HTS program at CERN

Daniel Schoerling

On behalf of the HTS team

Muon Collider Workshop, 2nd of April 2020

Outlook

- Mandate
- The elements of the HTS program (projects and technologies)
- Some thoughts
- Conclusion

Mandate

- Design, construction and measurements of magnets using high-temperature superconductors for particle accelerators and beam lines.
- Development of associated technologies, namely high-temperature superconductors and cables, insulation, splices and magnetic measurements for the application in magnets using high-temperature superconductors
- Establish collaborations with other institutes working in the field of high-temperature superconductors and their application in magnets
- Give support to other applications, detectors, high-field solenoid, medical and energy applications employing high-temperature superconductors

Accelerator magnets? For which machine?

Synchrotron radiation $\Delta \boldsymbol{E}_{turn} = P\frac{2\pi\rho}{c} = \frac{e^2}{3\varepsilon_0 E_0^4}\frac{E^4}{\rho}$; Magnetic rigidity $\boldsymbol{B\rho}[\boldsymbol{Tm}] = \frac{10^9 p}{cz} = 3.3356\frac{p}{z}$

Electrons $E_0 = 511\ keV$

- elementary particles
- linear : energy limited by the length. CLIC in 50 km would give (1.5+1.5 TeV). ILC is much lower energy.
- circular : energy limited by synchrotron radiation. For a FCC e-e in 100 km with 200+200 GeV the required RF voltage is 11 GeV/turn (three times more than that for LEP 200). With a beam current of 5.4 mA this gives about 60 MW RF power!

Protons $E_0 = 938\ MeV$

- state of the art is LHC : length 27 km, energy 7+7 TeV, $B = 8.3\ T$.
- FCC-hh would give 50+50 TeV, length 100 km, $B = 16\ T$: the limit is the magnetic field.

Muons $E_0 = 106\ MeV$

- elementary particles, synchrotron radiation much lower than with electrons
- muon colliders up to multiple TeV energies shall be compact machines and fast ramping : muon lifetime is very short (only $2.2\ \mu s$), though increases with the Lorenz factor. At 1 TeV $\gamma = \frac{E}{E_0} \sim 10000$

Other types of particle acceleration & physics beyond colliders (PCB)

The leading questions

Q6: What is the potential of HTS materials for high-field superconducting accelerator magnets ?
Q7: Is HTS a material suitable for accelerator magnet applications, from cables to magnets ?
Q8: What engineering solutions are required to build such magnets, including consideration of material and manufacturing cost ?

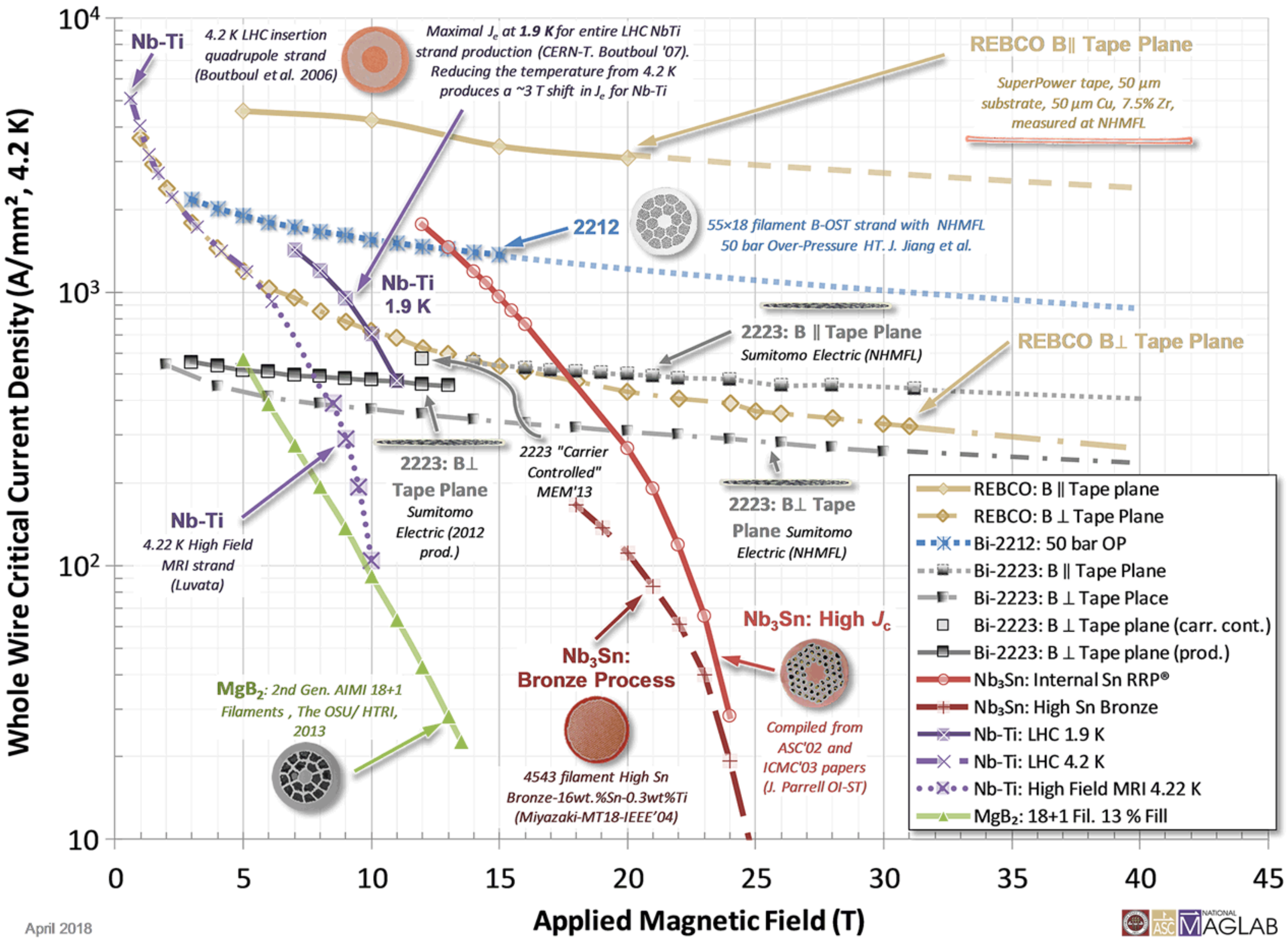
In this presentation we develop a program to address these questions.

