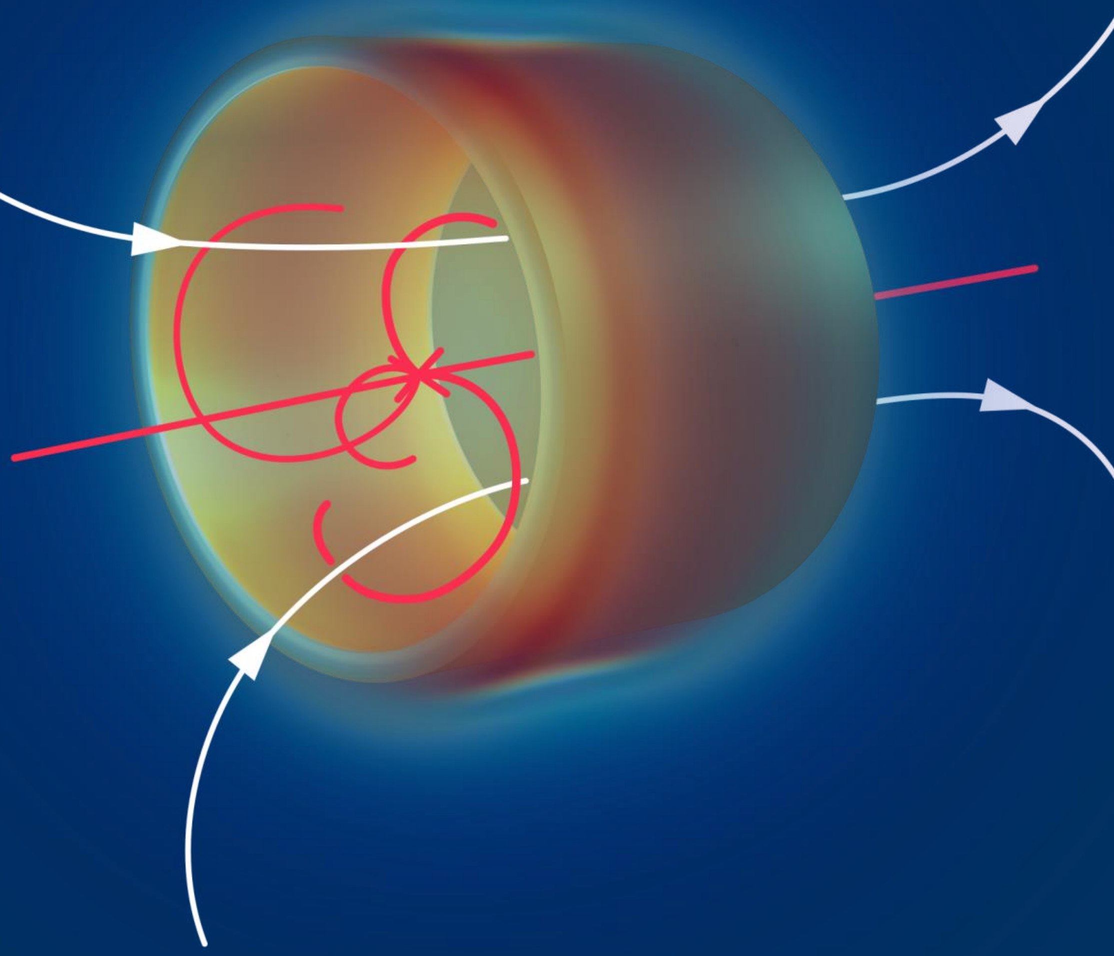
Superconducting Detector Magnets for FCC-hh

Matthias Mentink on behalf the CERN EP Magnet Team, 12-9-22

- Baseline conceptual design of the FCC-hh Detector Magnet configuration
- The conductor challenge
- The infrastructure challenge
- Long-term schedule considerations
- Summary



