supporting fast turnaround development



SOURCE: P. VEDRIN et. Al. European Strategy for Particle Physics. Accelerator R&D Roadmap



Structure of the Programme: 3 Focus Areas supported by 3 Cross-Cutting activities

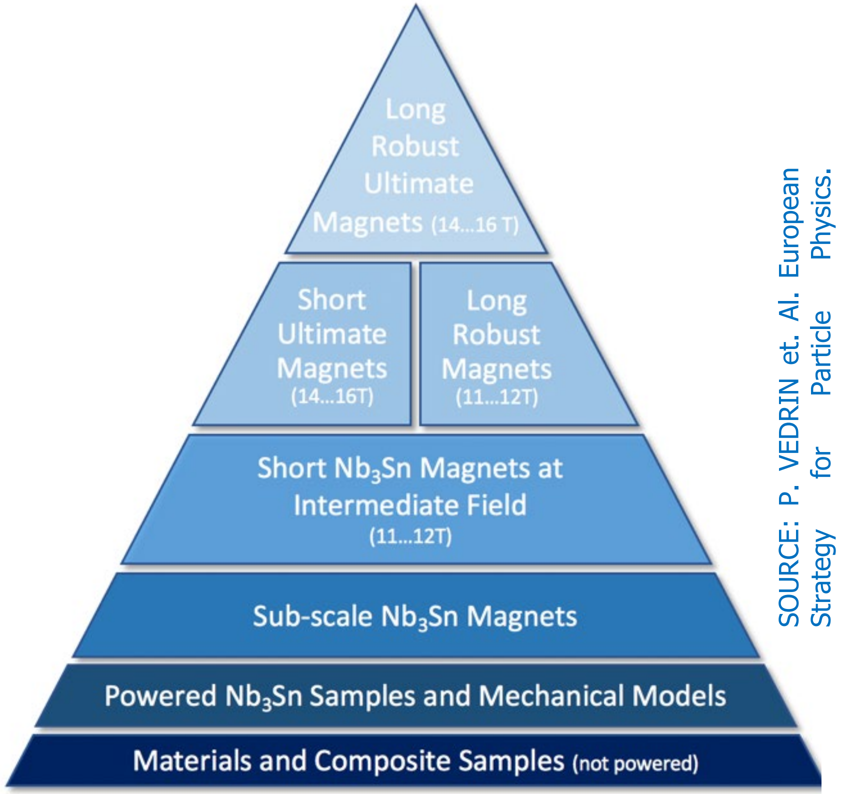
The HFM R&D Programme must achieve decisive progress in the 3 areas of **Performance, Robustness and Cost** for both Nb_3Sn & HTS **:**

Performance: Not only achieving the required field but retaining the performance avoiding degradation during operation