Aim

The aim is to build in the next 10 years an ‘accelerator-like’ short model magnet reaching around 20 T for a future circular collider (hadron or muons), which shows that

- these field levels can be reliably reached, managing effectively the mechanical stress
- ramps in the order of 10 min to nominal field are feasible
- protection, if powered in series, is feasible
- reasonable field quality level is within reach, acceptable for next-generation colliders (complimentary to the FCC present baseline)

Overview conductor options



https://fs.magnet.fsu.edu/~lee/plot/plot.htm

Same strategic decisions and thoughts

We believe that

- ReBCO tape is at the moment the most promising conductor option. We closely observe the development of BISCO conductor in the US.
- We have to go in small steps towards a 20 T magnet, starting with very small coils, simple winding geometries, inserts with lower field to inserts reaching 20 T in a background field. After this development, we have to take a decision, if a 20 T will be all HTS or a LTS/HTS hybrid
- It is too early too take a decision on the cable concepts (tape-stack, Roebel, CORC). At the moment, we focus on tape-stack and Roebel, but we observe closely the development of CORC in the US
- CCT is an interesting design option being pursued mainly in the US. Therefore, we do not study CCT for HTS at CERN at the moment
- Due to the larger margins (*T*, *B* and *J*) in HTS wrt LTS the quench behaviour is significantly different and we cannot build an HTS magnet in the same way as an LTS magnet. We need therefore a change in the way we look at the problem of quench detection and magnet protection
- Hybrid magnets risk to pose all the problems of HTS and LTS into the same device. Tests of HTS inserts in LTS outserts will give us more experience with this. Nevertheless, at the moment with the available knowledge we have we think that hybrids are more difficult than full HTS magnets.

The HTS program: Projects

PROJECTS, on-going and proposals		Status
Program Coordination	until 30.06.2020	ongoing
	after 30.06.2021	ongoing
High-field accelerator magnets for hadrons		ongoing
	Small Coils	ongoing
		ongoing
		ongoing
	Cloverleaf dipole	ongoing
		ongoing
	Feather-2 inserts	ongoing
		ongoing
	Quadrupoles for IR (triplets)	TBD
High-field accelerator magnets for electrons/positrons		ongoing
	Wiggler/undulator for damping rings	ongoing
		06/2022
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	30+ T solenoids for a muon source	TBD
Magnets for physics byeond colliders		
	HTS Demonstrator Magnet for Space	06/2021
		03/2021
Infrastructure built with HTS		TBD
	High-field solenoid insert for wire test station (6-10 T)	TBD
Medical accelerator magnets		
	NIMMS WP2 technology study	04/2020
	HITRI machine design study	06/2020
	I-FAST (Aries2)	06/2020
	GaToroid (until 12/2020)	
		12/2020

1st priority of the program (80+% of resources)