Motivation

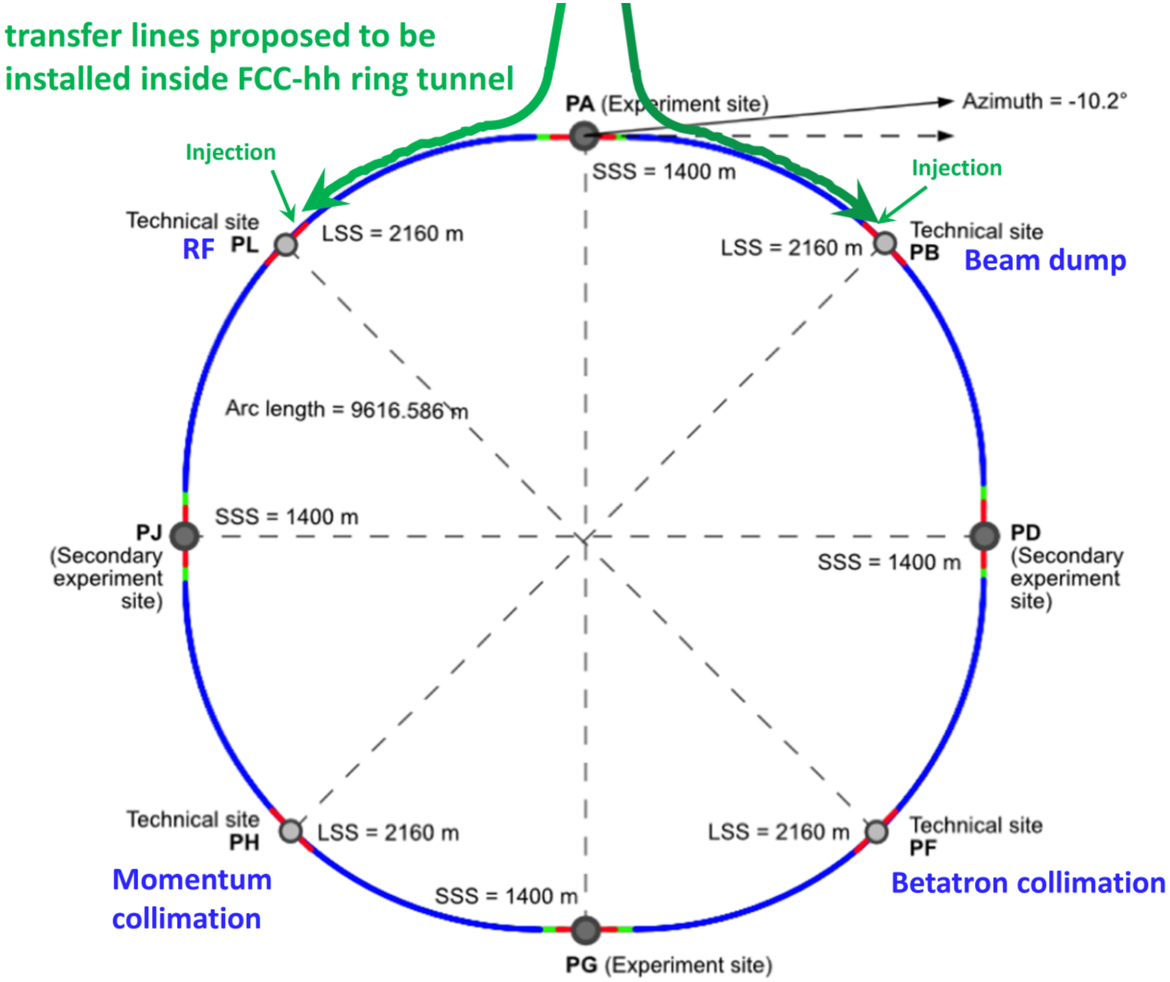
- As a successor to the LHC, the Future Circular Collider (FCC) project is proposed, featuring an underground accelerator complex with a length about 100 km, located in France and Switzerland

- Time-line:
  - FCC-ee (Electron-positron collisions), foreseen to operate in 2045 – 2060

  - FCC-hh (hadron-hadron collisions), foreseen to operate 2070 – 2090+

- FCC-hh (The FCC hadron collider)
  - 100 TeV particle collisions, i.e. more than 7x higher than the collision energy of the LHC

  - More collision energy → More powerful detector magnets are needed to study the collision products

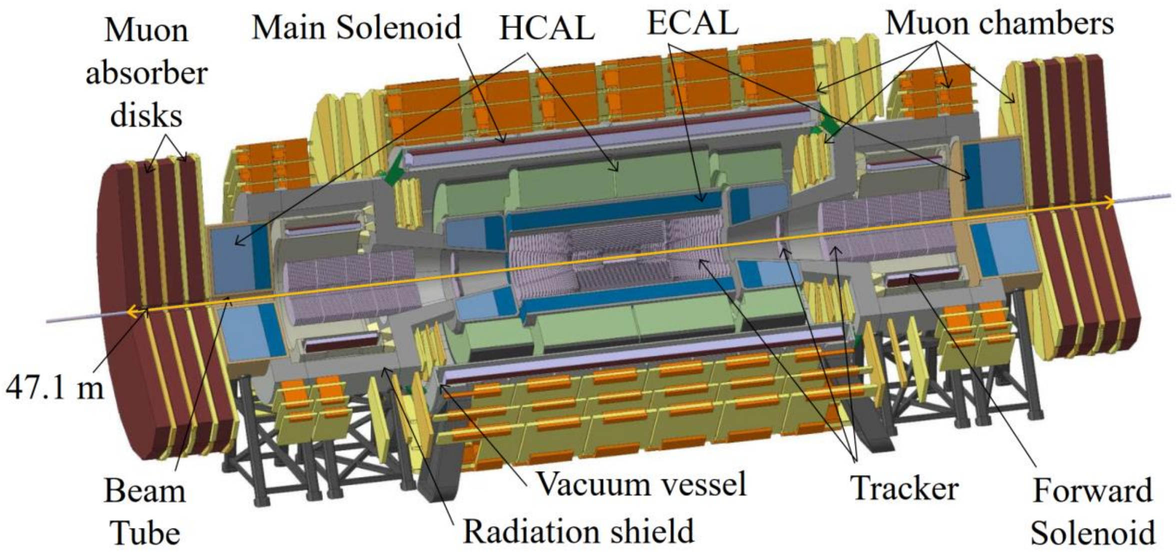


Layout of the FCC-hh accelerator [1]

