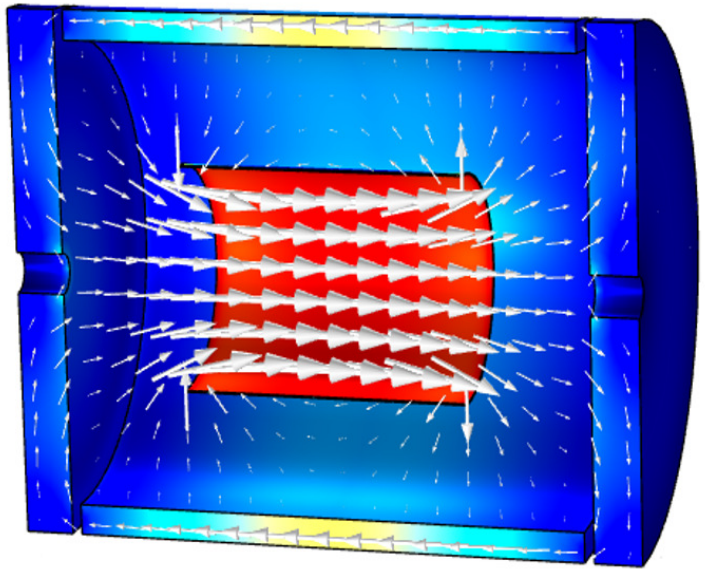
Ultra-transparent Solenoids for FCC Experiments

Matthias Mentink, Nikkie Deelen, Filip Malinowski, Helder Filipe Pais Da Silva, Veronica Ilardi, Tobias Kuhlenkampff, Herman ten Kate, Benoit Cure, and Alexey Dudarev

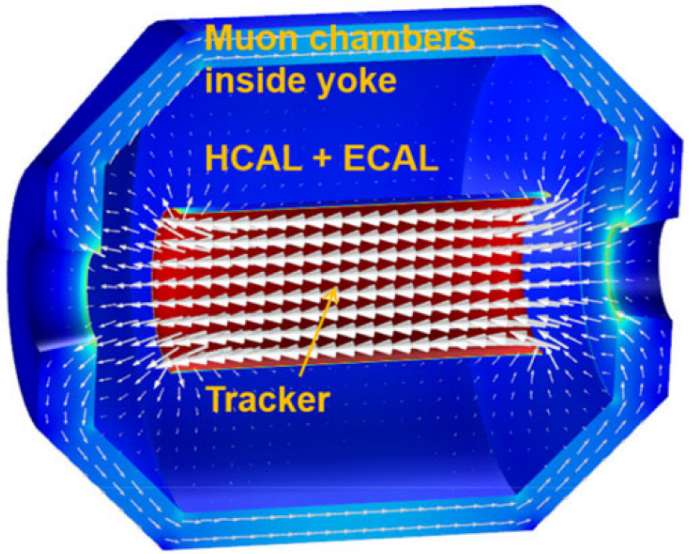
4th FCC Physics and Experiments Workshop, 11/11/20

Overview:

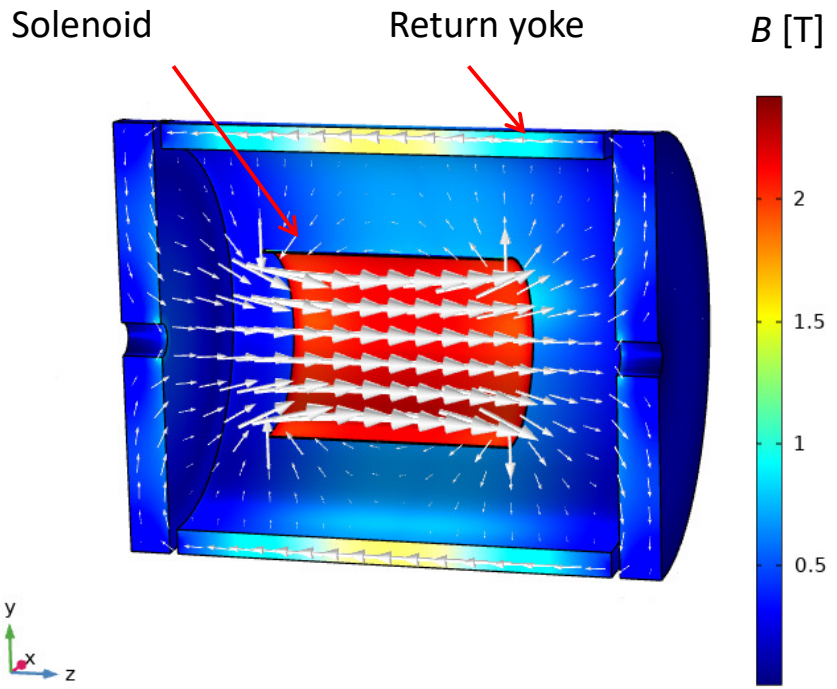
- Motivation
- How to obtain a transparent magnet?
- High-strength conductor development
- FCC-ee magnet design
- Quench protection
- Vacuum vessel transparency
- What is next?
- Summary