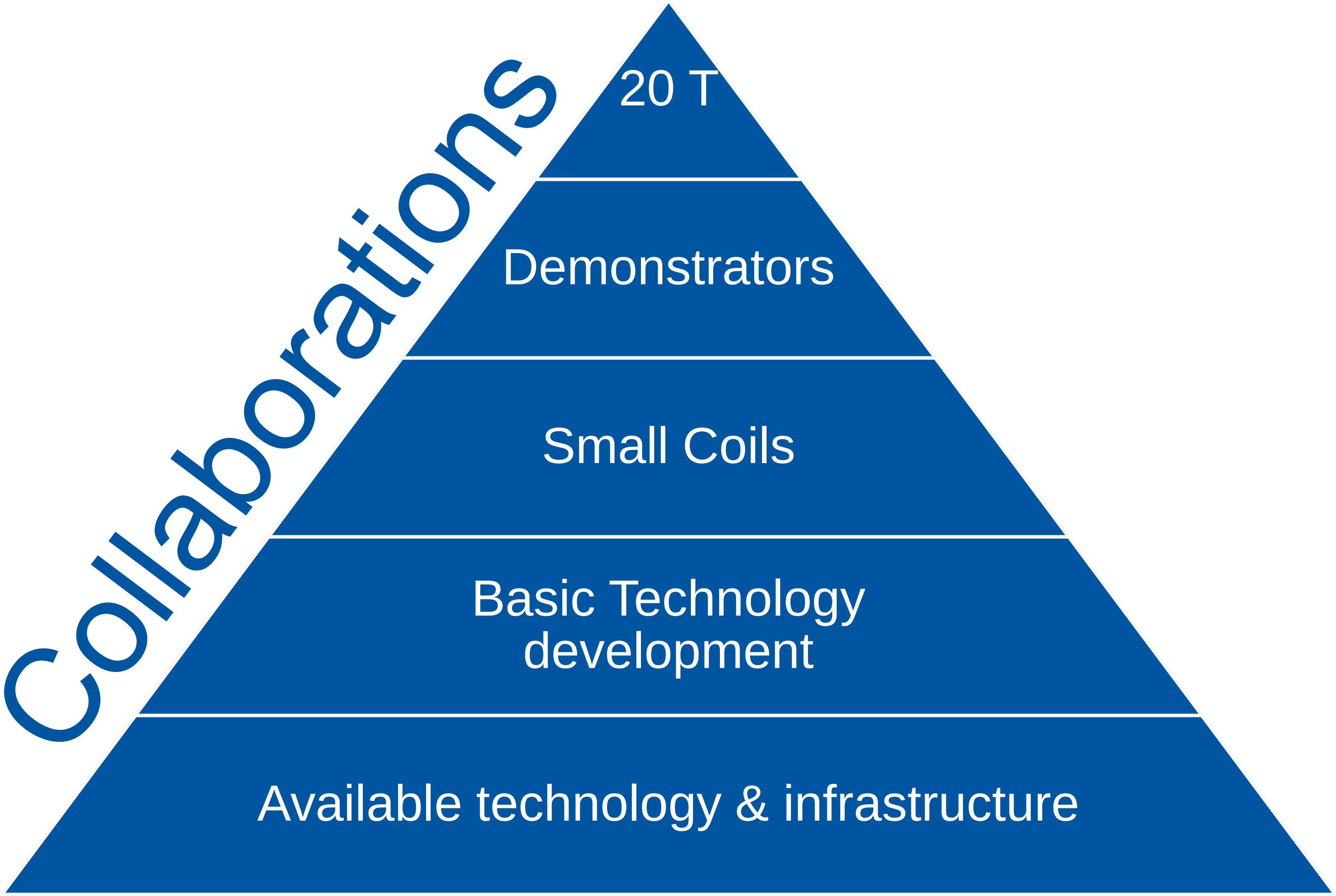
Core mandate of CERN

KT, related to CERN's physics program

Infrastructure of CERN

KT, activities to be discussed

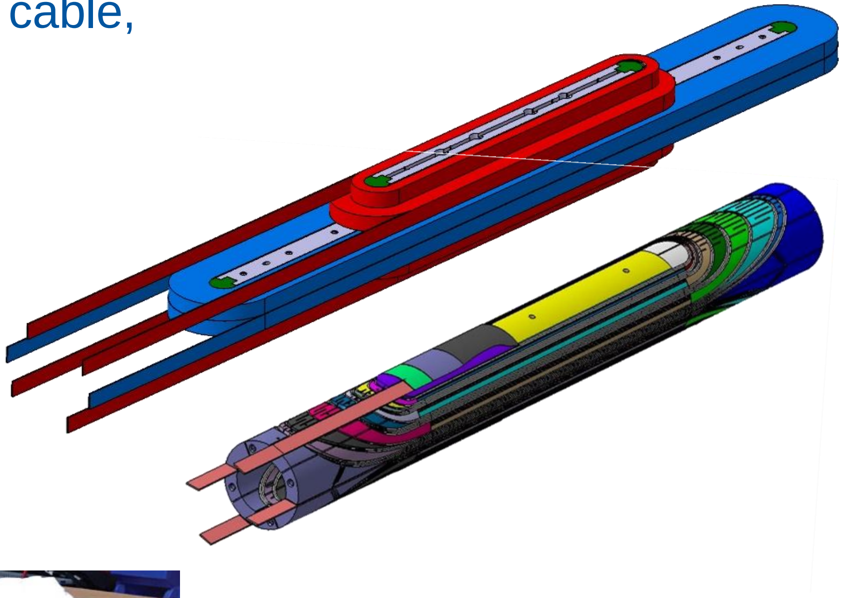
High-field accelerator magnets for hadron colliders: Flowchart



High-field accelerator magnets for hadrons

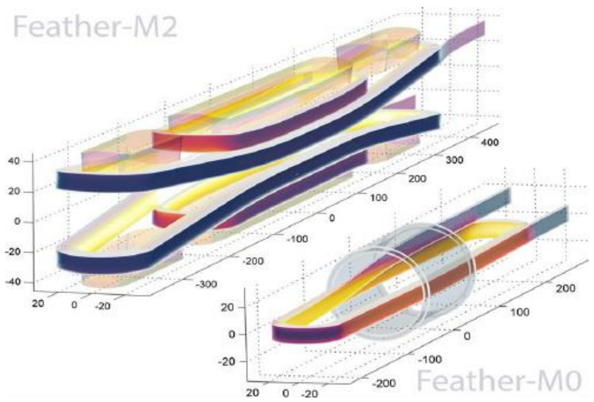
Core part of the program –today– is the development of a 20+ T magnet hadron collider style

EuCard1 and 2 magnets from CEA



Approach 1: EuCard2 (inserted in Fresca-2, magnet using transposed Roebel cable, insulated):

- Feather0, tested
- Feather2(1,2,3,4), tested, to be repaired; cable available for #5 and #6 and production for #7 underway (a field of ~4 T was reached)
- Cos-theta (CEA) to be tested at CERN