FCC-hh baseline detector, geometry

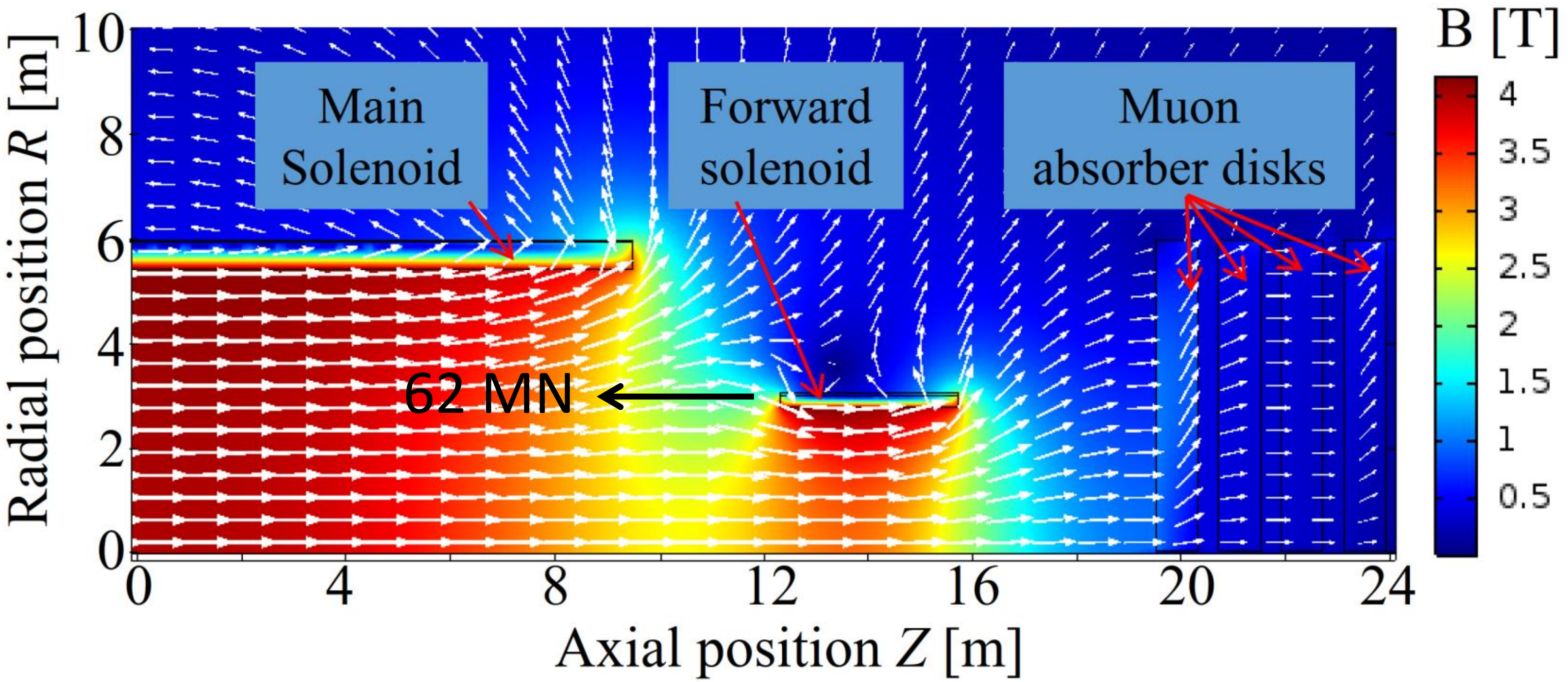
- A conceptual design effort for the FCC-hh detector magnet configuration was initiated about ten years ago
  - Under leadership of H. ten Kate, with participation of: C. Berriaud, E. Bielert, B. Cure, A. Dudarev, A. Gaddi, H. Gerwig, V. Klyukhin, M. Mentink, H. Silva, U. Wagner
  - Integrated into the overall FCC-hh detector design effort, under leadership of W. Riegler
  - Collaborating institutes: CEA-Irfu, University of Illinois, Skobeltsyn Institute of Nuclear Physics, CERN

- Resulting detector layout:
  - CMS-like geometry, with tracker, electron calorimeter, and hadron calorimeter inside the bore of a large superconducting solenoid
  - But also: Emphasis on forward physics, with forward solenoids and forward detectors
  - No return yoke



Conceptual FCC-hh detector design

FCC-hh baseline detector magnet configuration



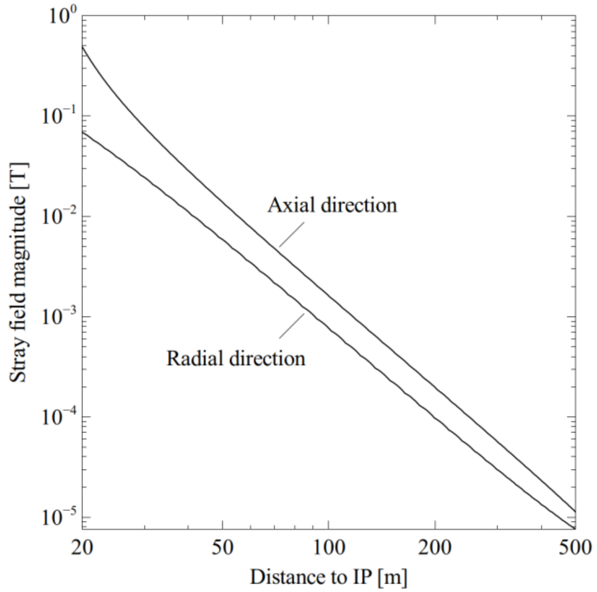
Property	Value
Total stored energy [GJ]	13.8
Operating current [kA]	30.0
Combined inductance [H]	30.7
Inductance main solenoid [H]	27.7
Inductance forward solenoid [H]	0.93
Mutual inductance, main-to-forward [H]	0.29
Mutual inductance, forward-to-forward [H]	0.001
Cold mass main solenoid [t]	1070
Cold mass forward solenoid [t]	48
Vacuum vessel main solenoid [t]	875
Vacuum vessel forward solenoid [t]	32
Average energy density [kJ/kg]	11.85
Minimum shaft diameter [m]	13

