IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2020.
Plenary presentation PT-3 given at ACASC/Asian-ICMC/CSSJ Joint Conference, 6-9 January 2020, Okinawa, Japan.

CERN

UNIVERSITY OF TWENTE.

A flavor of…….

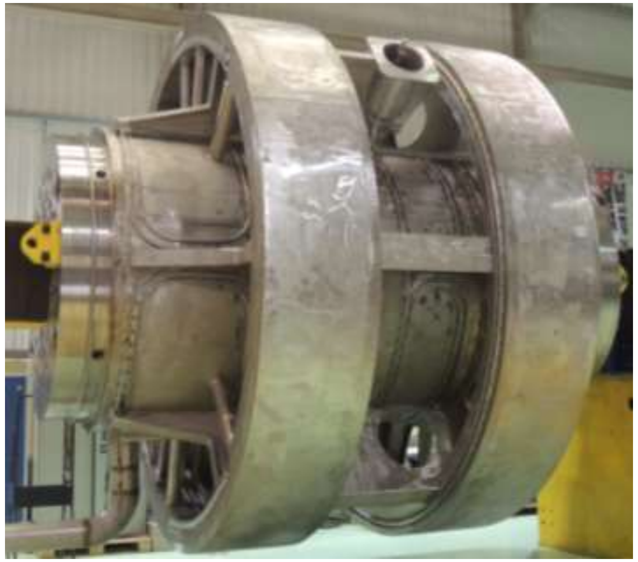
Superconducting Magnet Technology in Europe

Herman ten Kate

1. Content

- **A flavor of remarkable magnet designs and realizations in Europe are presented that are relevant today.**
- Disclaimer: by no means a full survey as too many interesting projects exist and can't be presented in 45 minutes.

- **High Field Facility magnets** – Nijmegen and Grenoble
- **MRI and NMR** – Iseult and Bruker Biospin
- **Fusion device magnets** – ITER, Tokamak Energy, DTT
- **Accelerators magnets** – HL-LHC, FAIR at GSI
- **Detectors magnets** – LC, FCC, BabyIAXO, MadMax, AMS-100
- **Magnets in a 3 MW wind turbine generator** - EcoSwing



2. Sc. Outserts for new 43 and 45 T hybrid magnets

❖ **Nijmegen:** On-axis field 45 T / 32 mm, 22 MW (new installation)

- Resistive Florida-Bitter type insert magnet 32.8 T @ 40 kA, 5 MJ
- Sc. Nb_3Sn outsert makes 12.3 T in 620 mm bore at 20 kA, 55 MJ, layer wound magnet, graded in 3 sections, using 3 CICCs.
- Supercritical He cooling at 4.6 K

Collaboration with US-NHMFL: common CICC design, outsert fabrication

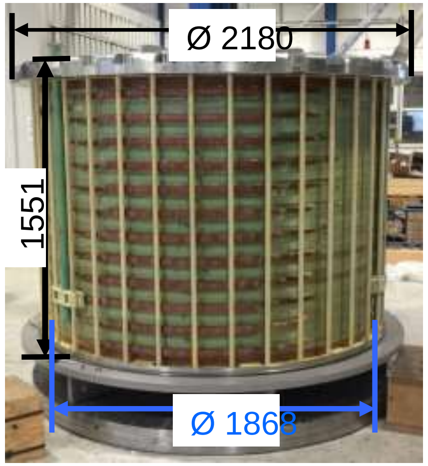
Outsert delivered, integrated, commissioning starting summer 2020.

❖ **Grenoble:** On-axis field 43 T / 34 mm / 24 MW (new outsert)

- Resistive poly Bitter + poly-helix inserts magnet generate 9 + 25.5 T
- Sc. NbTi/Cu cable in Cu channel outsert, makes 12.5 T @ 20 kA, 55 MJ
- Superfluid He stabilized at 1.9 K

Collaboration with CEA for design and Bilfinger Noell for coil winding

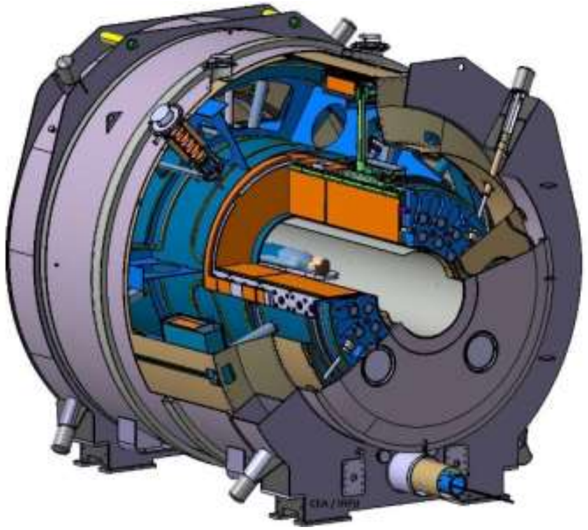
Outsert delivery early 2020, followed by system integration and commissioning.

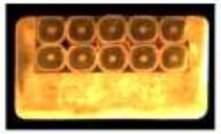


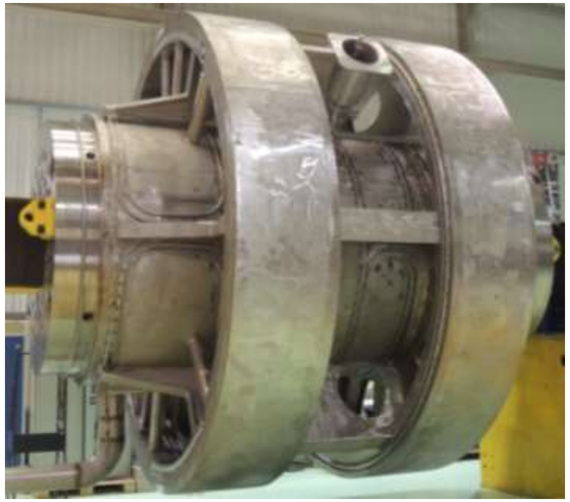
3.1 MRI Magnet – 11.7 T in Iseult

Remarkable achievement in 1st of its kind R&D magnet for MRI brain research in Paris, July 2019.

- A record magnetic field of 11.7 T in the Iseult MRI magnet
- CEA design, French-German collaboration, manufactured by GE-France
- 11.7 T in 900 mm bore, 338 MJ, 1483 A
- Cryostable NbTi/Cu cable embedded in Cu profile
- 170 sf-He wetted double pancakes at 1.8 K in main coils, 2 shielding coils
- Overall size 5.2 m long, 5 m diameter, 132 t
- **System accepted, now being installed, 1st MRI pictures taken**
- **Next step?** Some 3 14 T MRI projects initiated, (Boston, China, 1 in Europe)







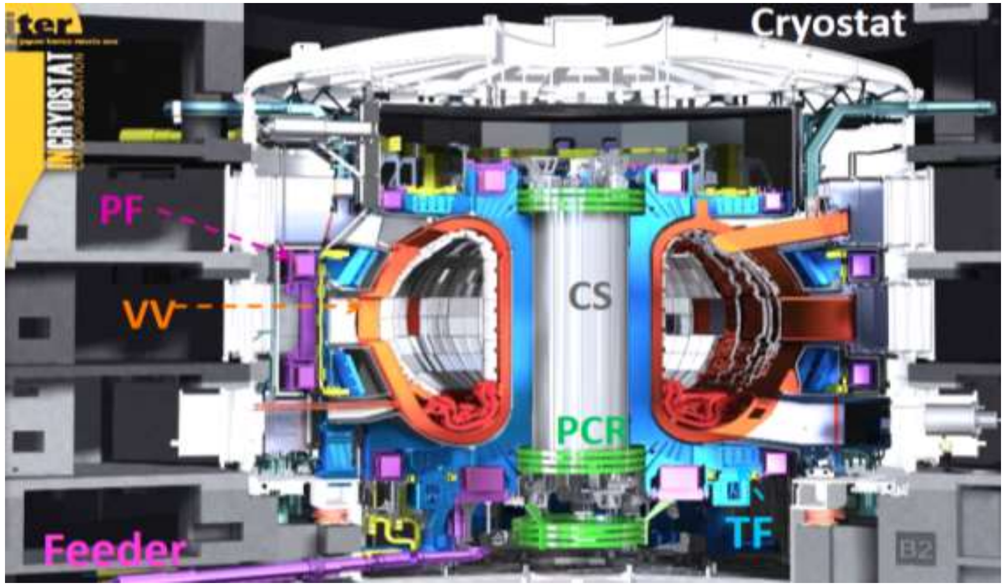
3.2 High Field NMR - 1.2 GHz / 28.3 T

Remarkable achievement in a commercially produced magnet

- August 2019, Bruker announced a record magnetic field of 28.3 T in 2 NMR magnets in a series of at least 7 orders placed
- The magnet is a hybrid of NbTi, Nb_3Sn, and ReBCO coils with a 54 mm free bore
- Stepped up in magnetic field in recent years from 1.0 GHz (23.5 T) to 1.1 GHz (25.9 T) to 1.2 GHz (28.3 T) today

Now 1.2 GHz, 28.3 T

4.1 Fusion magnets – ITER



International Thermonuclear Experimental Reactor

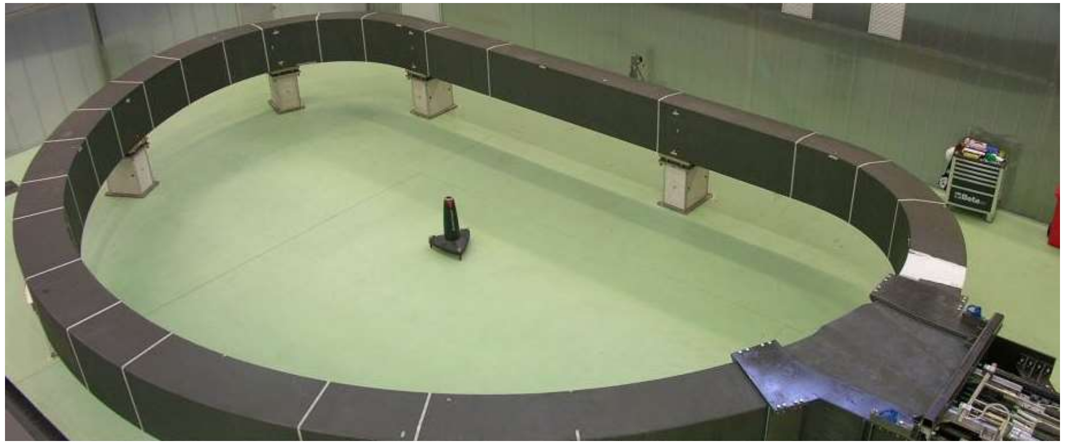
- Aiming at 500 MW fusion energy
- Started 1995, sited 2005 in Cadarache, France
- At ~ 60% of construction
- **Superconductors done, coils in progress, next true challenge is magnet system integration**
- **1st plasma ~2027, ready for 1st fusion ~2035**

System	# units	Energy GJ	Peak field T	Conductor length km	Weigth t
Toroidal Field	**18 coils**	**41**	**11.8**	**82.2**	**6540**
Central Solenoid	**6 modules**	**6.4**	**13.0**	**35.6**	**974**
Poloidal Field	**6 coils**	**4**	**6.0**	**61.4**	**2163**
Correction Coils	9 pairs	-	4.2	8.2	85
	48 coils	52	4-13	130 km	

Fusion magnets – ITER TF coils

EU task for Toroidal Field coils

- Double pancakes TF coils (70) made wound and impregnated
- Winding packs (10) assembly in progress, largely completed
- **Insertion in coil casings of winding packs, in progress**



1st coil impregnation completed, ready for the casing

1st TF coil in casing, closing welding

Coil casing completed, ready for the casing

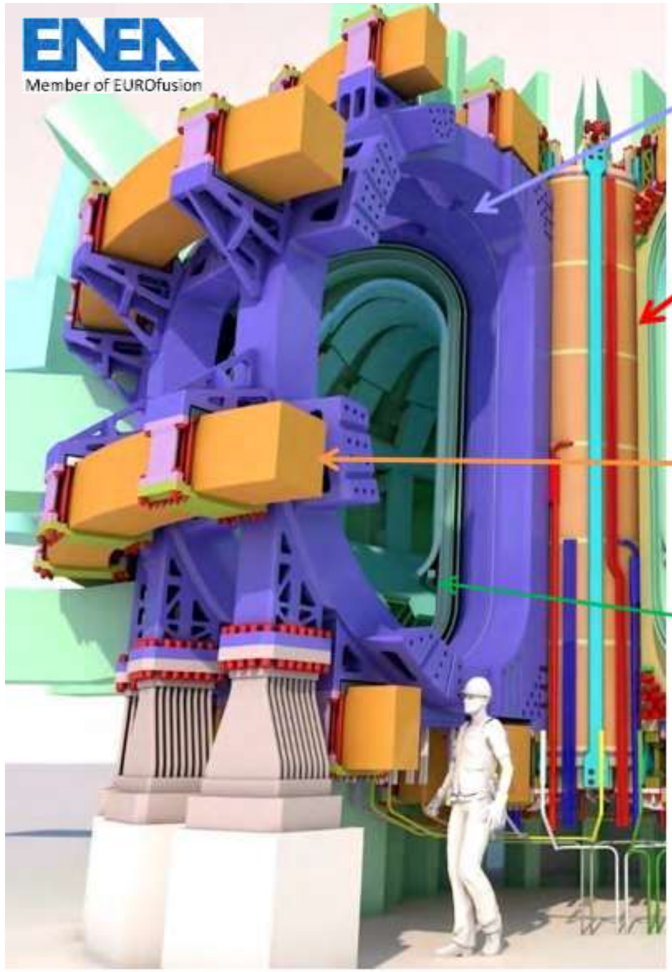
Fusion magnets – ITER PF coils

EU task for Poloidal Field Coils PF2-5

- Wind, stack, impregnate and complete the 4 largest PF coils on site at Cadarache
- Other 2 small ones by RF and China, PF1&6
- **Work in progress**