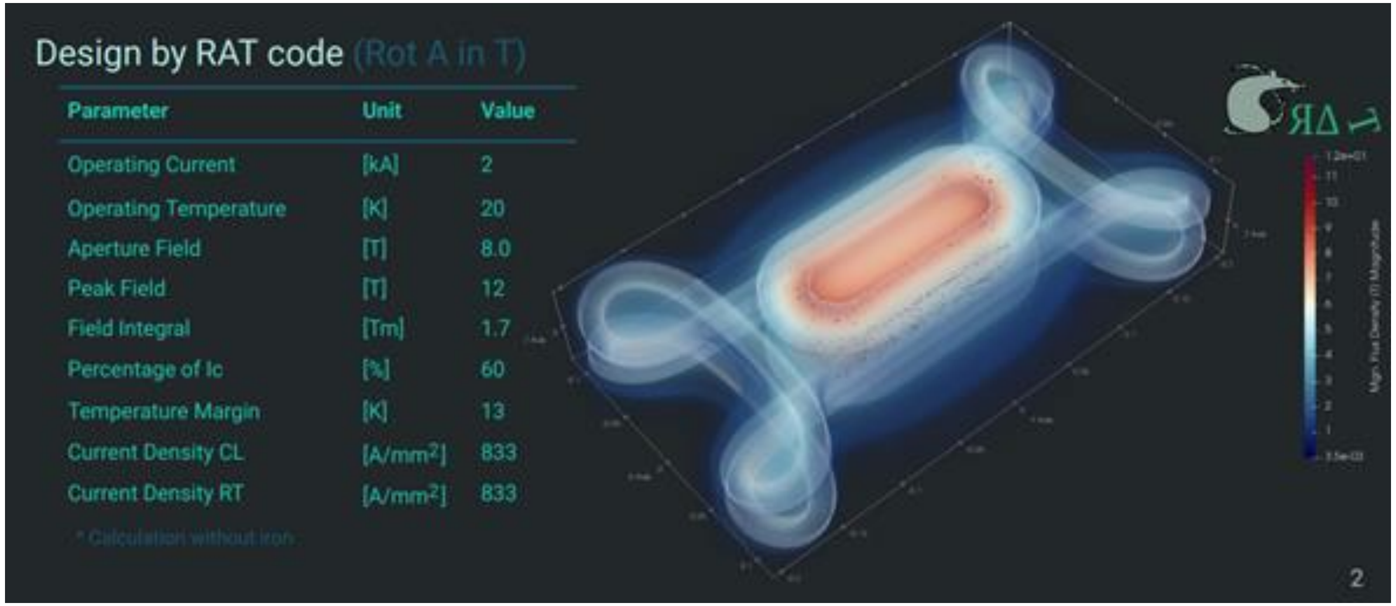


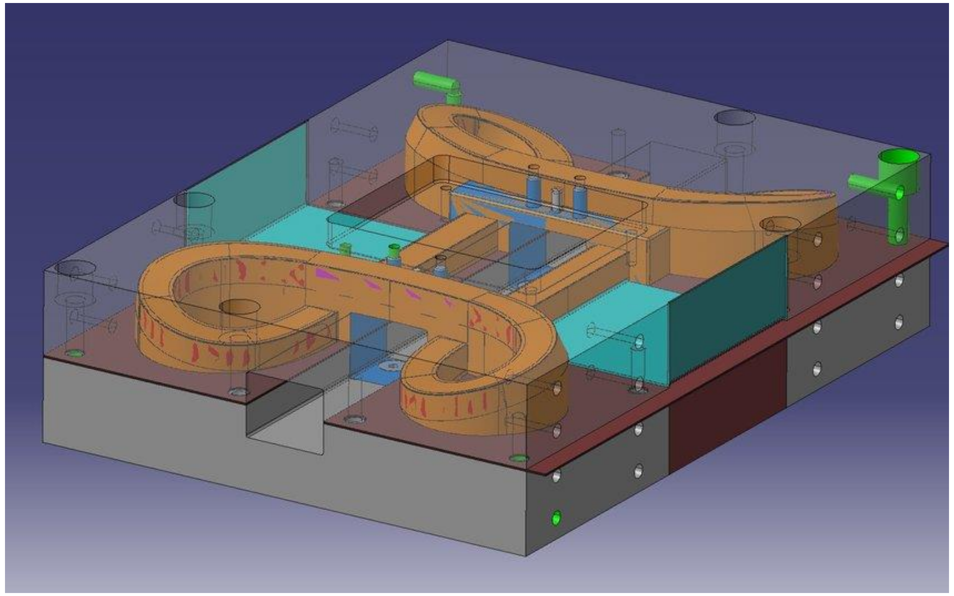
Review in September 2021 to decide which technological route shall be continued

High-field accelerator magnets for hadrons

Approach 2 (non- or partially insulated coils wound directly with one or several tapes)

- Small solenoidal coils with different levels of insulation and different numbers of tapes (8 coils to be wound until mid 2021)
- Cloverleaf 3-4 T (two magnets to be built until mid 2021), no test facility available for inserting these magnets
- Imagine new geometries

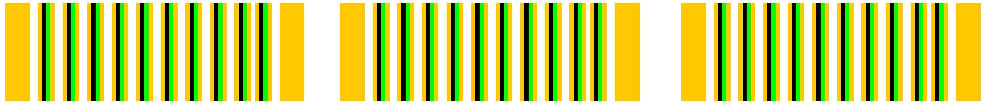




High-field accelerator magnets for hadrons: Small coil program

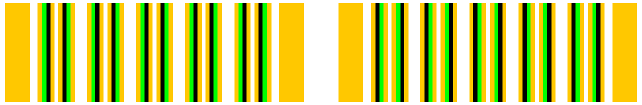
- The aim of the small coil program is to develop the technology (winding, manufacture) of non-insulated coils. Simulation tools shall be developed to extrapolate the results to 3-4 T and higher field magnets and take the decision on how to build these magnets.
- Smaller test set-ups for calibration of models could be integrated (TBD)

Inner and outer diameter of all coils is the same
Same batch of tape used for all coils (500 m in total)



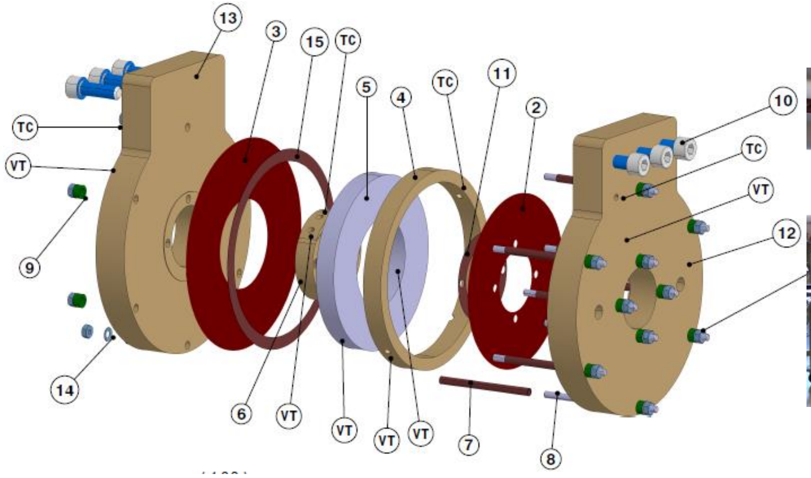
Coil Type A:
Coil 1: Single tape, non-insulated, fully soldered, face to inside
Coil 2: Identical to coil 1
Coil 3: Single tape, non-insulated, dry wound