Various properties of the FCC-hh detector magnet configuration

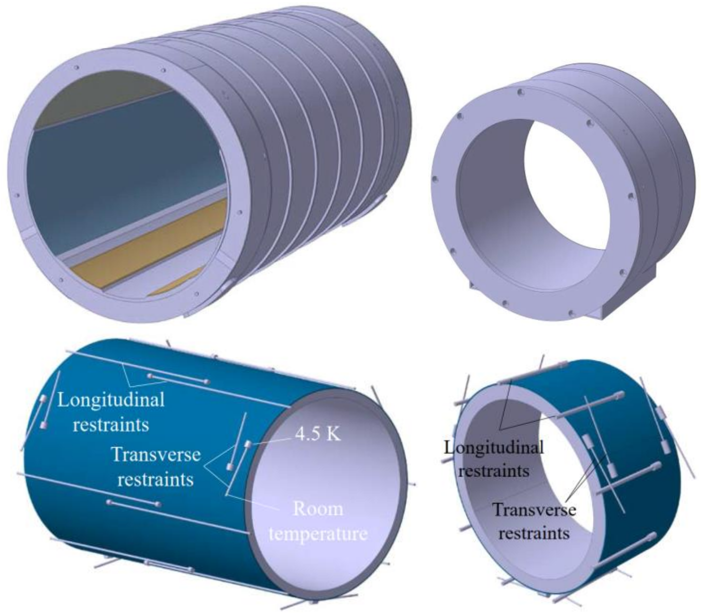
Three superconducting solenoids [2]:

- One 4 T main solenoid, weighing 1.95 kt (cold mass + vacuum vessel), a 10 meter free bore diameter, 20 meter long vacuum vessel
- Two smaller 4 T forward solenoids, each weighing 80 t
- Strong attractive force: 62 MN on each forward solenoid towards the main solenoid
- Combined stored magnetic energy: 14 GJ, more than 5x higher than CMS, currently the record-holder of stored magnetic energy in a superconducting detector magnet