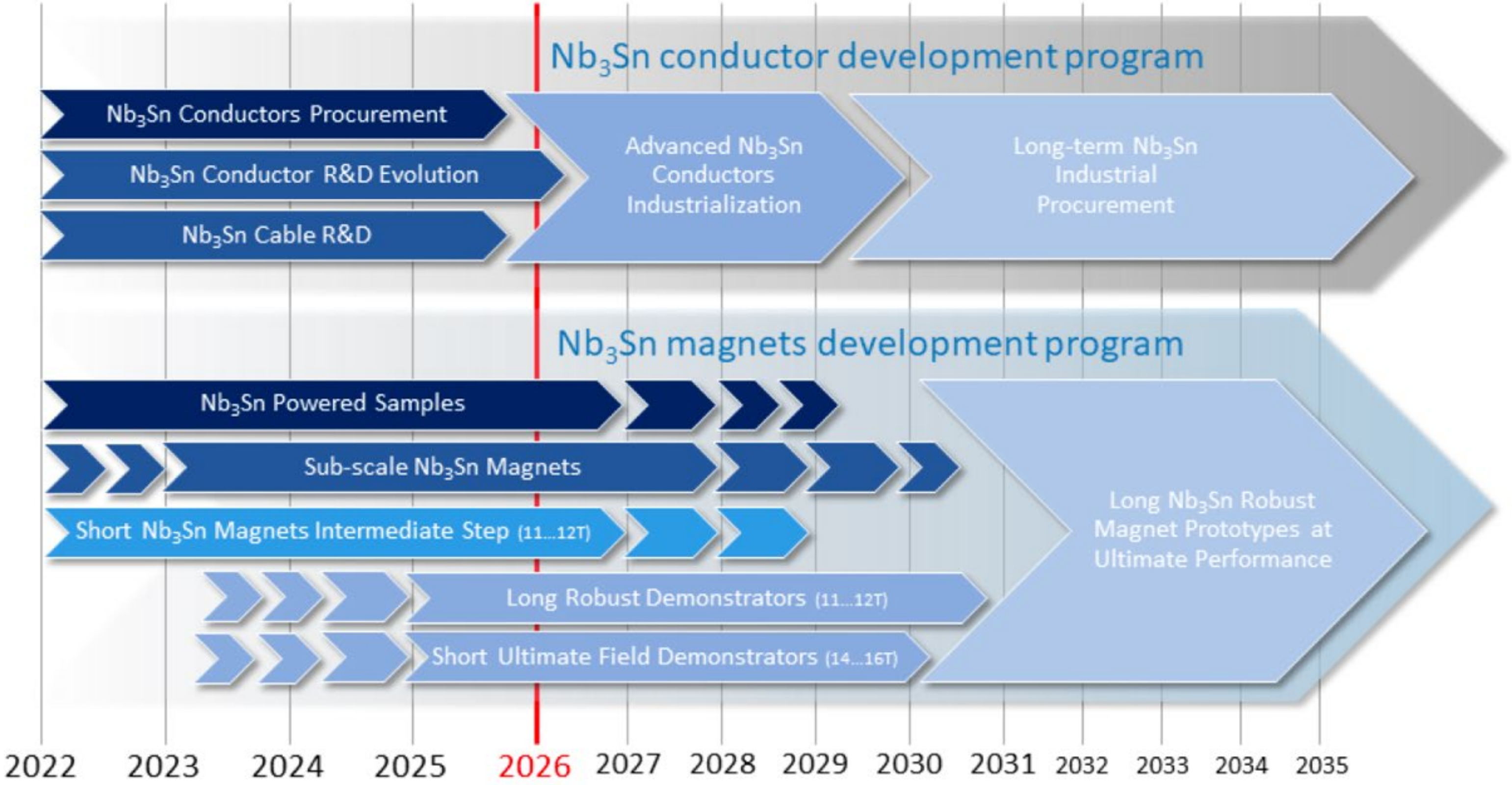
Technology Robustness: Measured in terms of scalability referred to dimensions and number of units

Cost Target: based on an accelerator scale production. It will impact on the design, process and material optimization