Coil Type B:
Coil 4: 2 tapes + 2 Cu tapes insulated with C-shaped polyimide
Coil 5: 2 tapes + 2 Cu tapes insulated with glass sleeve



Coil Type C:
Coil 6: Double tape, non-insulated, fully soldered, Tape face-to-face
Coil 7: same as coil 3 but tape back-to-back

Coil Type D:
Coil 8: Single tape, metal-insulated, fully soldered, face-to-face, thin co-wound metal strip (20% of substrate resistance)
Coil 9: same as coil 5, except for metal strip:120% of sub. resistance

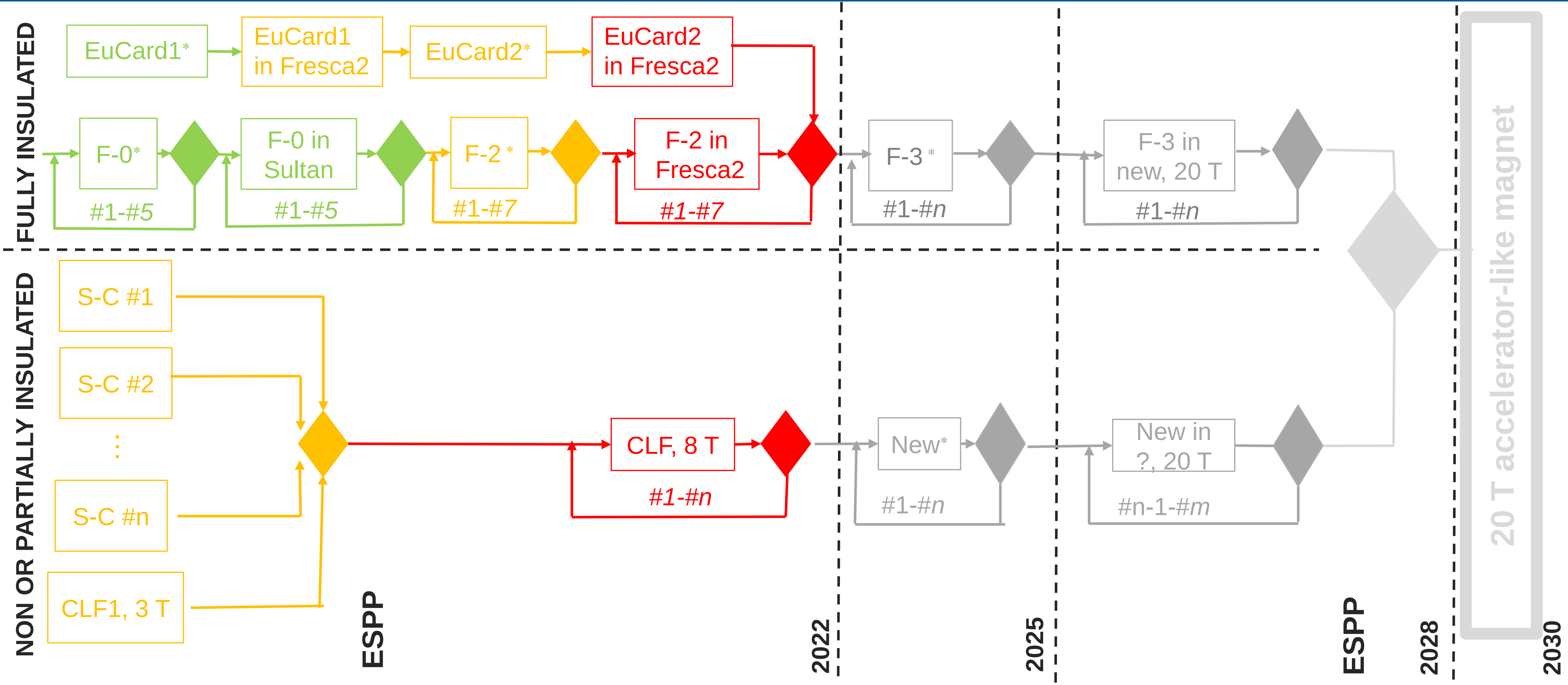


High-field accelerator magnets for hadrons: Fresca-2

- Feather-2 (5-7) to be tested during next year (see detailed planning)
- EuCard2 cos-theta test in Feather2:
  - July 15th to October 14th 2020: insertion / test and removal of EuCARD HTS insert
  - October 15th, 2020 to January 14th, 2021: EuCARD2 cos theta insertion, tests and removal.

Access to a high-field large aperture test station from 2020 until 2028 is essential for the HTS program.
At the moment only a 6 T magnet is available (D1), after Fresca-2 (Facility for the acceptance tests of the superconducting cables for LHC) is used for cable acceptance