4.2 Fusion magnets – DTT, Divertor Tokamak Test-facility

- 6 T sc R&D tokamak
- At ENEA-Frascati/Italy
- Purpose: testing diverter concepts and techniques for next step DEMO
- Demonstration of a DEMO like heat exhaust system
- Since 30 Nov 2018, 7 years project, to be used medio 2025
- 26 km of Nb_3Sn and 16 km of NbTi based CICCs



18 Toroidal Field coils
Nb_3Sn Cable-In-Conduit Conductors
5 *Double-Pancakes* (3 regular + 2 side)

6 Central Solenoid module coils
Nb_3Sn Cable-In-Conduit Conductors
6 *independent modules*

6 Poloidal Field coils
4 NbTi Cable-In-Conduit Conductors
2 Nb_3Sn Cable-In-Conduit Conductors
6 *independent modules*

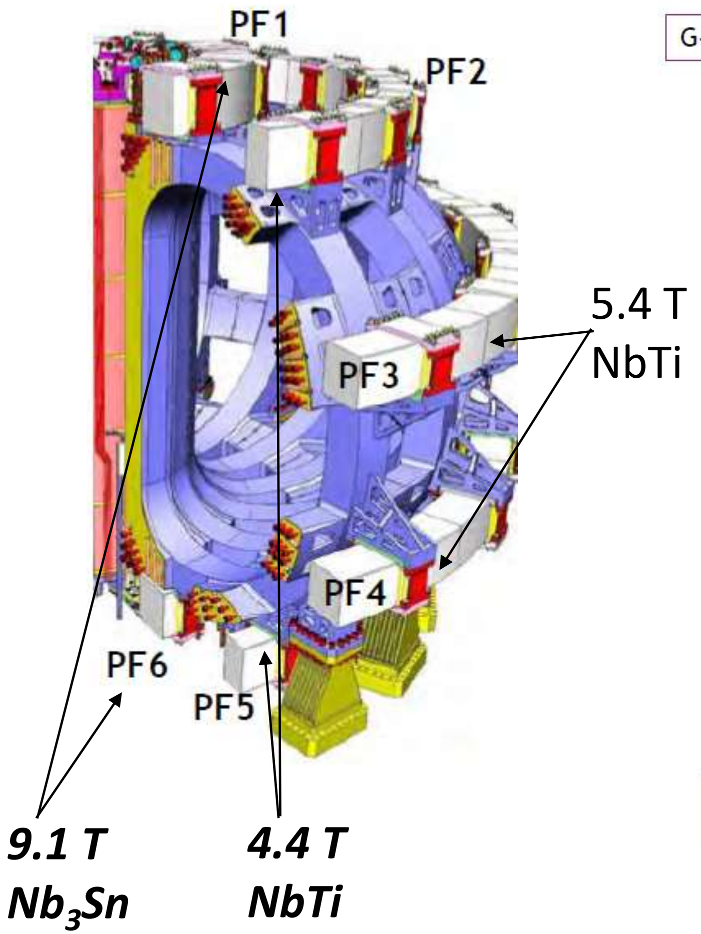
6 In-vessel Cu coils

Present design based on proven and reliable technologies

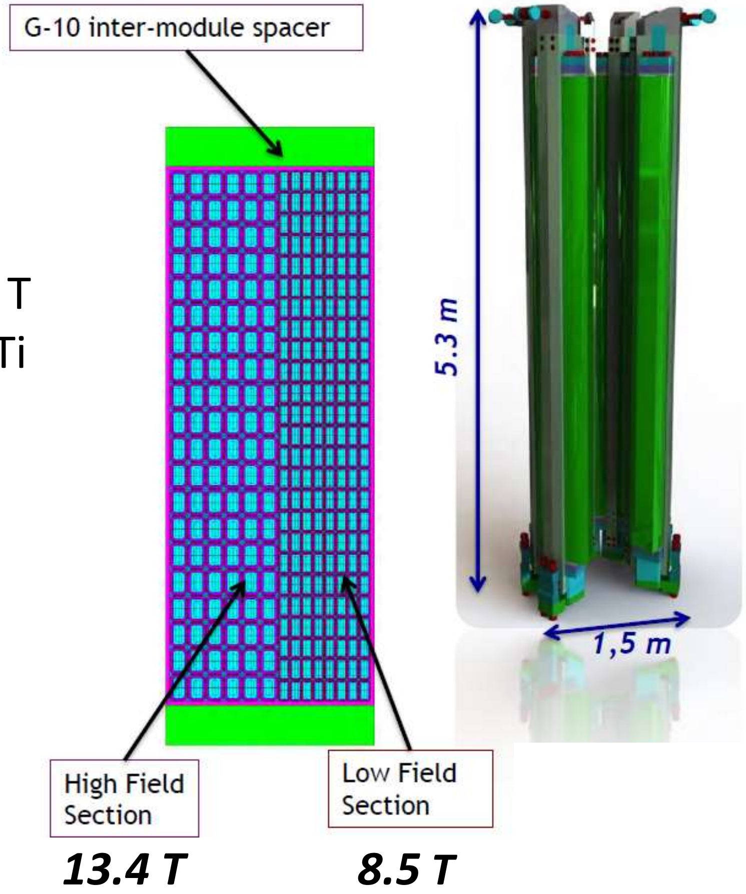
Possible future upgrade: innovative additional HTS coil to be inserted in the CS 10% flux increase + test bed for next generation magnets

Fusion magnets – DTT coils for PF, CS and TF

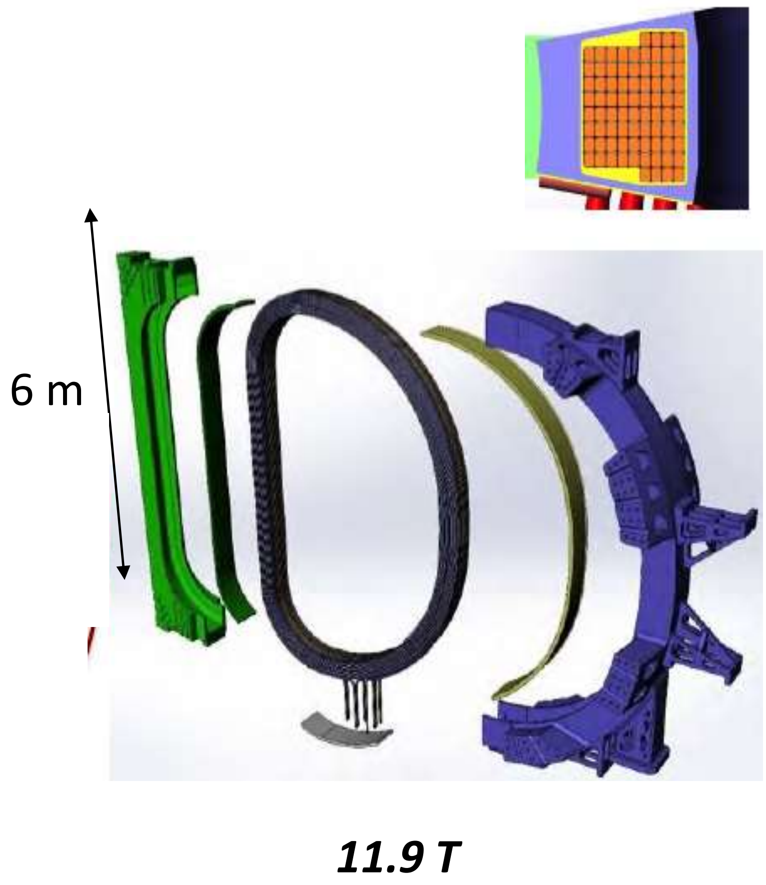
Poloidal field coils



Central Solenoid



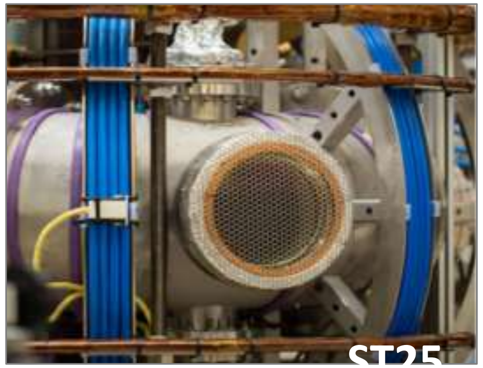
Toroidal Field Coils



https://indico.cern.ch › attachments › CERN2019

4.3 Fusion magnets – Compact Tokamak System

Step 1:
Validating approach

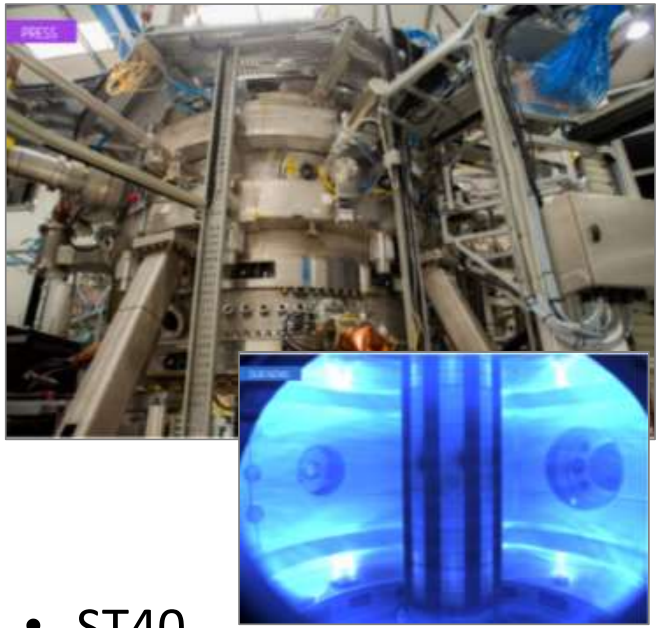


- Copper coils < 0.25 T
- Hydrogen fuel
- Plasma pulse 3 ms

Step 2:
Introducing HTS technology

- All HTS coils (2015)
- Plasma pulse 5 s

Step 3:
Achieving fusion temperature



- ST40
- 15 million °C
- 125 kA in the TF coils
- Field of 1.5 T at 0.4 m

Step 3a:
HTS magnet: game changer

!