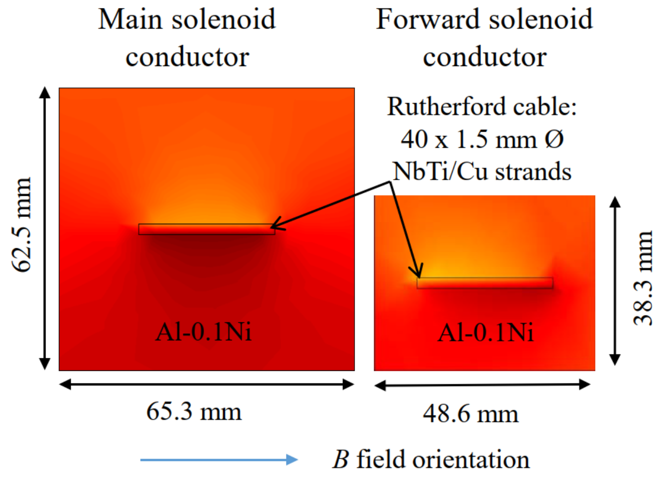
Implications



Magnetic stray field



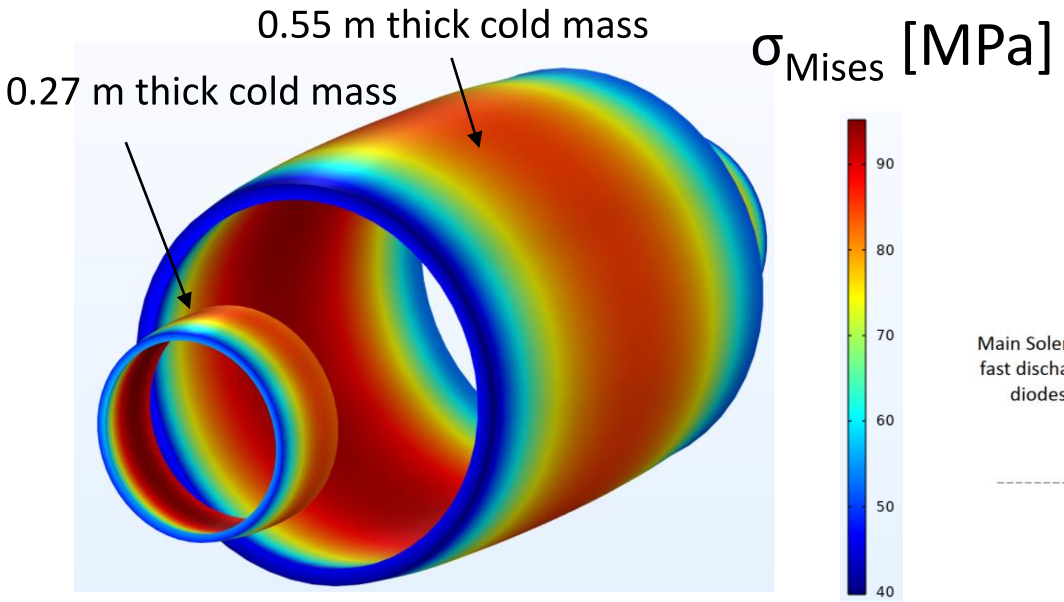
Vacuum vessel and coil suspension



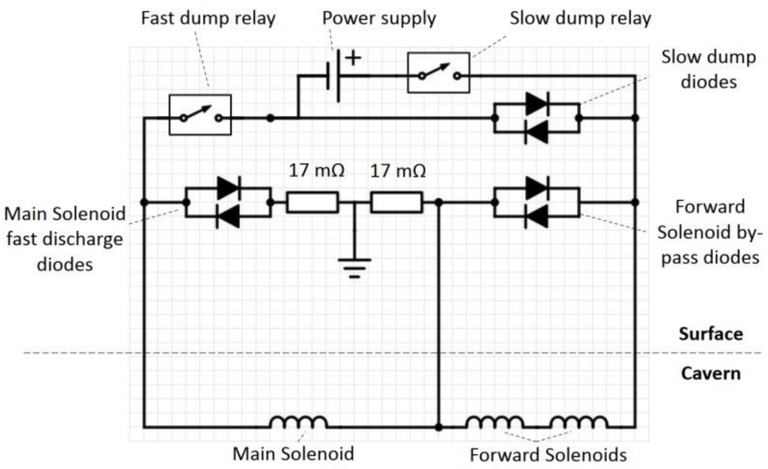
Proposed conductors

- Magnetic stray field: No return yoke, so a significant stray field is present
- Strong coil suspension needed, to hold the cold mass weights and the 62 MN net Lorentz force between the forward and main solenoids
- Conductor: Nicked-doped aluminum + Nb-Ti/Cu Rutherford cable (Main solenoid: 83 km, Forward solenoid: 7.7 km each)
  - For solenoids, the thickness of the coil scales with the radius. Main solenoid: large coil thickness (0.55 m) and a relatively low current density
  - Enormous stored magnetic energy → Large operating current (30 kA) to maintain a manageable inductance
  - Combination of the two: **Implies a very large conductor, 3x larger cross-section than CMS** (more on this later)

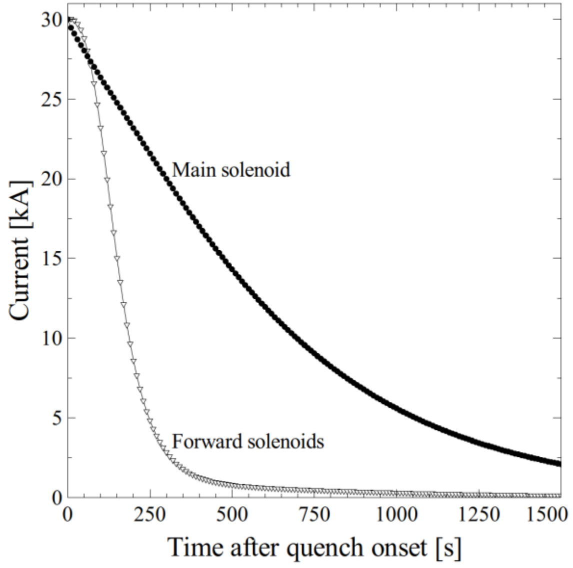
Cold mass mechanics, powering, and quench protection



Cold mass Von Mises stress at nominal current



Powering circuit

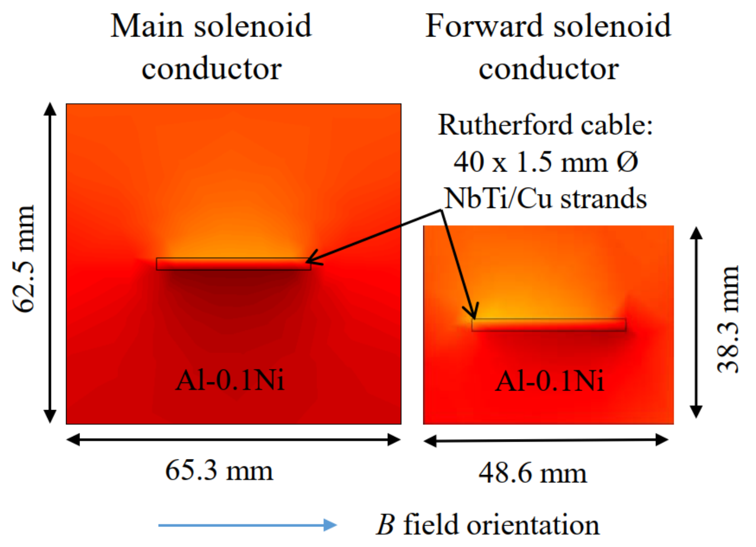


Fast dump discharge

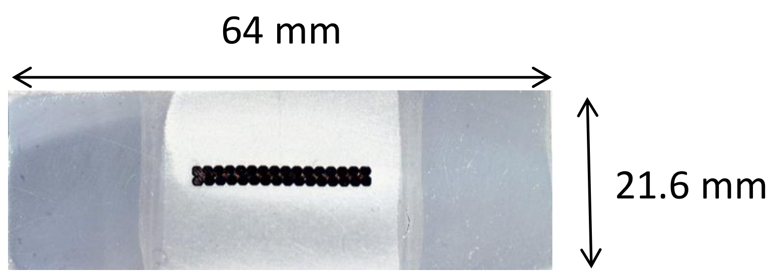
- Cold mass mechanics:
  - Energy density: 11.9 kJ/kg (CMS: 11.7 kJ/kg)
  - Peak Von Mises stress: 95 MPa, peak tensile strain: 0.13%
  - Use of a mechanically reinforced conductor is unavoidable, and the choice of aluminum-based conductor and cold mass looks favorable in terms of overall weight

- Powering and quench protection
  - Combined powering for simplicity and cost savings
  - In case of quench: Quench heaters + energy extraction, where the main and forward solenoids are individually discharged: $T_{Max} < 90$ K