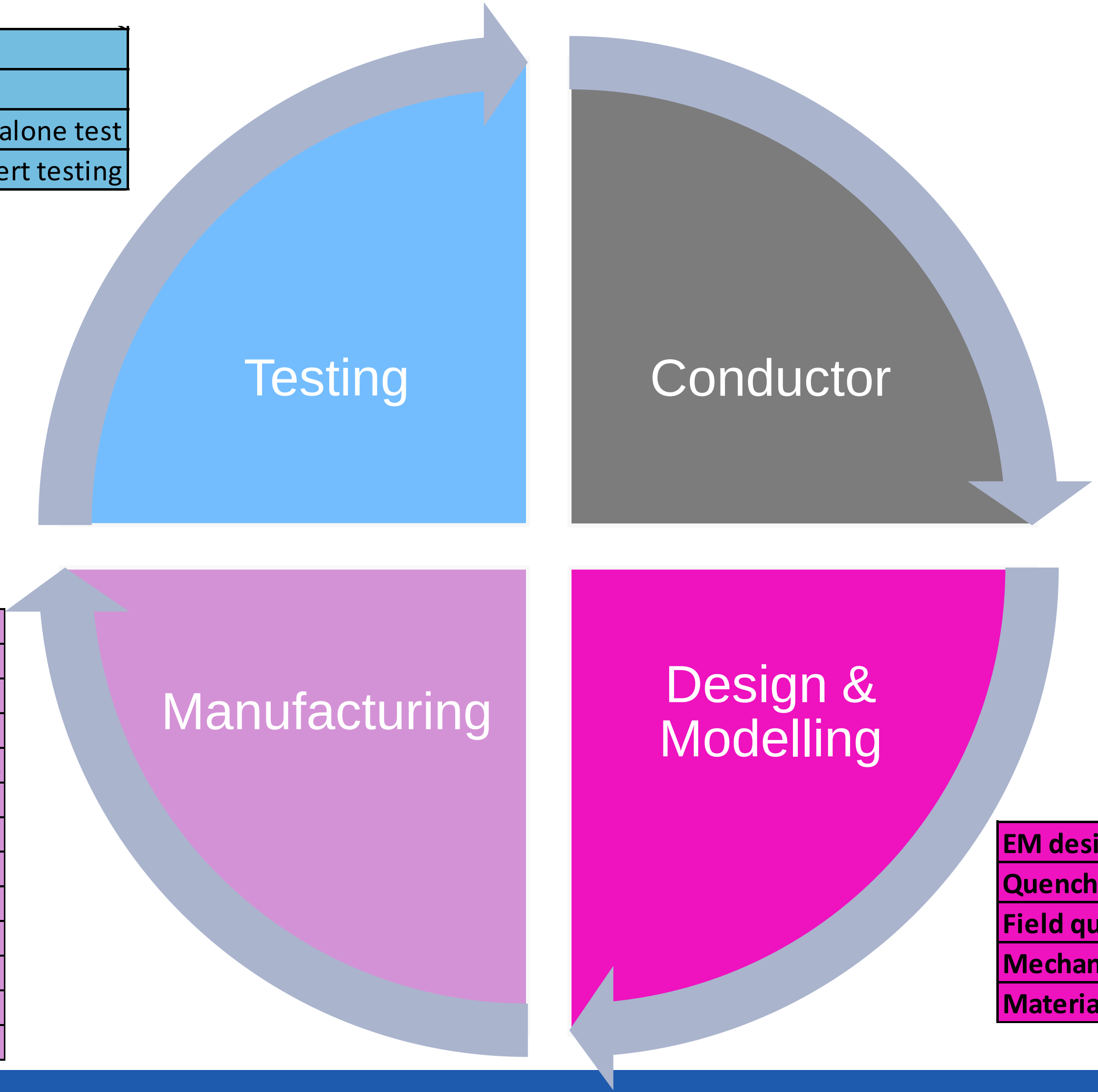
High-field accelerator magnets for hadron colliders: Flowchart



* Stand-alone test of insert magnets

High-field accelerator magnets for hadron colliders: Key areas

Magnetic measurements	
Cold testing	
	Stand-alone test
	Insert testing



Characterization basic conductor properties (ReBCO)	
	Ic(B, T, α)
	Ic(ε)
	Magnetization
	RRR
	Bending
	Thermo-mechanical properties
Development and characterization of cable concepts	
	Roebel cable
	Stacked-soldered tapes
	Other and new cable concepts
Development and characterization splice and joint technology	
	Clamped joints
	Soldered joints
	Persistent joints

Magnet fabrication	
	Tooling
	Procedures
	Manufacturing
	QA & QC
Insulation and impregnation technology	
	Development of insualation schemes
	Soldering of coils
	Development of soldered tape stacked coils
Instrumentation	
	Voltage measurements
	Temperature measurements
	Stress/strain measurements

EM design of coils
Quench detection and protection analysis
Field quality
Mechanical modelling
Material charateristics & charaterization

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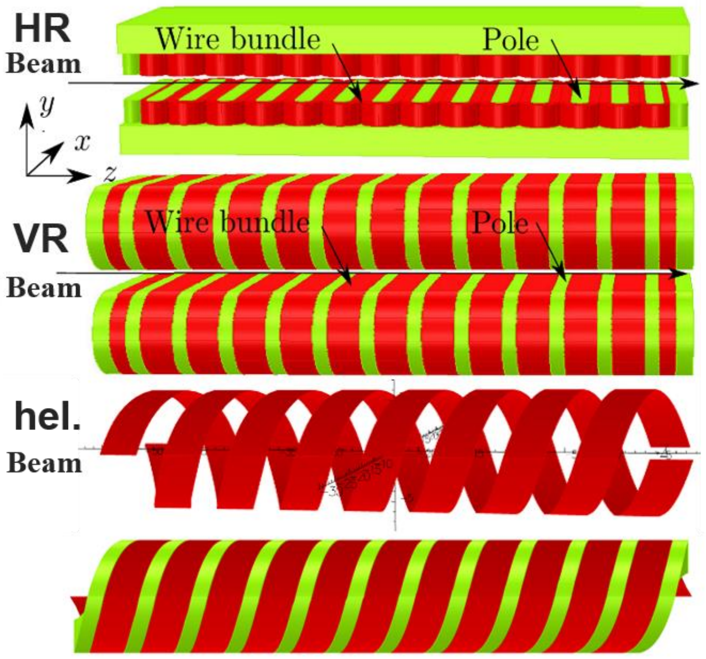
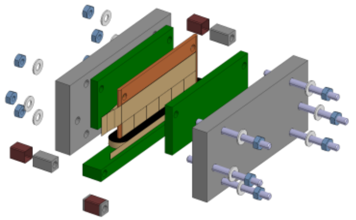
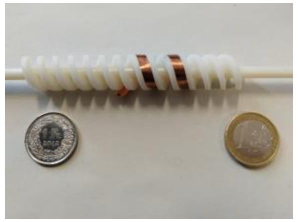
High-field accelerator magnets for leptons: Wiggler/Undulator

- Horizontal planar undulator
  - Advantages: High tape efficiency, relatively easy to repair in case of problems
  - Disadvantages: Large number of joints (~250 joints/m), very small bending radius of tape (1.25-6 mm)
- Vertical undulator
  - Standard design for undulators, bending radius adjustable
  - Large number of joints for tape probably unavoidable
- Helical undulator
  - √2 more efficient than a planar undulator, very compact magnet design
  - No feasible winding scheme yet developed

The aim is to build a short 4-5 prototype magnet and prove that the predicted fields can be reached, the magnet can be protected. Moreover, the field quality shall be predicted and measured.