The Nb_3Sn Conductor & Magnet R&D Programme

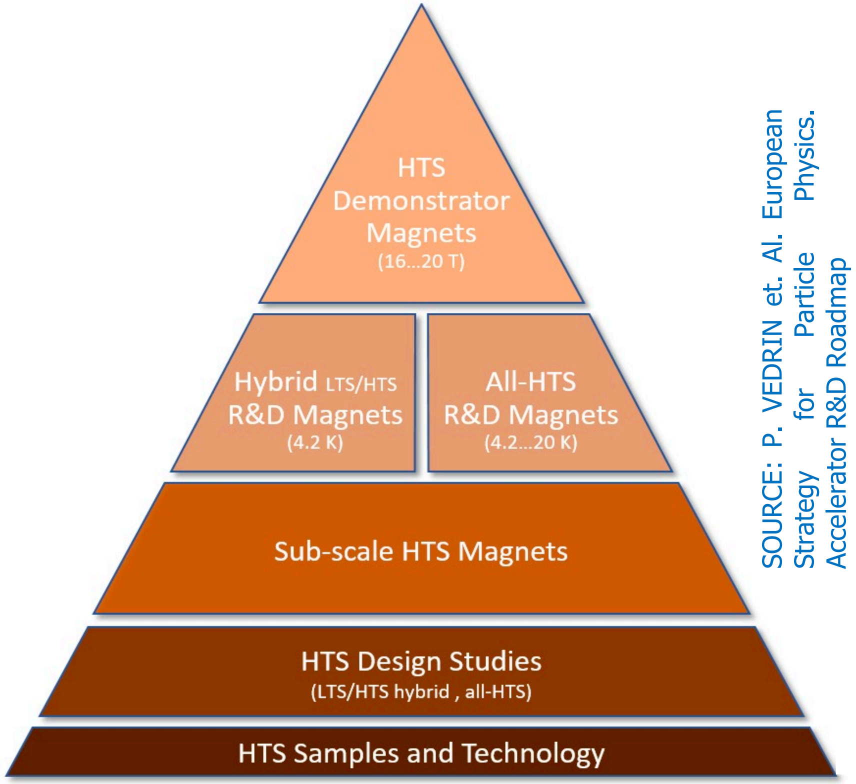


SOURCE: P. VEDRIN et. Al. European Strategy for Particle Physics. Accelerator R&D Roadmap