Challenge: Conductor



Proposed conductors for FCC-hh

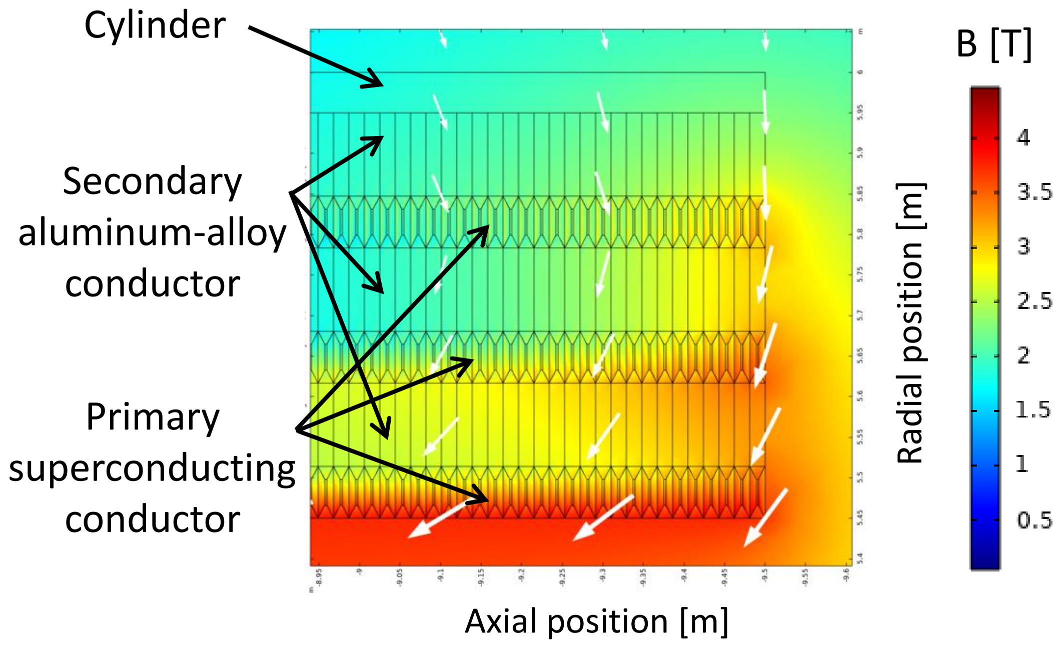


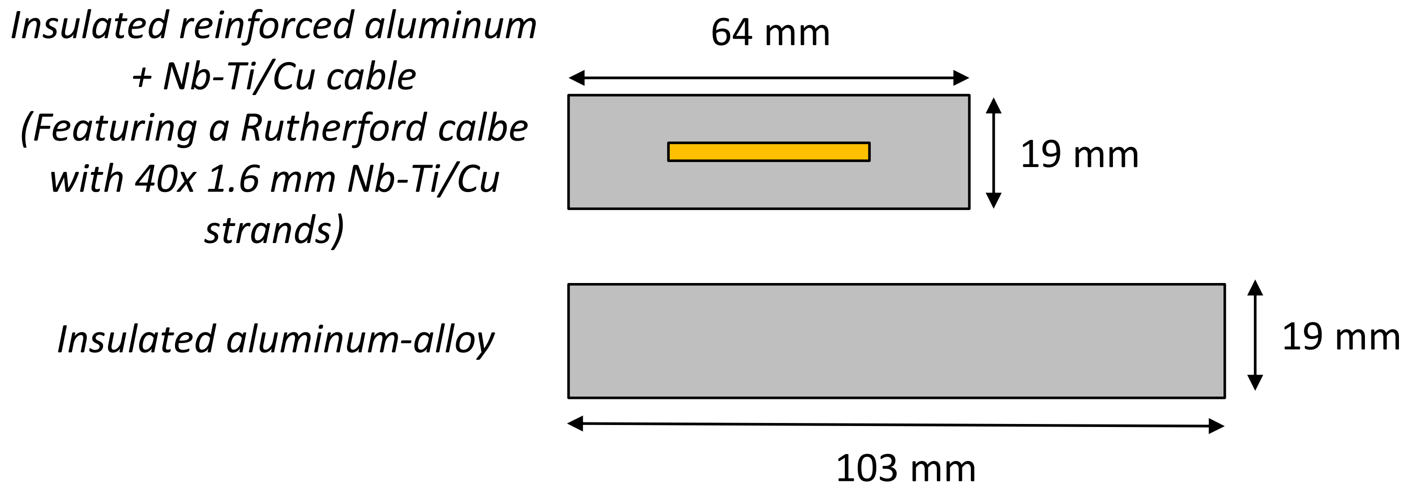
The CMS conductor
Courtesy: The CMS collaboration

- Main solenoid:
  - Very large mechanically reinforced aluminum-based conductor, with a 3x larger cross-section than the CMS conductor
  - Moreover, it is wound into 8 layers (whereas CMS has 4)

- Is this technically feasible?
  - To be demonstrated
  - Alternatives should be considered, if this turns out to be very challenging

Possible alternative: co-winding layout (1/2)