- HTS non-isolation coil 24.4 T @ 21 K

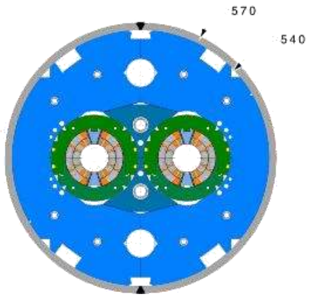
Step 4:
Achieving energy breakeven conditions

Step 5:
Delivering fusion power

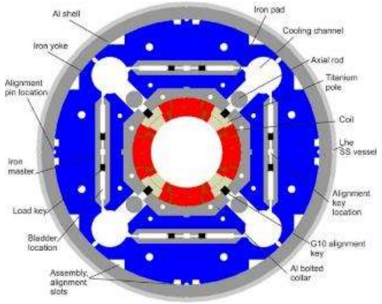
https://www.tokamakenergy.co.uk/

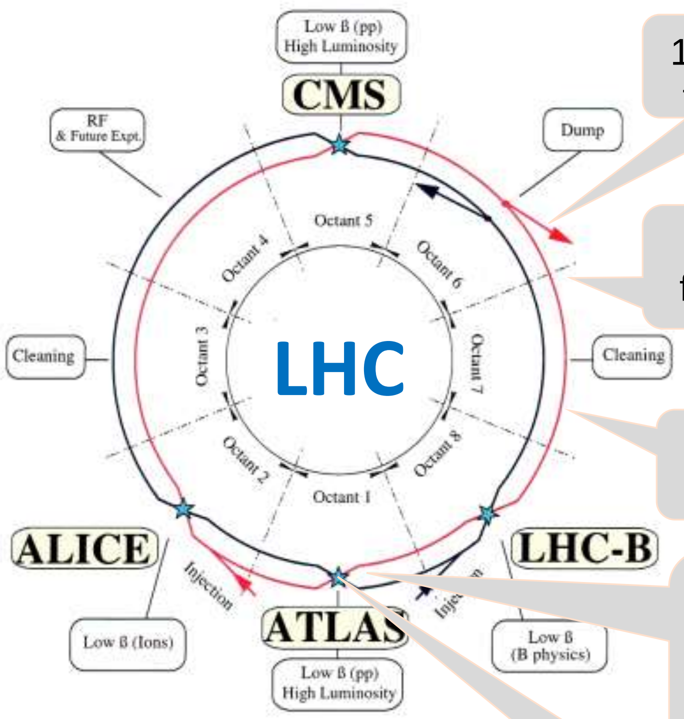
5.1 Nb_3Sn Accelerator magnets for High-Luminosity LHC

- **6 Arc dipole magnets**
  6.752 m length, 11.23 T bore field,
  11.8 T peak at 11.85 kA



- **10 IR quadrupole magnets**
  7.15 m length, 132.6 T/m gradient
  11.4 T peak at 16.47 kA
- **20 IR quad magnets**, 4.2 m length, produced in the US





1232 dipoles for bending

386 quads for focusing

~ 6000 correctors

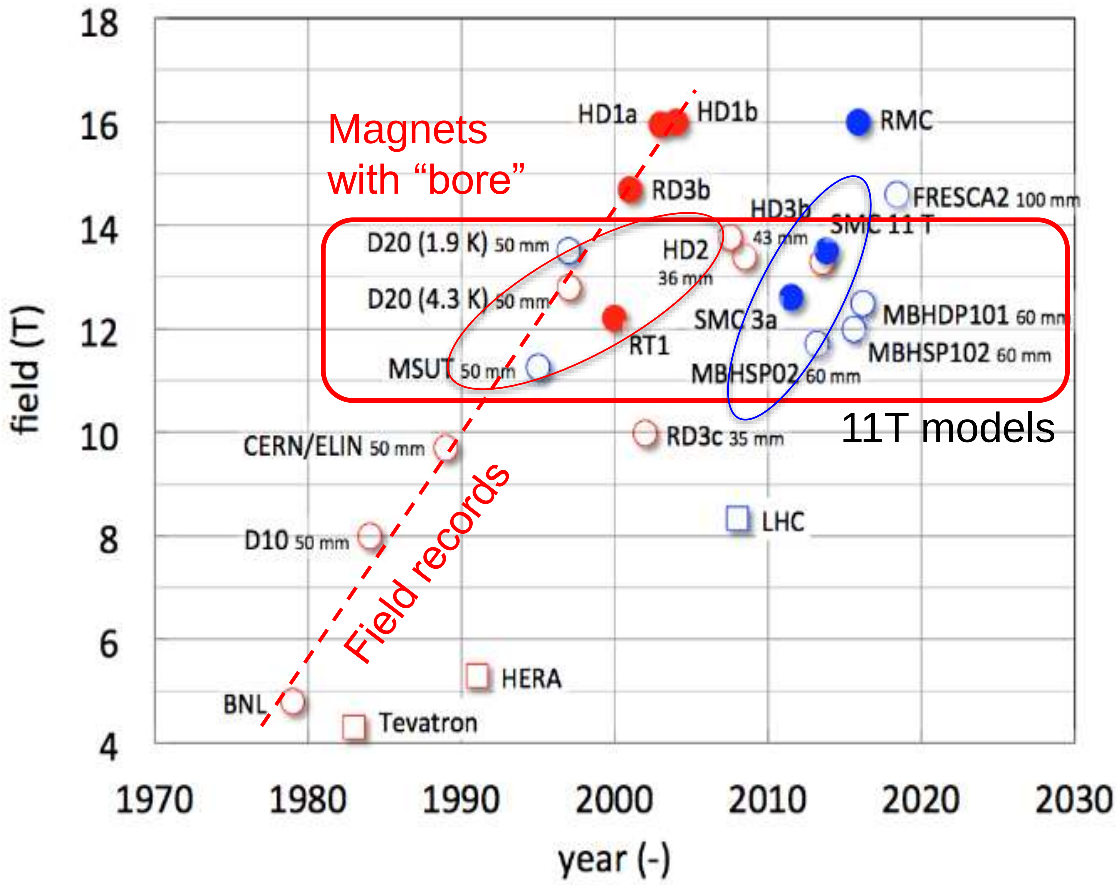
Insertion & **Final Focusing magnets**

ATLAS and CMS detector magnets

- In total some 40 cold masses to be installed in the LHC tunnel in 2023-24
- **Final Focusing Quadrupole magnets are vital for achieving the higher luminosity.**

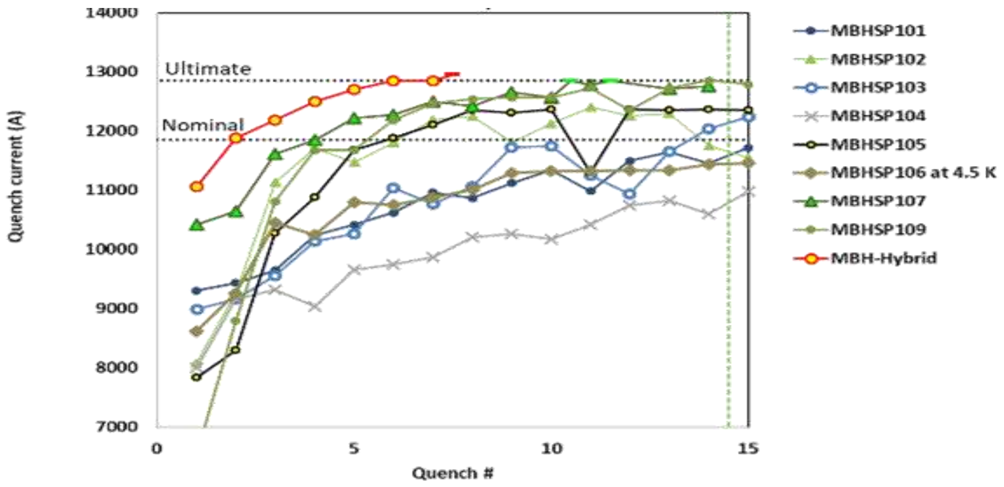
Accelerator magnets – Record R&D magnets

- Nb3Sn dipole magnet development since 1990
- 16 T achieved in magnets without bore
- Since 2014 "Fighting" to arrive at 11 T production magnets with bore
- **Main problems are degradation by coil handling (damage) and training (disturbances)**

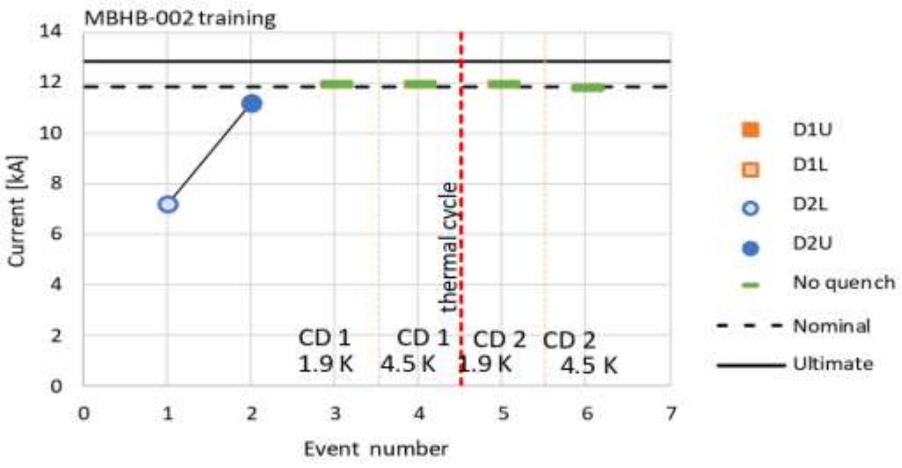


Accelerator magnets – HL-LHC 11T dipoles & Quads

- 11T dipole magnet development since 5 more than years at CERN. Similar for Quads in US and CERN
- Finally this autumn 2019 the first long dipole magnet accepted with short training!
- Similar situation for quads, acceptable long magnet soon expected.



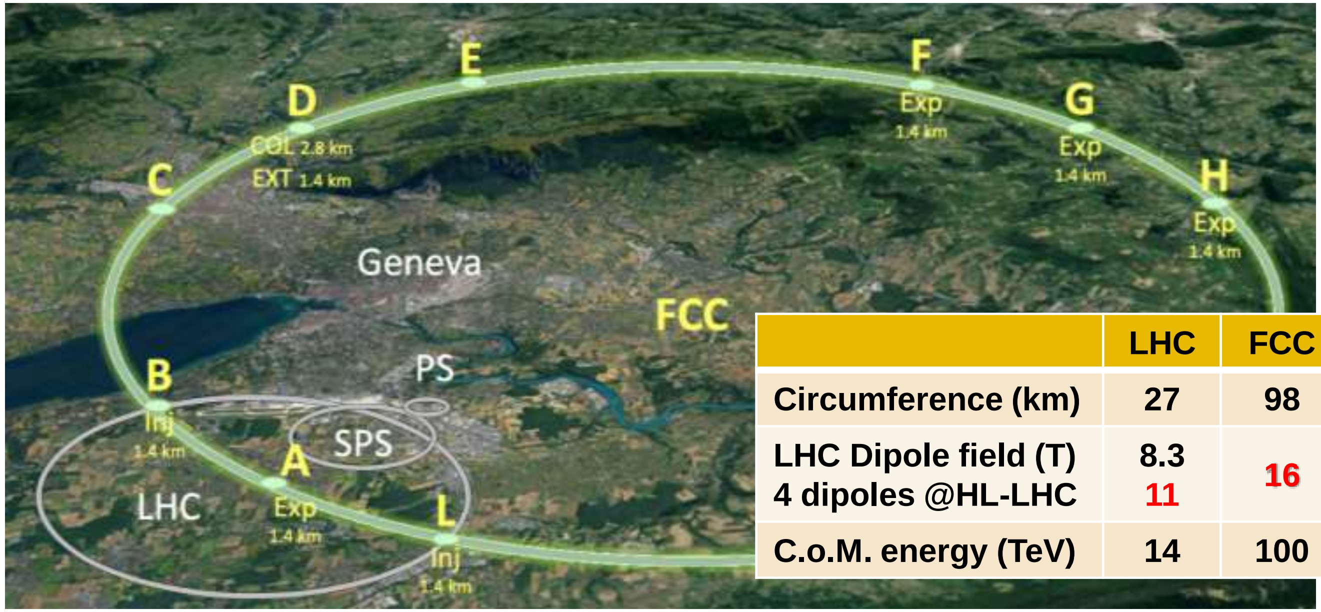
Not acceptable long training in 11T dipole models



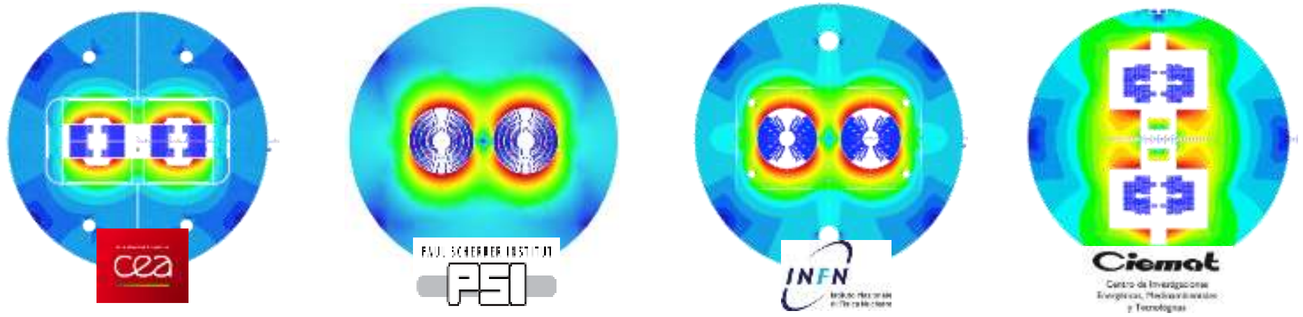
Short training in "accepted" 1st 11T dipole

5.2 High-Field Nb_3Sn magnets - for FCC

- **FCC 16 T dipole magnets** conceptual magnet designs being developed with partners
- Nothing built yet, just exercises
- Long term R&D for 2020-2040
- Intensity and extend of the program will highly depend on the outcome of the European Strategy for High Energy Physics and its eventual endorsement by CERN council



	LHC	FCC
Circumference (km)	27	98
LHC Dipole field (T) 4 dipoles @HL-LHC	8.3 11	16
C.o.M. energy (TeV)	14	100



Flavor of FCC type 16 T dipole magnet conceptual designs by collaborators

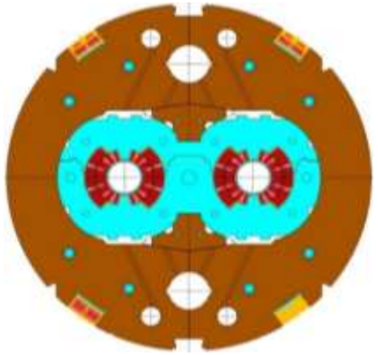
5.3 Nb_3Sn Rutherford cables for accelerator magnets