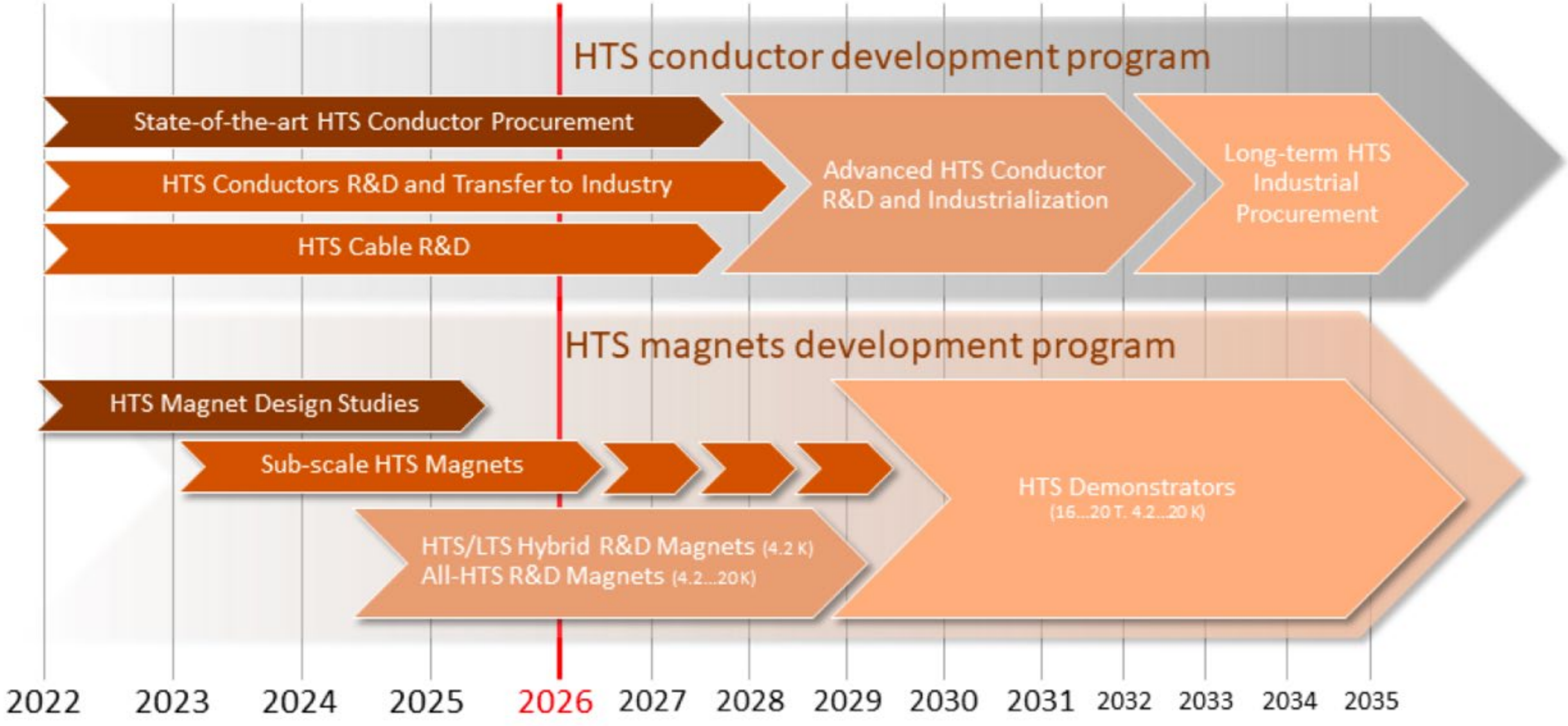


On the left hand side, the Technology Pyramid towards the development of Nb_3Sn ultimate dipole magnets. The first tasks are shared, then two final objectives are pursued in parallel: The left path towards ultimate-field Nb_3Sn Accelerator Magnets, the right path towards long Nb_3Sn robust Accelerator magnets. On the right hand, the timeline to achieve the Pyramid goals.