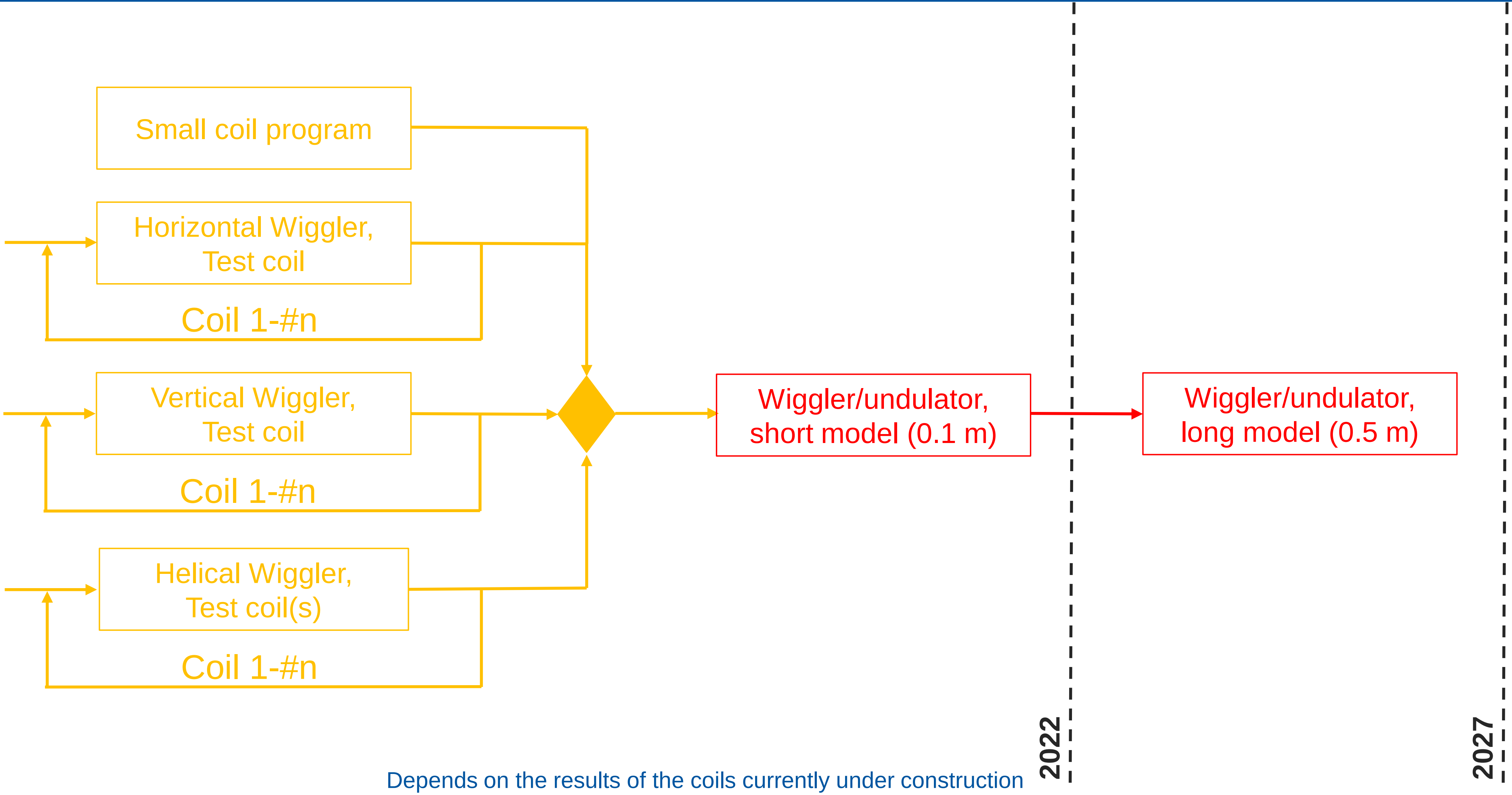






Small prototype program is funded from FCC, CLIC, and TE

The HTS program: Undulators/Wigglers Flowchart



Depends on the results of the coils currently under construction

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CERN

High-field accelerator magnets for muons

arXiv:1901.06150v1 [physics.acc-ph] 18 Jan 2019

Input to the European Particle Physics Strategy Update

Muon Colliders

The Muon Collider Working Group
Jean Pierre Delahaye[1], Marcella Diemoz[2], Ken Long[3], Bruno Mansoulié[4], Nadia Pastrone[5] (chair), Lenny Rivkin[6], Daniel Schulte[1], Alexander Skrinsky[7], Andrea Wulzer[1,8]

[1] CERN, Geneva, Switzerland
[2] INFN Sezione di Roma, Roma, Italy
[3] Imperial College, London, United Kingdom
[4] CEA, IRFU, France
[5] INFN Sezione di Torino, Torino, Italy
[6] EPFL and PSI, Switzerland
[7] BINP, Russia
[8] LPTP, EPFL, Switzerland and University of Padova, Italy

Muon colliders have a great potential for high-energy physics. They can offer collisions of point-like particles at very high energies, since muons can be accelerated in a ring without limitation from synchrotron radiation. However, the need for high luminosity faces technical challenges which arise from the short muon lifetime at rest and the difficulty of producing large numbers of muons in bunches with small emittance. Addressing these challenges requires the development of innovative concepts and demanding technologies.
The document summarizes the work done, the progress achieved and new recent ideas on muon colliders. A set of further studies and actions is also identified to advance in the field. Finally, a set of recommendations is listed in order to make the muon technology mature enough to be favourably considered as a candidate for high-energy facilities in the future.