For efficiency-cost-volume reasons current density in accelerator windings must be at least some 400 A/mm^2 at requested field:

- 8 T at LHC, **11 T for HL-LHC** and **16 T for FCC**
- Conductor Jc development underway for 1500 A/mm^2 at 16 T, 1.9 K
- Goal reached in short wire sections

- Next step: maturing production, further increase to some 1800 A/mm^2 for achieving margin and robustness, and making long lengths

Main issue is Surviving Transverse Pressure on cable wide face



Cos θ dipole magnet layout, winding pack and cable

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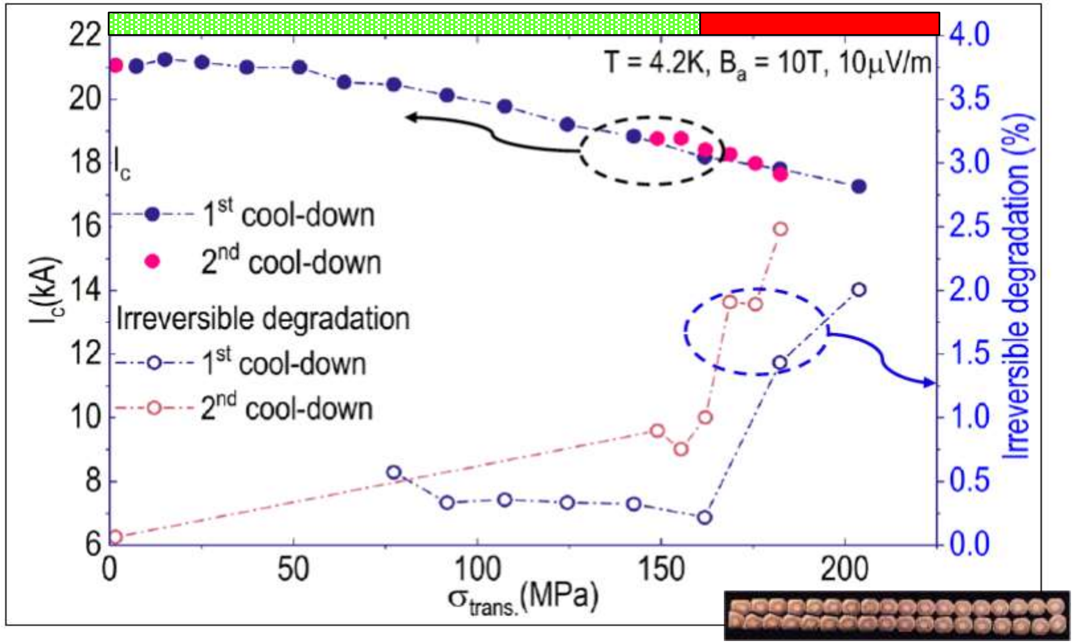
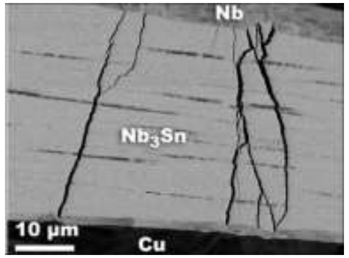
Nb_3Sn Rutherford cables under transverse pressure

- Critical current affected by pressure
- **Reversible part** due to lattice deflection
- Reversible part some 10-20% at 150 MPa!
- **Irreversible damage**, filament cracking
- Starts at some 150-200 MPa

Note: measured with pressure uniformly applied, in real coil not the case, thus worse to expect.



- ✓ **Transverse pressure of some 150 MPa OK** in perfectly impregnated cables, but Ic then some 20% less, eating from the margin, thus reduced stability!
- ✓ Strand and cable mechanical optimization possible to some extend, not more, a **principle limit for not-reinforced Rutherford cables** !

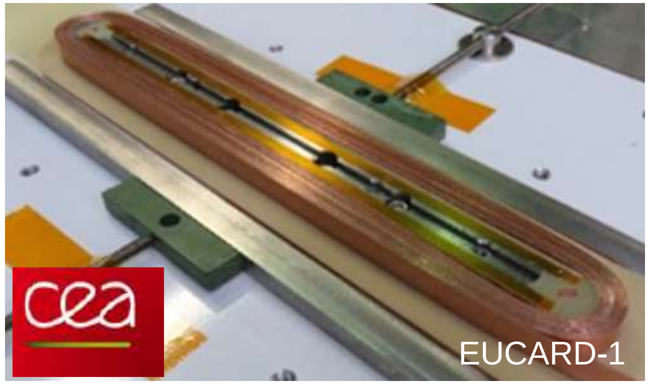


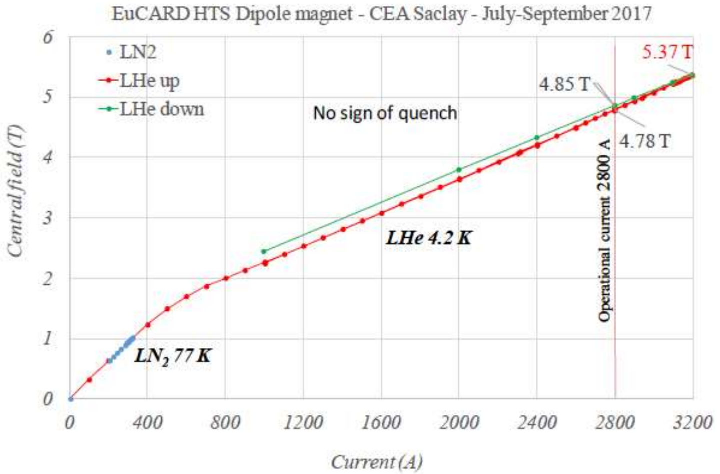
Filament cracking

5.4 *Re*BCO - Dipole magnet demonstrators towards 20 T

_Re_BCO dipole development at CEA

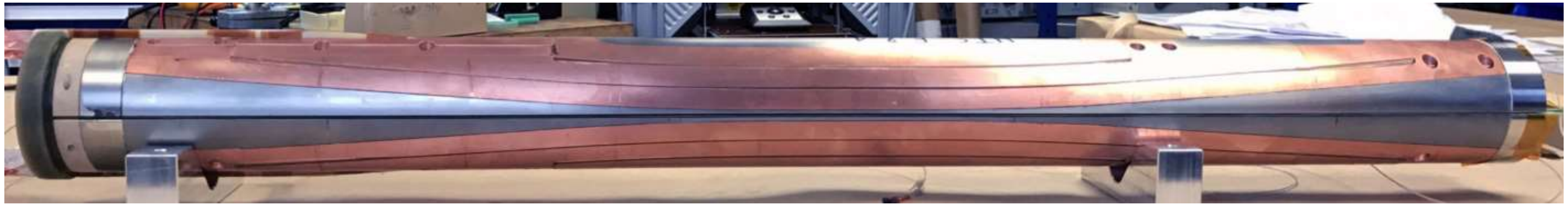
- Design for full-size dipole variants
- Demonstration racetrack coil reached 5.37 T





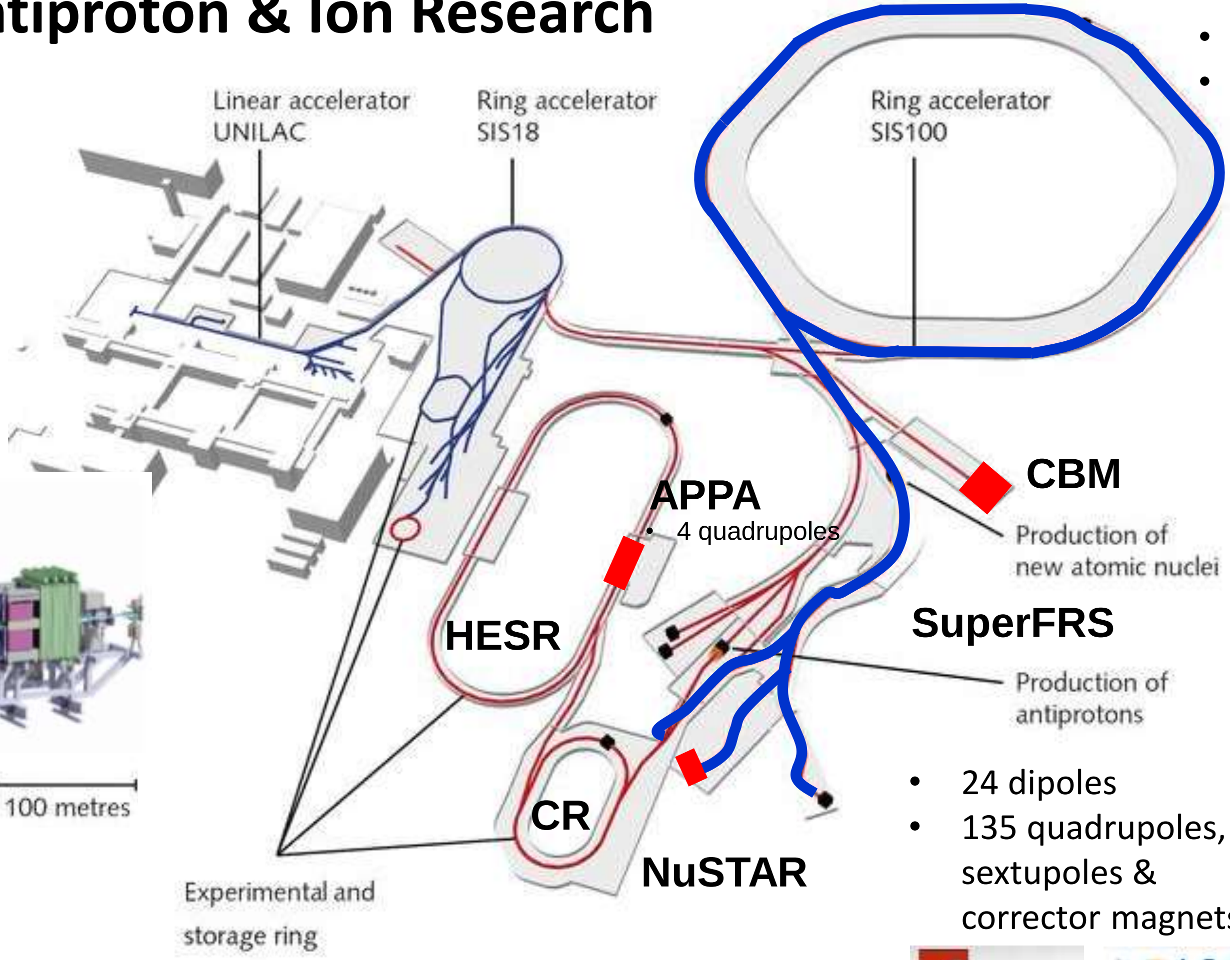
_Re_BCO Feather series dipole insert development magnets at CERN

- Coil 1: using SuperOx/SuNAM type Roebel cable, reached 3.35 T
- Coil 2: using Bruker type Roebel cable, **presently at test, so far > 4.1T**
- Further coils planned and test in Fresca2 background field



5.5 FAIR at GSI – Dipole and Quads status

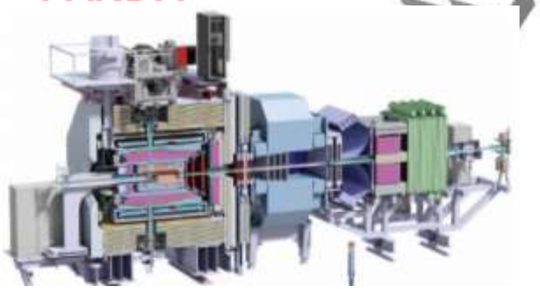
Facility for Antiproton & Ion Research



- 108 dipoles
- 303 quadrupoles, sextupole and corrector magnets

BILFINGER

PANDA



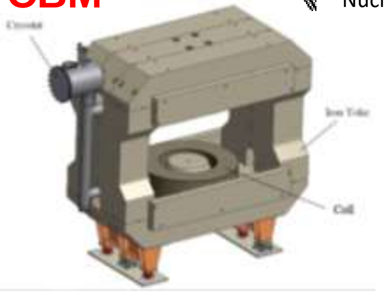
Budker Institute of Nuclear Physics

- 24 dipoles
- 135 quadrupoles, sextupoles & corrector magnets

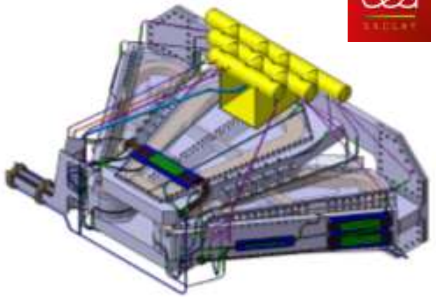
ELYTT ENERGY ASG

CBM

Budker Institute of Nuclear Physics



R^{3}B-GLAD



FAIR at GSI - SIS100 Magnet production status

Dipole Magnets

BiLFINGER

- Number of magnets: 108
- **Manufactured and tested: 54 (50%)**
- Magnetic field: 1.9 T
- Ramp rate: 4 T/s
- Magnet length: 3.1 m
- Curvature radius: 52.6 m
- Nominal operational current: 13.1 kA