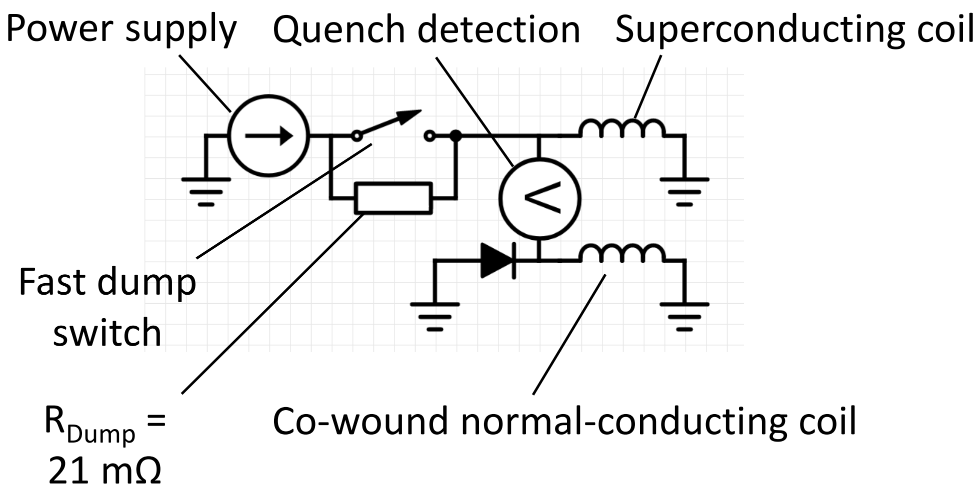




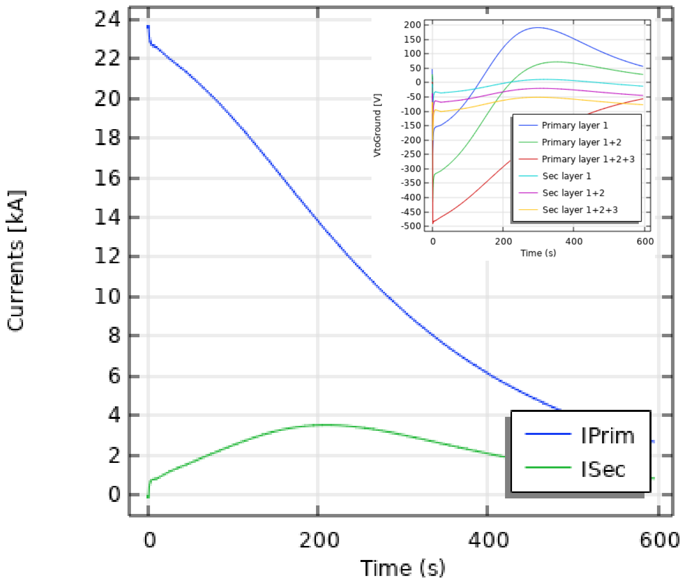
Alternative layout:

- Three layers of superconducting conductor (106 km) at operating current of 23.6 kA, co-wound with three layers of normal-conducting conductor
- Mechanics:
  - Superconducting cable radially presses into the normal-conducting cable, and so the Von Mises stress is identical to the 8-layer variant (σ_{Mises} = 96 MPa, tensile strain max: 0.13%)
  - The current is concentrated in half the layers rather than homogeneously distributed in the coil, therefore the axial shear stress at the interfaces is higher but still looks acceptable (1.8 MPa)

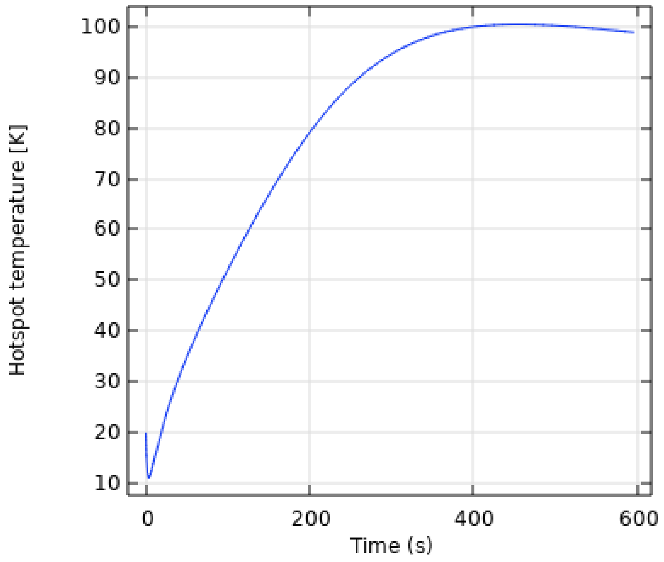
Possible alternative: co-winding layout (2/2)



Considered simplified circuit



Simulated currents and voltages



Resulting hotspot temperature

Operational and quench implications:

- During operation: The secondary coil acts as co-wound voltage tap, for nearly perfect inductive correction → Very straightforward and sensitive quench detection
- In case of quench:
  - Superconducting windings are discharged over a dump resistor
  - Due to inductive coupling, secondary normal-conducting windings temporarily carry current, thus acting as an inductively powered quench heater and rapidly quenching all the superconducting windings
  - Result: A homogeneous quench with T_{Max} = 100 K, and acceptable voltages ($V_{toGroundMax}$ ≤ 500 V)

→ Interesting alternative winding concept, to be studied further

Challenge: Infrastructure (1/2)

Credit: CMS, CERN

A preliminary study of infrastructure for the FCC-hh detector magnet was performed by B. Cure [3]

- The CMS approach: During industrial production, the cold mass was split into five modules, followed by assembly at CERN
  - 45 tonnes per module, axial length of 2.5 m, and an external diameter of 7.1 m
  - **The CMS magnet approached the limit of what could be transported to Pays de Gex**