Contact: Nadia Pastrone, nadia.pastrone@cern.ch
Webpage: https://muoncollider.web.cern.ch

- High-field muon collider dipoles (open midplane, static)
- Muon source: High field solenoids (30+ T)

Depending on the outcome of the European Strategy Review one can imagine the following initiatives:

- Excellence initiative (EU project): Magnet expert and beam dynamics expert develop together a lattice for muon colliders
- European project similar to EuroCirCol for muon colliders (but much more open)

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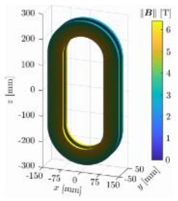
		Enrico Felcini	12/2020

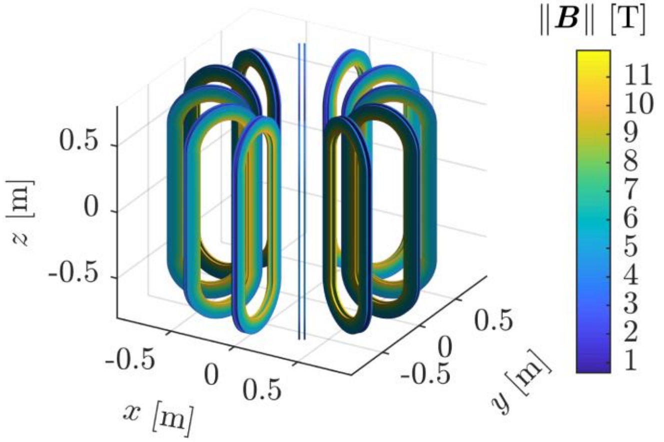
Magnets for physics beyond colliders

- HTS Demonstrator Magnet Space (funded through ASI)
  - One dummy coil and one full coil to be built until Spring 2021 to show the feasibility

Input from hadron program

Mini-scale coil (no HTS) → Sub-scale coil (no HTS) → Sub-scale HTS coil →





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Infrastructure

- High-field insert solenoid for wire test station: 6-8 T
- Test station for inserts
  - Fresca-2 (until end of 2020)
  - D1 (from end of 2020, but only 6 T)
  - Fresca-3 (timeline to be defined), availability of this magnet starting from 2021 is critical for the success of this program!

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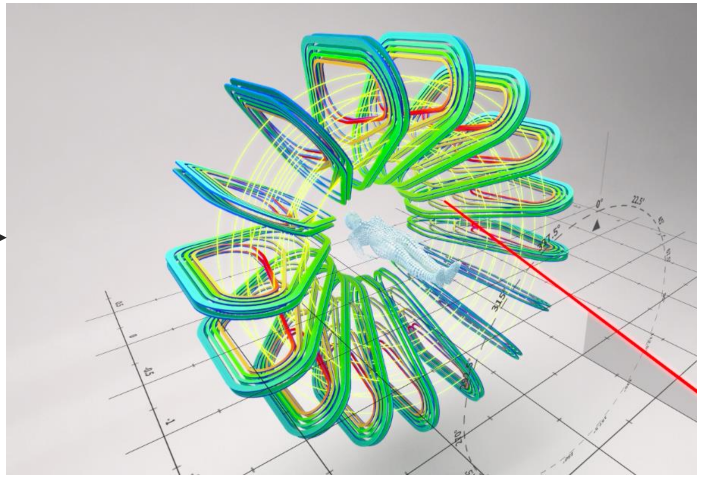
GaToroid: Flowchart

Small coil program

Dummy1, single SS, no insulation → Dummy2

→ Sub-scale HTS coil, 1/3, 600 mm →



2020

Production planning coil winding

PRODUCTION PLAN HTS COILS		2020												2021											
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Feather	Coil #5																								
	Coil #6																								
	Coil #7																								
Small coils	Coil #1																								
	Coil #2																								
	Coil #3																								
	Coil #4																								
	Coil #5																								
	Coil #6																								
	Coil #7																								
	Coil #8																								
	Coil #9																								
Cloverleaf	Coil #1																								
	Coil #2																								
	Coil #3																								
	Coil #4																								
	Coil #5																								
HDMS	Coil #1 (Dummy 1 +2 ?)																								
	Coil #2 (Double pancake)																								
GaToroid	Coil #1 (Dummy)																								
	Coil #2																								
Undulator	Coil #1 VR, Dummy																								
	Coil #2 VR, 1 tape																								
	Coil #3 VR, 1 tape																								
	Coil #4 VR, 2 tape																								
	Coil #1 HR, Dummy																								
	Coil #2 HR, 1 tape																								
	Coil #3 HR, 1 tape																								
	Coil #4 HR, 2 tape																								
	Coil #1 Helical																								
	Coil #2 Helical																								
	Coil #3 Helical																								
	Mirror model																								

Depends on length of Covid-19 period

Collaborations with external partners

- We are currently establishing collaborations for developing simulation tools, performing involved simulations (quench, electromagnetic design)
- Many collaborations are with long-term partners of CERN, discussions on the potential work are on-going. We try to establish also collaborations with ‘new’ collaboration partners, mainly to develop simulation tools

Conclusion

- We are very interested and ready to participate to a μ-collider study!
- A first step for us would be to contribute to a sound functional specification for the lattice and the main magnets (field strength, aperture, ramping time, field quality, etc.)
- The progress of the HTS program will depend on the availability of highly-qualified and skilled personnel and the availability of a high-field, large aperture test station after the end of 2020
- We are in discussion with several potential collaboration partners. Their contribution is essential for the success of this program