Quadrupole Magnets Doublets Modules

BiLFINGER

- **First of Series Module is being tested 1/83**
- In total 83 Quadrupole Doublets Modules
- Each module: 2 units including Quadrupole, Steering magnets and beam diagnostic device
- 11 types of Quadrupole Doublets Modules
- Operational current of quadrupole magnets: 10.5 kA
- Operation current of steering magnets: 250 A

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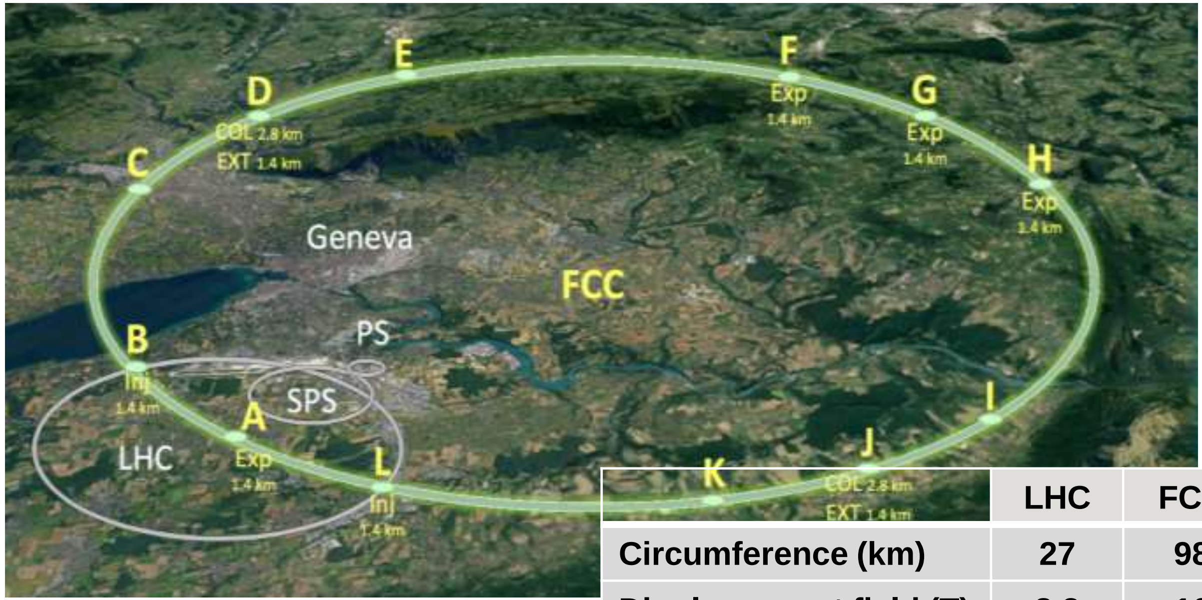
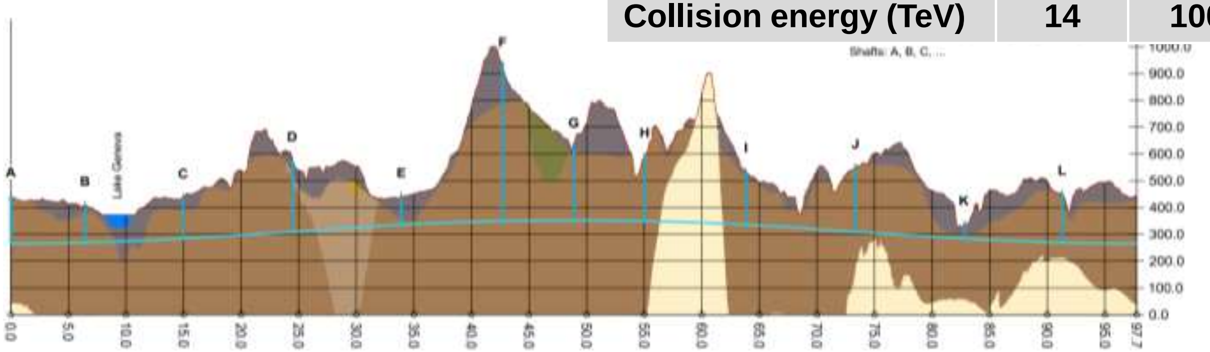
6.1 Future Circular Collider - options

Program maximizing physics opportunities

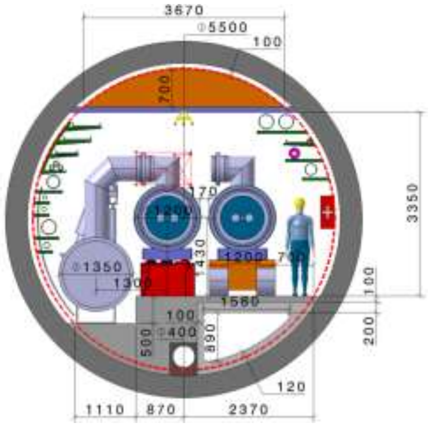
- **Stage 1: FCC-e⁻e⁺ as first generation Higgs factory.**
- **Stage 2: FCC-hh ~100 TeV, highest energy frontier, ions & eh options.**
- **Ambitious high-field magnet R&D program**
- Common infrastructure
- **Integrated project, compliant with HL-LHC exploitation, seamless continuation of HEP in Europe.**



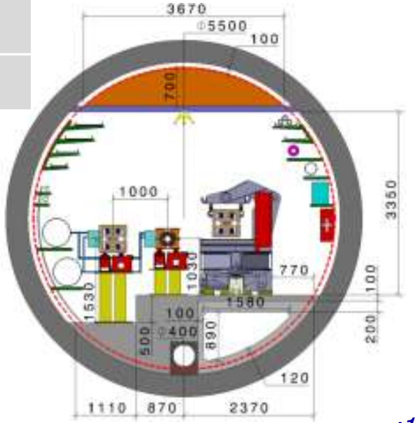
	LHC	FCC
Circumference (km)	27	98
Dipole magnet field (T)	8.3	16
Collision energy (TeV)	14	100



FCC-hh



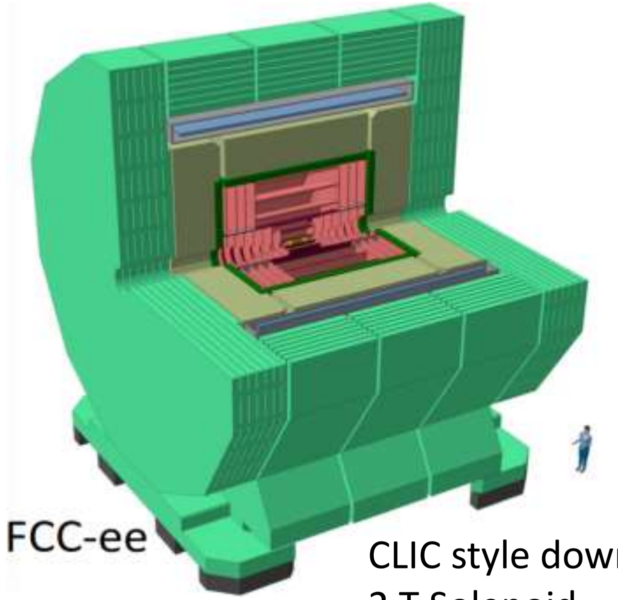
FCC-ee



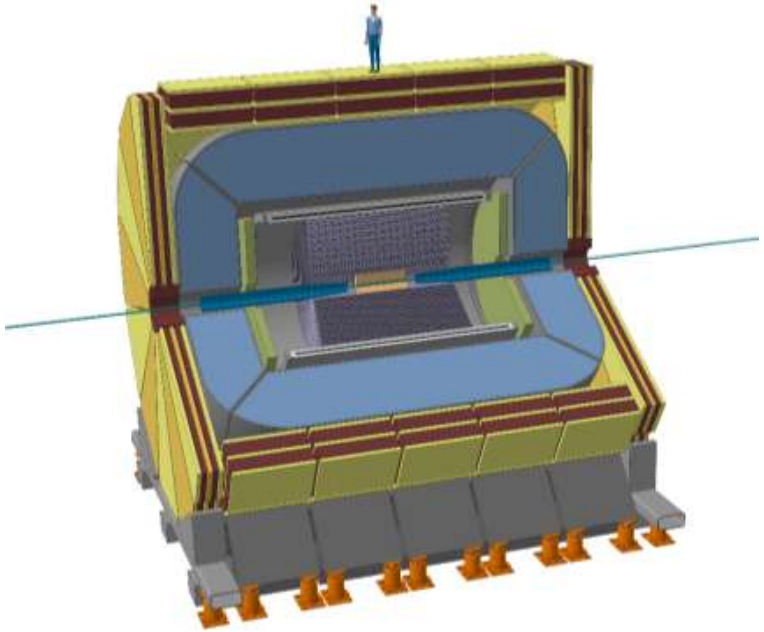
6.2 Magnets for FCC e^-e^+ collisions detectors

For FCC-e^-e^+ two detector designs are proposed:

- **a 2 T solenoid around the calorimeter**, essentially a downscaled CLIC design, not further presented here
- **a challenging 2 T solenoid "ultra-thin & transparent" around the tracker**, accepted as baseline



CLIC style downscaled
2 T Solenoid



IDEA detector, innovative thin solenoid around tracker

Solenoid inside or outside the calorimeter

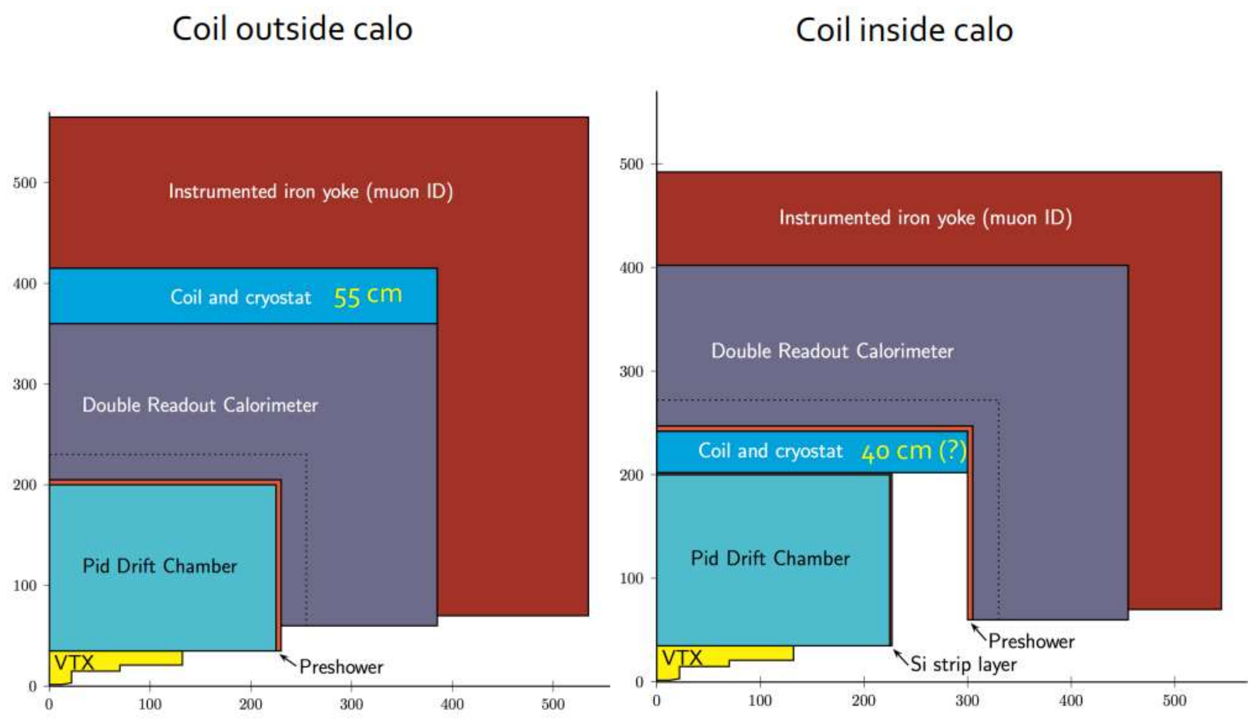
Motivation:

- Magnetic field is only required in the tracker + muon chambers, but most stored magnetic energy (some 80%) is wasted in the calorimeter space!

Obvious savings when coil is positioned inside:

- **Factor ≈ 4.2 in stored energy**
- **Factor ≈ 2.1 in cost!**

But design is not obvious and requires R&D and a demonstrator.



Solenoid *outside* or *inside* calorimeter?