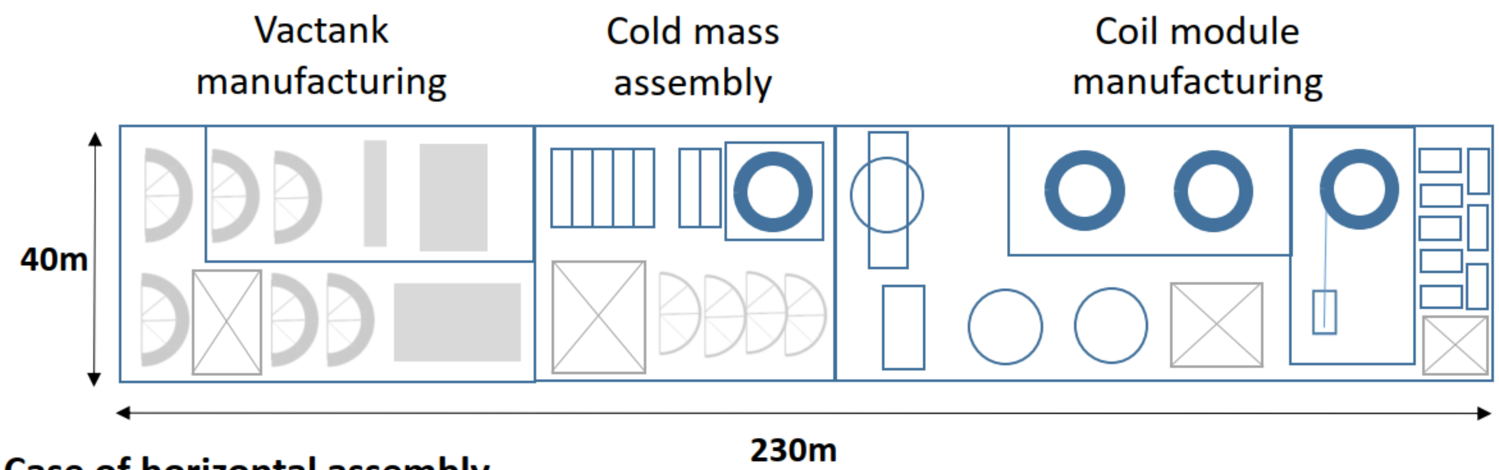
- The weight of the FCC-hh main solenoid cold mass is 1070 t
  - Assuming it is produced in seven modules: 150 tonnes per module with an axial length of 2.8 m and an outer diameter of 11.7 m
  - **The CMS approach featuring coil production in industry followed by assembly at CERN looks very challenging for the FCC-hh detector magnet**

Challenge: Infrastructure (2/2)

FCC-hh detector magnet

Surface = 9200m² **Height = 23m**

How the surface hall could look like…



Case of horizontal assembly.

Preliminary study of FCC-hh magnet infrastructure needs [3]

What is the alternative?

- **Construction of a complete magnet manufacturing facility at CERN**
- A preliminary layout of such a facility, based on the CMS magnet project experience, is shown above

Long-term schedule considerations

- Operation of FCC-hh foreseen for 2070 – 2090+ [4]

- The closest similar magnet projects are the ATLAS and CMS superconducting detector magnets
  - 15 years from start of engineering design to commissioning
  - Strong support from multiple institutes (7-9) and a significant human resource allocation

- The FCC-hh detector magnet features more than 5x larger stored magnetic energy than CMS, featuring multiple very large superconducting magnets, and with likely full construction at CERN
  - A strategic vision is needed to make these magnets a reality
  - An appropriate time-scale is on the order of 20 years (i.e. 2050), with strong support from multiple institutes

- **Challenging project!**

Summary

Baseline conceptual detector magnet layout for FCC-hh:

- Featuring three 4 T superconducting aluminum-stabilized Nb-Ti/Cu-based solenoids, including a main solenoid with a free bore of 10 meters, and a length of 20 meters
- Excellent pseudo-rapidity coverage, including for particle products nearly parallel to the beam pipe

Technical implications:

- Very large combined stored magnetic energy of 13.8 GJ, i.e. more than five times higher than CMS
- No return yoke → Significant magnet stray field
- Three solenoids in close proximity → Net attractive force of 62 MN

Challenges:

- Conductor
  - Conductor with a very large cross-section in eight layers, feasibility to be studied
  - Alternative conductor types and winding scenarios may be considered
- Magnet infrastructure needs
  - Significant transportation challenges of components due to size and weight
  - Likely coil winding, cold mass assembly, and vacuum vessel production has to be done entirely at CERN, requiring a large facility

Long-term schedule:

- FCC-hh is foreseen to start operation in 2070
- Given the size of the detector magnets, an engineering, construction, and commissioning effort of ~20 years should be foreseen

References

[1] FCC-hh project, https://home.cern/science/accelerators/future-circular-collider

[2] M. Mentink, H. Silva, A. Dudarev, E. Bielert, V. Klyukhin, B. Cure, H. Gerwig, A. Gaddi, C. Berriaud, U. Wagner, and H. ten Kate, "Evolution of the Conceptual FCC-hh Baseline Detector Magnet Design", IEEE Trans, on Appl. Supercond. 28, p. 4002710, (2018)

[3] B. Cure, "FCC-hh SC magnet infrastructure needs, preliminary answers", presented at the 8th EP Magnet Working Group (2022), https://indico.cern.ch/event/1166920/

[4] F. Giannotti, "FCC Week 2022, welcome address", https://indico.cern.ch/event/1064327/timetable/