The HTS Conductor & Magnet R&D Programme

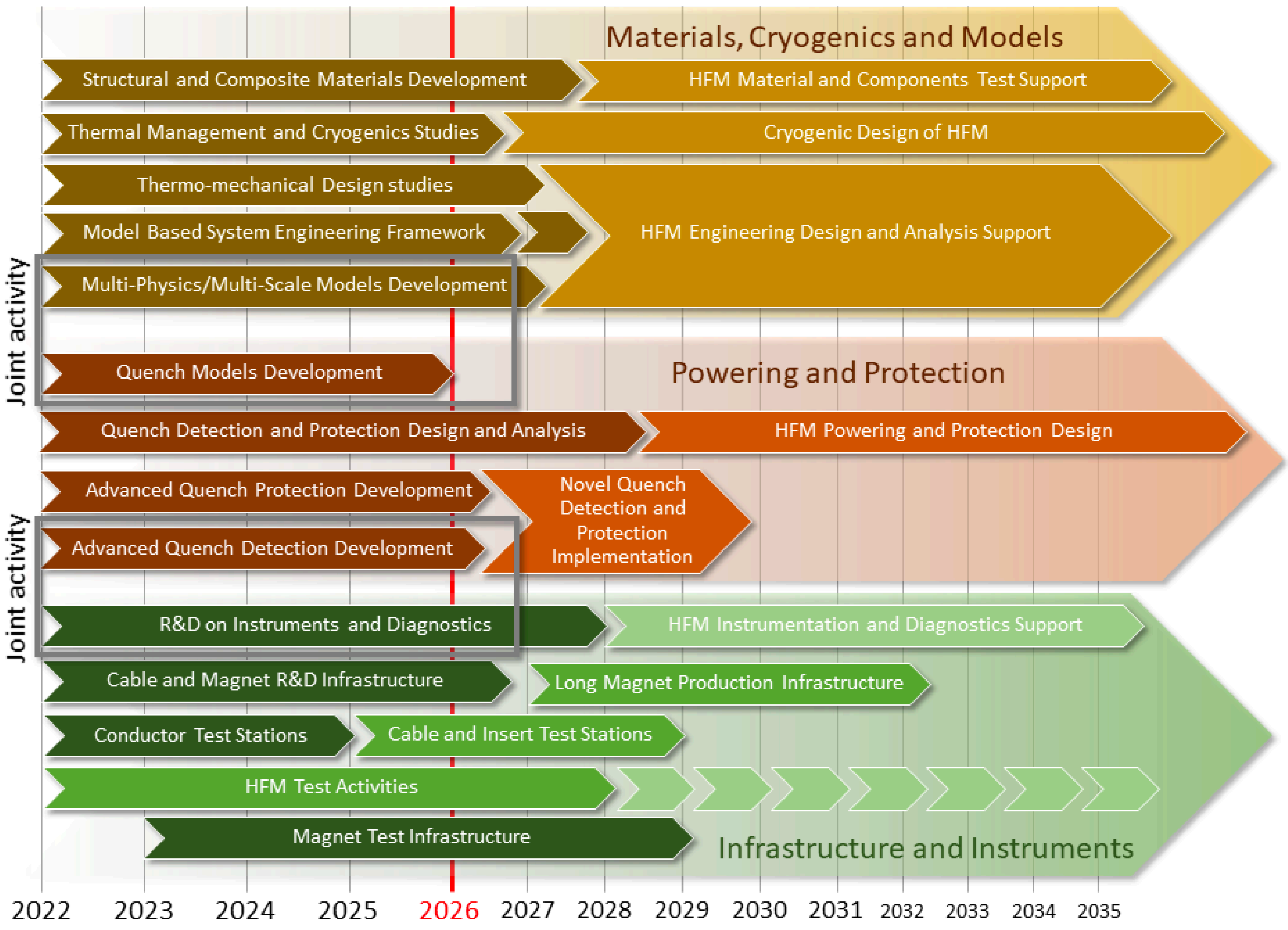


SOURCE: P. VEDRIN et. Al. European Strategy for Particle Physics. Accelerator R&D Roadmap



On the left hand side, the Technology Pyramid for HTS magnets. The first steps are exploratory and depend heavily on the results of the design studies. Sub-scale magnets will precede the work on the two identified routes of hybrid or all-HTS magnets. It will conclude in the design, construction and test of HTS demonstrator magnets

The HFM Associated Technologies R&D Programme



SOURCE: P. VEDRIN et. Al. European Strategy for Particle Physics. Accelerator R&D Roadmap

MATERIALS: It includes all the materials & components for the construction of magnets (exc. Superconductors). Characterization at room & cold of mechanical, thermal, electrical & tribological properties. **CRYOGENICS**: To deal with the extra He consumption @ 1.9K required for FCC versus HTS @ 10K **MODELS**: Integration of new modelling & simulation tools.

POWER & PROTECTION: Will be devoted to developing strategies and methods to detect and safety dump the magnet stored energy, specifically for Nb_3Sn & HTS.

INSTRUMENTATION & INFRASTRUCTURES: Workshops for the construction of short magnets as well as cryogenic facilities for small components, short magnets and demonstrators as well as identification of critical missing capabilities including manufacturing infrastructures for cables and magnets and test stations and instrumentation for wires and magnets

Summary & Conclusions

> Present and future Particle Accelerators require powerful magnets that can only be superconducting magnets

> Although the major needs come from bending magnets, other types should also be superconducting

> In this context, three possible scenarios appear:

* LTS Magnets: Limited to ≈ 12-16T. Affordable & use a well known technology
* HTS Magnets: Unaffordable for the All-HTS. Possibility of working at higher temperatures (≈ 20 K)
* Hybrid Magnets (LTS+HTS): Allows increasing the field up to 20 T

> ESPPU Roadmap for future accelerators establishes three global sequential phases: Completion of the HL-LHC, Construction of a Higgs Factory and Development of a highest possible energy Hadron Collider

> Future Accelerator magnets requirements can be grouped in **Electron Colliders** (SC are not relevant although there will be many) **Hadron Colliders** where SC magnets will be protagonist and **Muon Colliders** with also a great presence of SC magnets

> At this moment field up to 14T with LTS and 5 T with HTS in a 13T background field have been achieved

> A number of Roadmaps and R&D Programmes are ongoing or have been running recently in USA, Europe, China & Japan

> In 2021 CERN´s Council endorsed LDG to carry out a Roadmap on HEP Accelerator Magnets with the goals of demonstrating the Nb_3Sn magnet technology for large scale deployment and the suitability of HTS for Accelerator Magnet Applications.