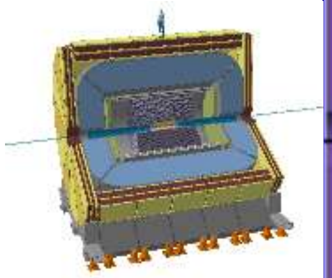
Solenoid for the "ultra-thin" IDEA detector

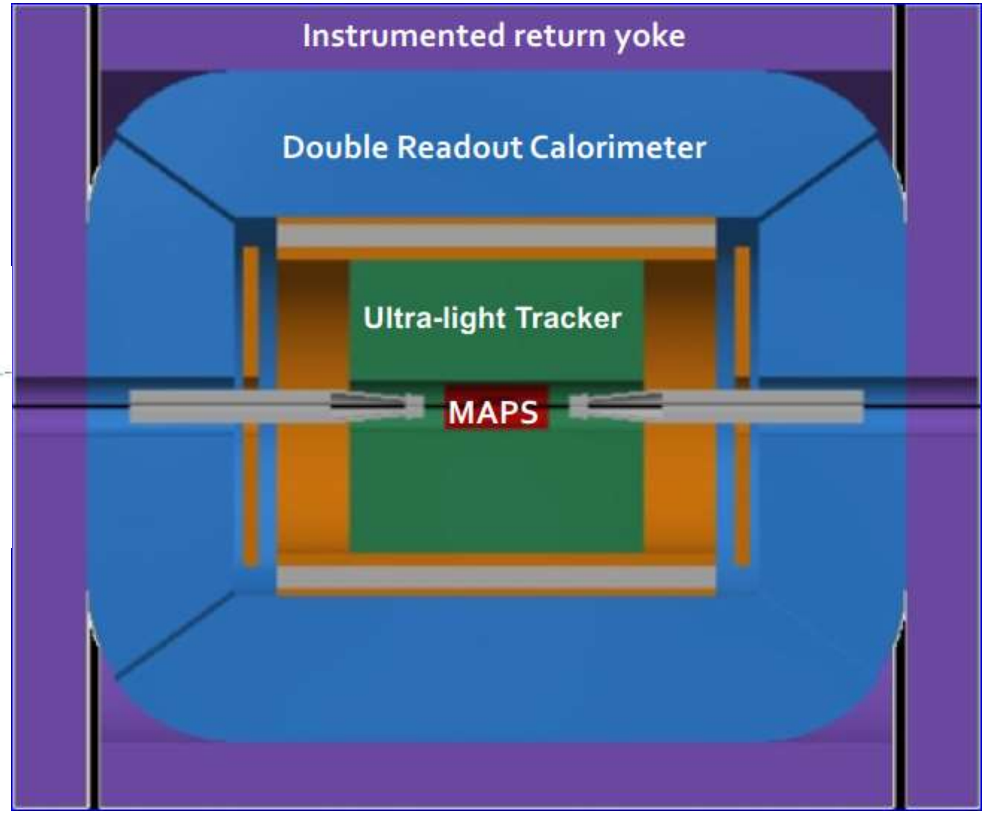
Requirements:

- 2 T in thin Solenoid with radiation length $X_0 < 1$ in radial direction!
- Radial envelope < 300 mm.
- Magnetized iron for muon detection.

Strategy:

- ✓ Reduce thickness of cold mass.
- ✓ Reduce thickness of cryostat.
- ✓ Magnetic flux return by a light return yoke.





IDEA detector (***I***nternational ***D***etector ***E***lectron ***A***ccelerators), an innovative thin solenoid around tracker

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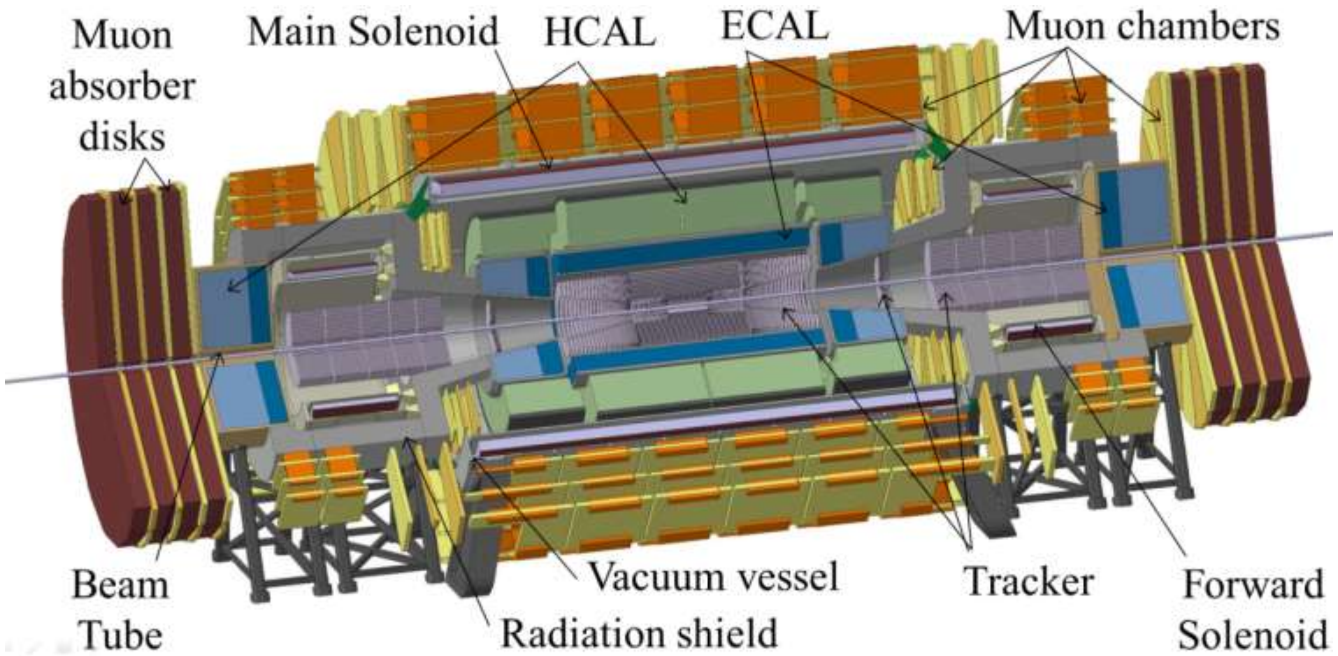
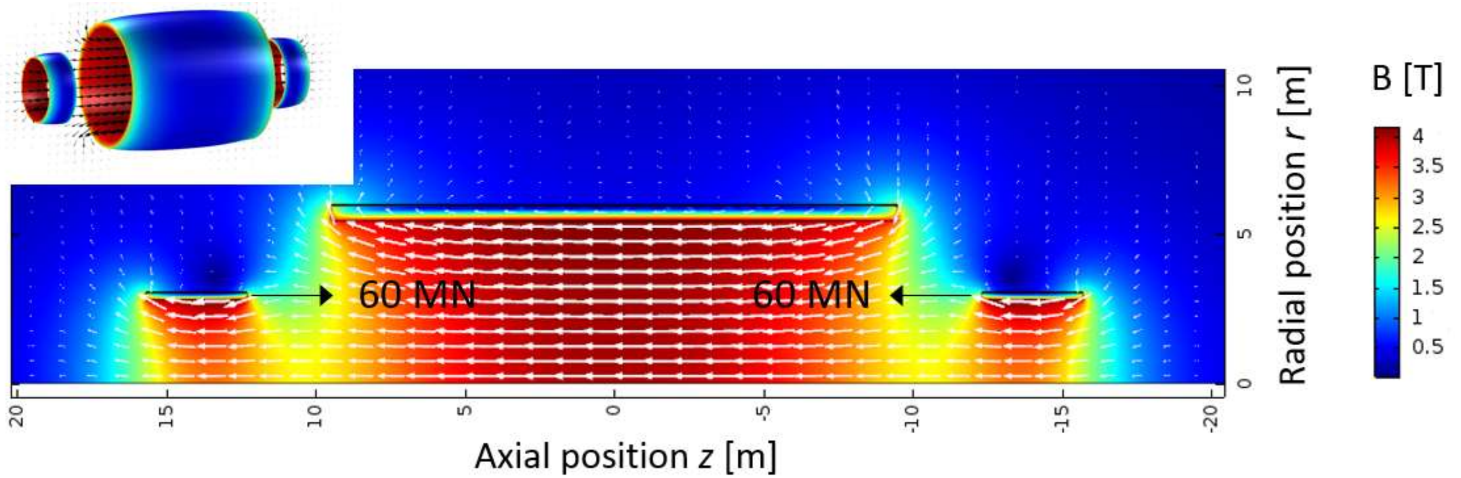
6.3 FCC-proton-proton collisions Detector - Baseline

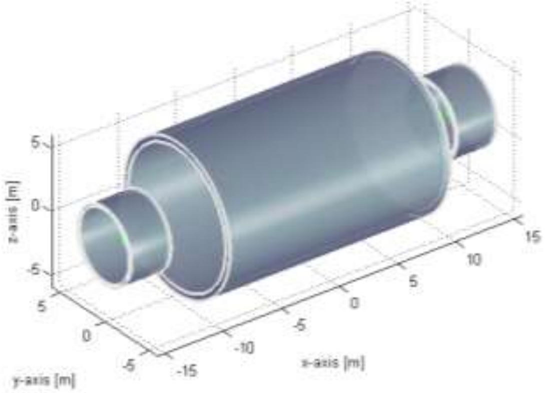


Main solenoid:
- Trackers and calorimeters inside bore, supported by the bore tube
- Muon chambers (for tagging) as outer layer in barrel region

Forward Solenoids (forward dipole is an option):
- Tracker inside solenoid
- Forward calorimeters after forward solenoids
- Enclosed by radiation shield
- Muon station behind

4T/10m-bore Solenoid with 4T Forward Solenoids



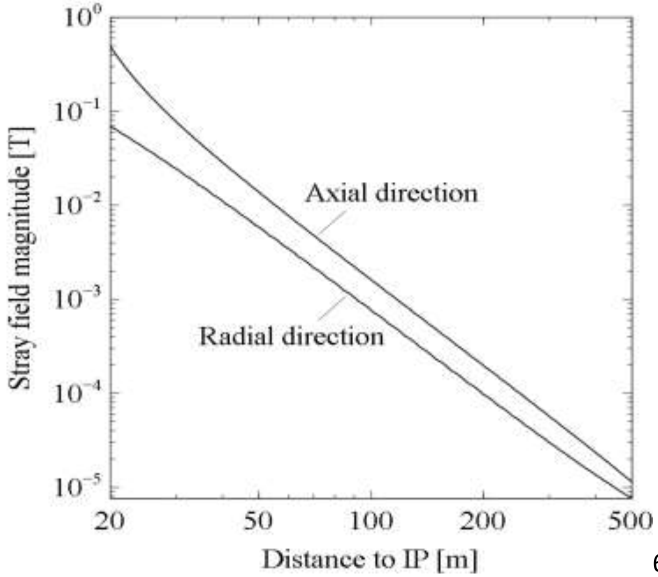


Concept:

- 4 T in 10 m free bore
- Magnetic shielding not required
- 60 MN net force on forward solenoids handled by axial tie rods.

Result:

- **Stored energy: 14 GJ, energy density 12 kJ/kg**
- Main solenoid cold mass 1070 t, forward solenoids 48 t
- Lowest degree of complexity from a cold-mass perspective
- But with significant stray field to be coped with.



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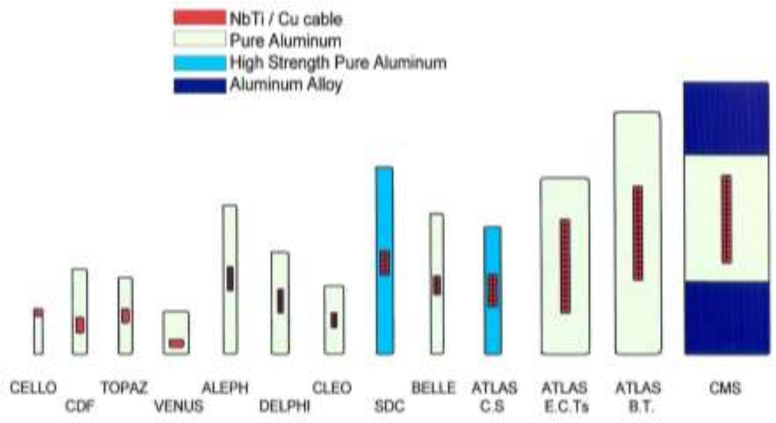
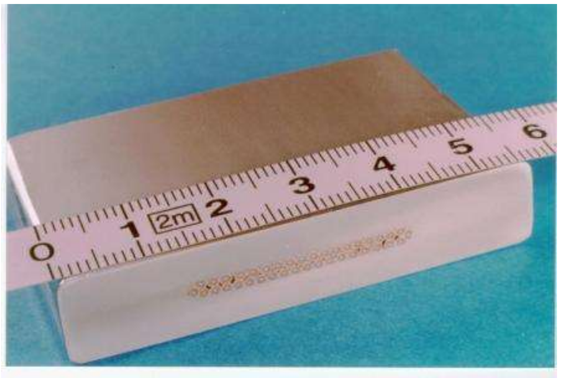
6.4 Al stabilized conductors for Detector Magnets

For maximum MPZ, stability, minimum weight and maximum particle transparency

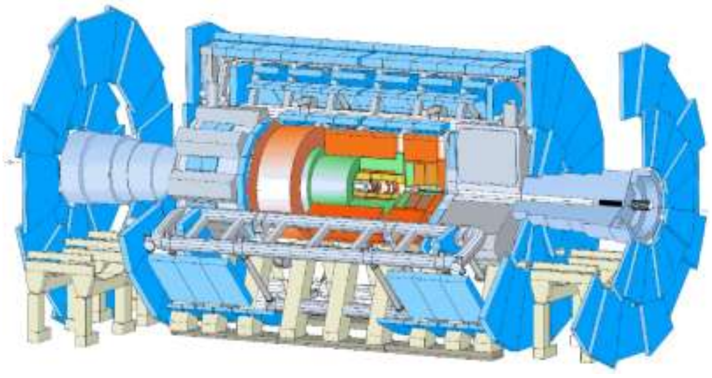
- *Simplicity of conduction cooling*, affordable since no dynamic operation, quasi stationary
- High-purity Al stabilized, RRR 2000, *maximum MPZ* (m), much larger λ/ρ than copper!
- *Particle transparency* for minimum particle scattering
- **But higher collision energy implies larger dimension**, tracking length and field (BL^2), thus higher coil winding stress, **requiring conductor reinforcement** (pure Al yields at 17 MPa)



Increase of section for larger detectors



ATLAS conductor 65kA@5T,4.2K



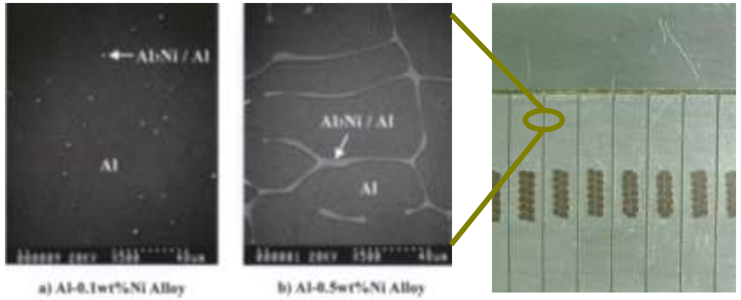
ATLAS magnet system, 4T/22m, 1.6 GJ

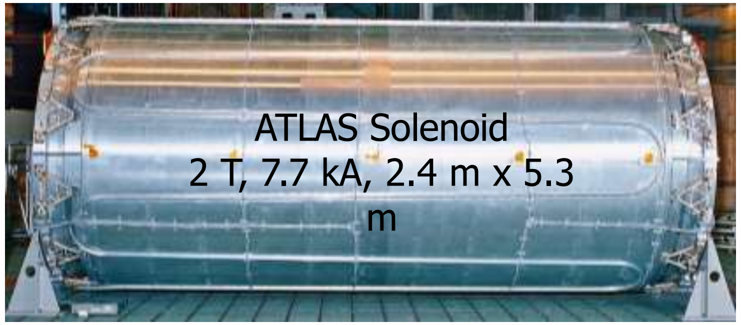
How to reinforce pure Al ? - Proven solution and R&D

Option 1

Micro-alloy pure Al with Ni or Zn

Used in the ATLAS Solenoid

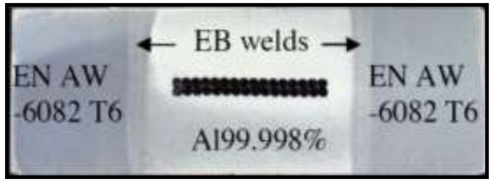




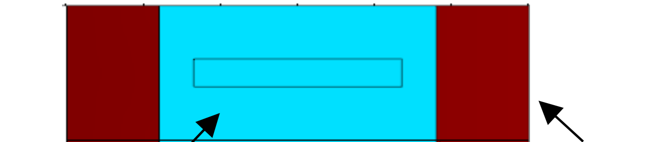
Option 2

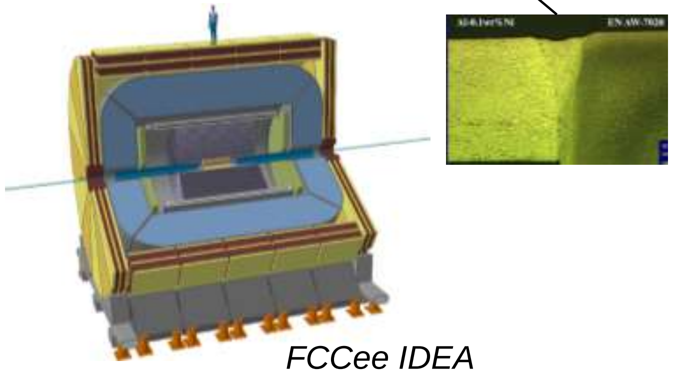
Reinforce with Al-alloy side bars, EB-welded to the pure Al of the NbTi/Cu/Al conductor

Using **Al 6082** T6
(Used in CMS Solenoid)

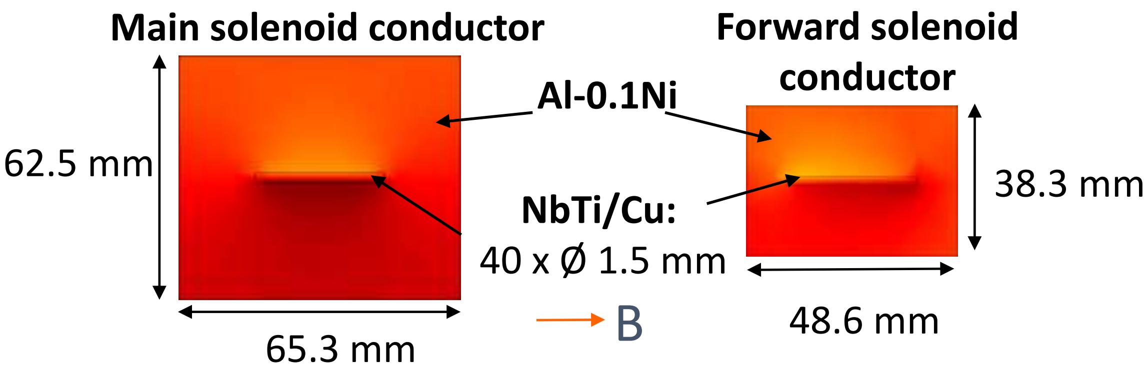


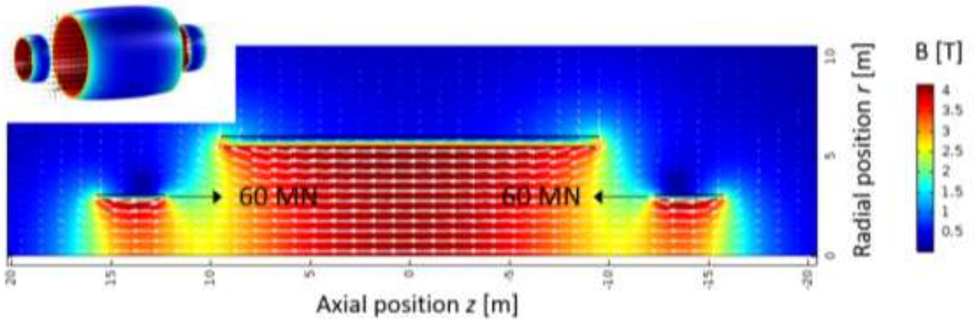
Using **Al 7020/7068**
(R&D for FCC-IDEA)

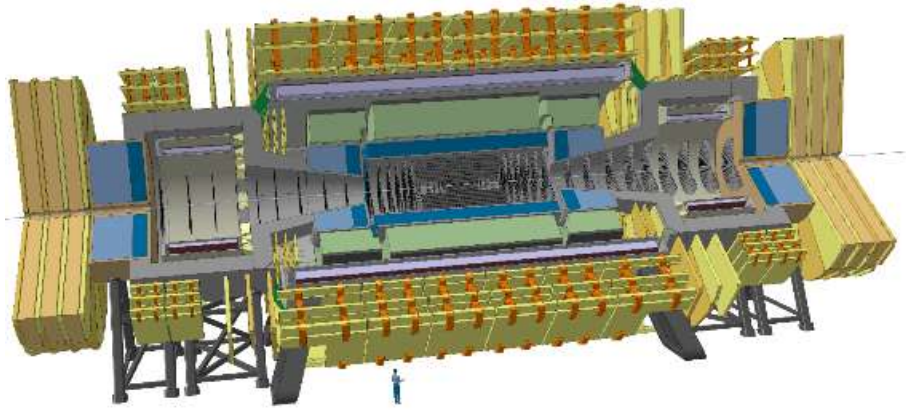




Super-Conductors for 4T/10m detector solenoids







Next generation of Aluminum-stabilized Rutherford conductors for 30 to 40 kA at 5 T:

- Peak magnetic field on conductor 4.5 T
- Current sharing temperature 6.5 K
- 2 K temperature margin when operating at 4.5 K
- **Nickel-doped Aluminum (≥0.1 wt.%)** combining good electrical properties (RRR 600) with mechanical properties, 146 MPa conductor yield strength

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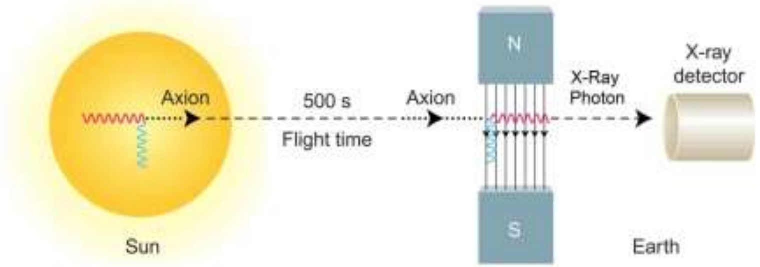
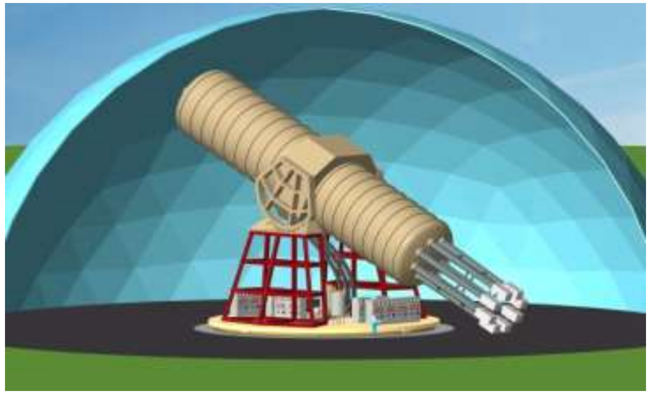
6.5 Detector magnets – Axions search with BabyIAXO

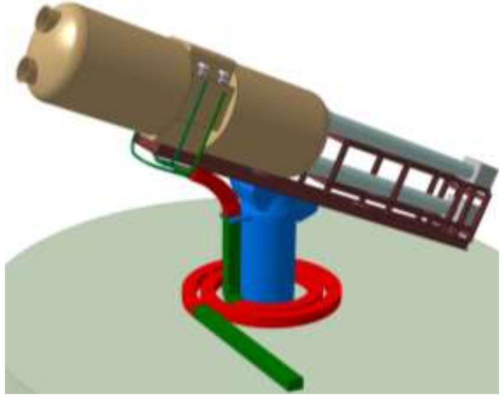


$$f_M = L^2 \int B^2(x,y)dxdy \rightarrow L^2B^2A$$

Principle of Solar Axion detection



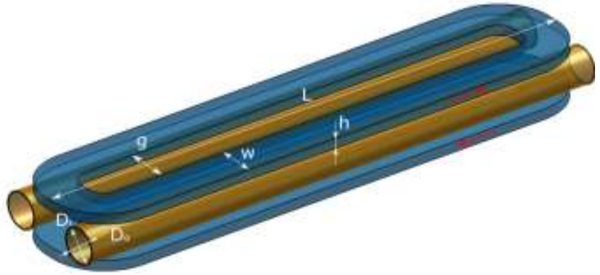
IAXO: D4 x L20, 8 bores, 2.5T/660MJ



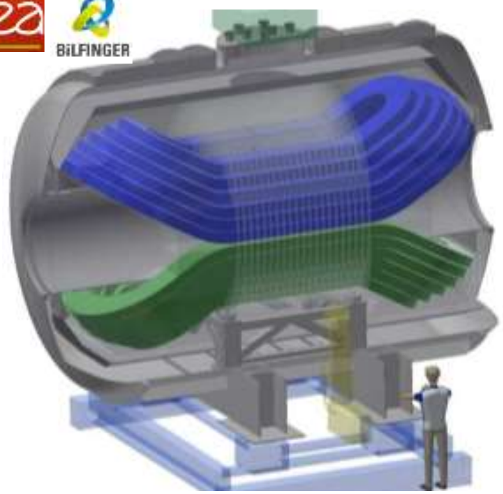
BabyIAXO: L10m, 2 bores, 2.5T

BabyIAXO, pathfinder for IAXO, fully functional solar axions detector

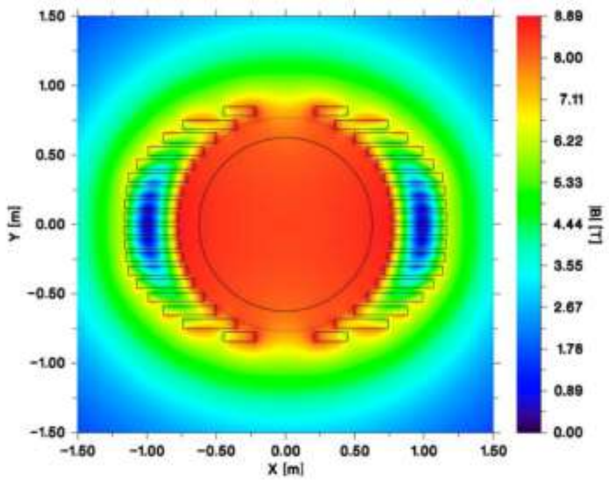
- 10 m long racetrack coils, NbTi/Cu - Al stabilized conductor, 10 kA, 50 MJ
- Cryocooler operated at 4.5 K using 2 single stage and 4 double stage units
- BabyIAXO production starting this year
- Designed by CERN, installation foreseen at DESY-Hamburg
- **In construction design phase, realization in next 5-10 years**



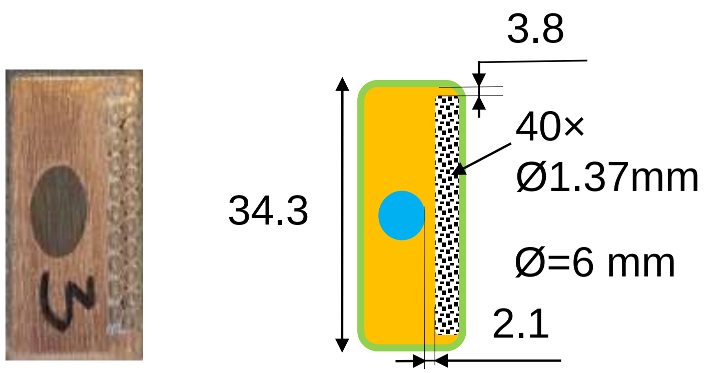
6.6 Detector magnets – Axions search with MadMax



MadMax Dipole for Axions



Magnetic field in 1.35m bore



NbTi/Cu Rutherford cable in Copper bar, sf He in 6 mm hole for cryo-stability

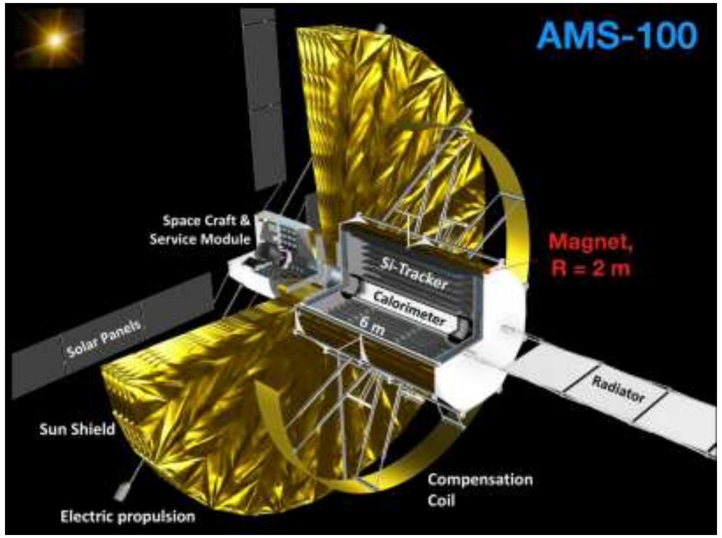
Proposed Axions – dark matter Experiment by MPI-MadMax Collaboration, installation at DESY Hamburg

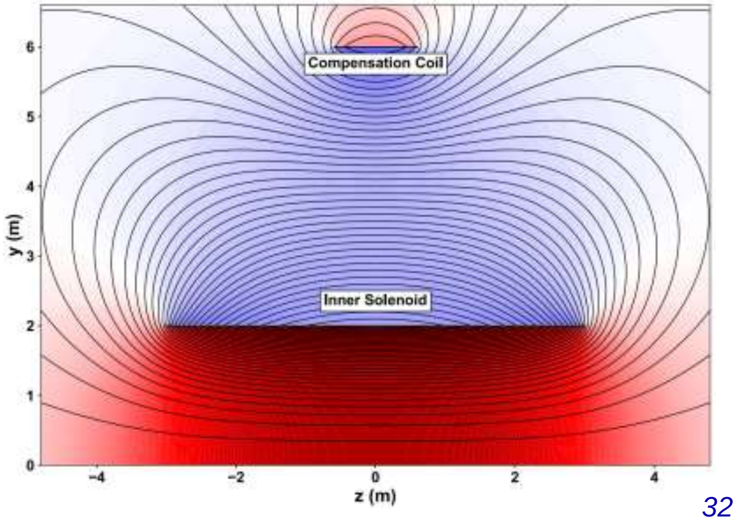
- In magnetic field Axion decay to photons detection requiring a large bore dipole magnet
- Largest high-field dipole design, ultimate use of cryostable sf He containing NbTi/Cu conductor at 1.9 K
- **1.35 m bore, 5 m long, 50 A/mm^2, 9.87 T, peak field, 480 MJ, 1.9 K**
- **In advanced design phase, realization in next 5-10 years**

6.7 Detector magnets – Spectrometer in space AMS-100

Spectrometers for cosmic rays analysis in space, now one: AMS-2

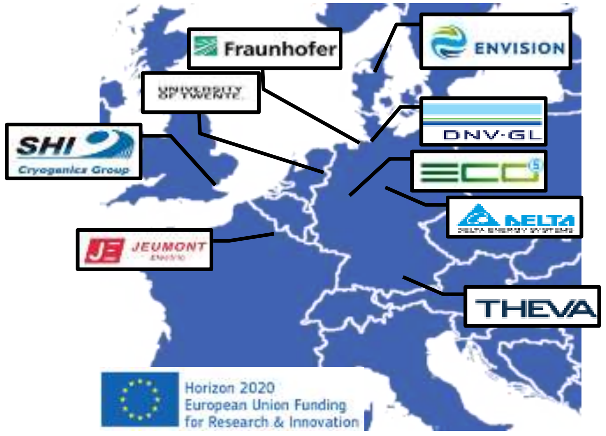
- Following AMS-2 results, factor 10 in energy requested
- Position a new one in Lagrange Point-2, 1.5 Mkm from earth
- **1 T, 4 m bore, 6 m long, 75 m^3, 40 MJ, 50 K operation**
- **Ultra-thin & transparent, for 4π acceptance, few mm only!**
- **Torque compensated with a foldable 12 m bore outer coil**
- Fully automatic, rocket launch resistant and size-compatible
- ReBCO tape based controlled-insulation coil technology
- 22 tapes // for main coil, 2 tapes // for compensation coil
- 1st step is a reduced scale path finder system
- Some 200 km of 12 mm tape required
- Just started, development and realization in next 10-15 years!
- NASA & ESA very interested in HTS coils in space for development of magnetically shielded rockets for long missions.

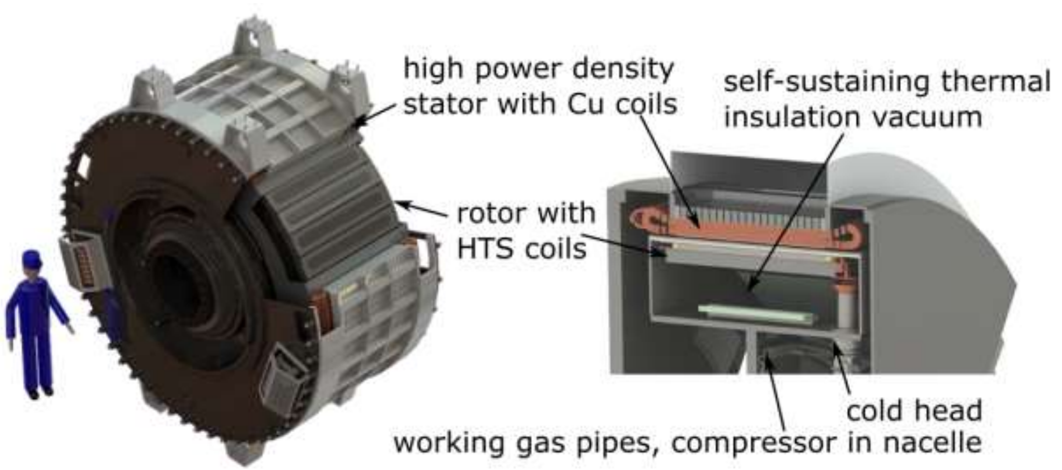




7. EcoSwing – 1st Sc. wind turbine

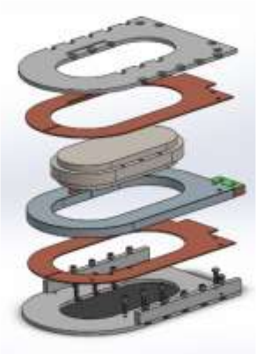
- Demonstration of a full-scale 3 MW direct-drive superconducting wind generator
- Installation on an existing modern wind turbine in Thyborøn, Denmark and got for 1st time unique field experience
- 4 m OD, 30 t, 15 rpm, 40 HTS racetrack coils, operating at 30 K using 9 rotating cryocoolers

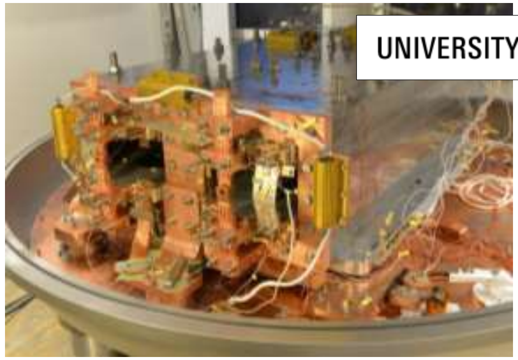




Old and new generator in same casing

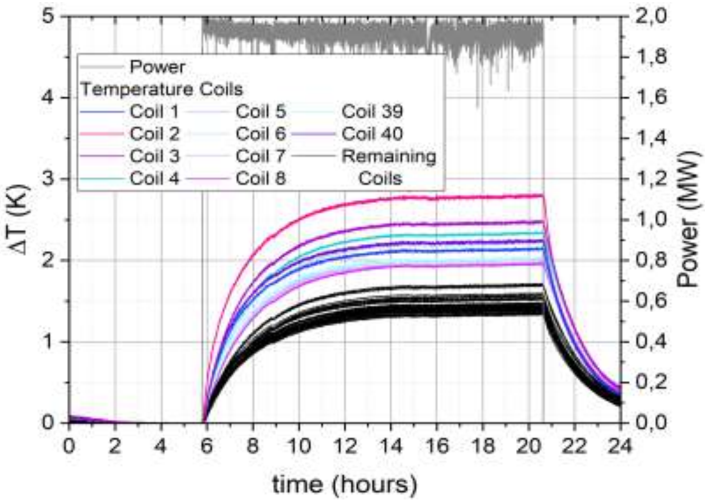
EcoSwing - Turbine coils production, assembly and test





UNIVERSITY OF TWENTE.

40x 1.4m coils (43 built, 91% yield), 48 kg 500 m of 12 mm ReBCO, 20 km in total, tested at 30 K, mounted on rotor, mass 30 t, 9 rotating cryocoolers, 14 days cool down to 22 K, excitation in steps up to 3 MW.



- ✓ First time ever!
- ✓ Achieved target output power ~3 MW
- ✓ More than 650 h of grid operation
- ✓ More than half year problem-free cryogenic operation
- ✓ Waiting for next initiative......

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CERN

8. Conclusion

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A selection of remarkable superconducting magnets under development in Europe were presented, a few to remind….

- ✓ 43 and 45 T hybrids in Grenoble and Nijmegen respectively
- ✓ 11.7 T/900 mm bore MRI and 28.3 T NMR demonstrated

- ✓ Fusion: ITER magnets coming in, new DTT R&D tokamak, HTS@Tokamak Energy
- ✓ Accelerators: HL-LHC Dipoles and Quads maturing, FAIR dipole production at 50%, 1st Quad
- ✓ Detector magnets: FCC ee and hh versions, ultra-transparent solenoids, BabyIAXO & MadMax, AMS-100 ReBCO solenoid in space
- ✓ Sc wind turbines: success of 3 MW ReBCO based EcoSwing…………