Motivation



4 T ultra-transparent solenoid for FCC-hh (option)

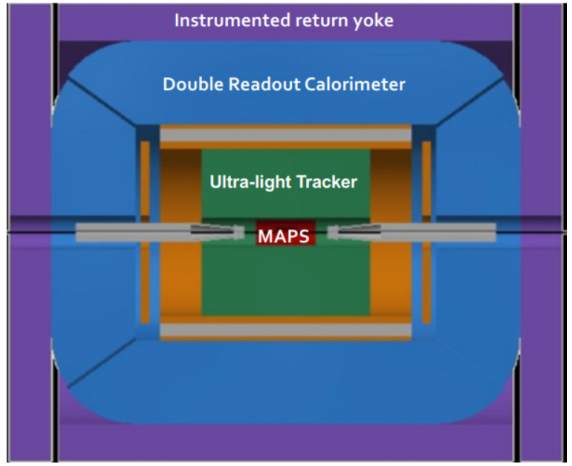


Magnetic Configuration of IDEA concept with 2 T ultra-transparent solenoid for FCC-ee (baseline)

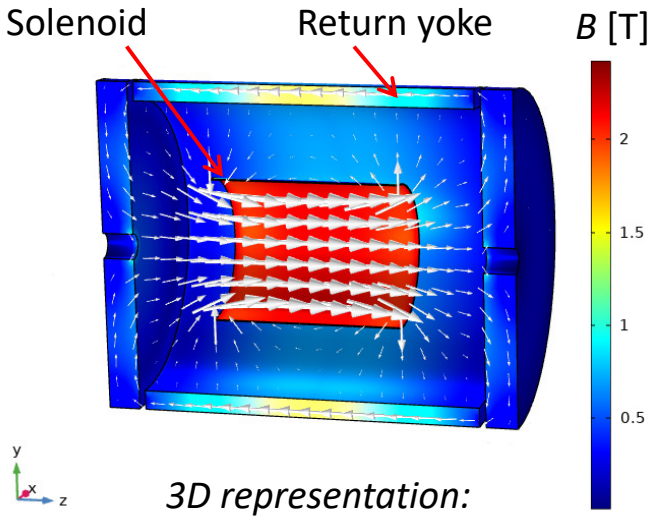
Ultra-transparent superconducting solenoids:

- 4 T variant as option for FCC-hh [1]
- **2 T variant was accepted as one of two baseline concepts for FCC-ee [2-5] (focus of this presentation)**

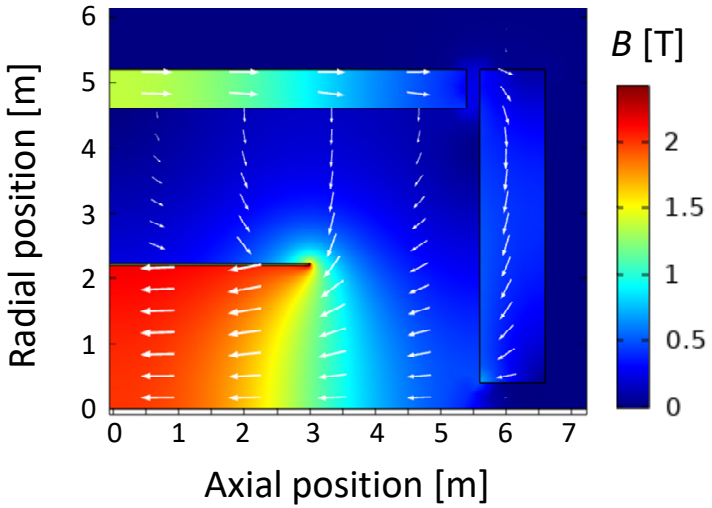
Motivation: FCC-ee IDEA concept



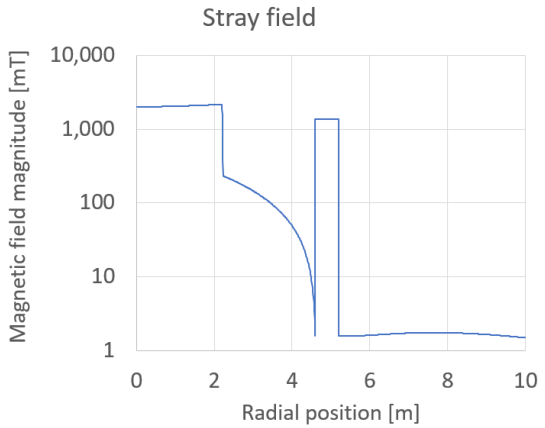
IDEA concept [2,3]



3D representation: Solenoid + yoke



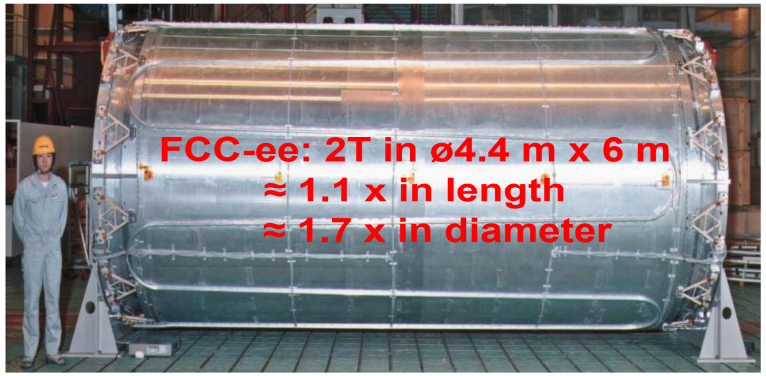
Magnetic field map



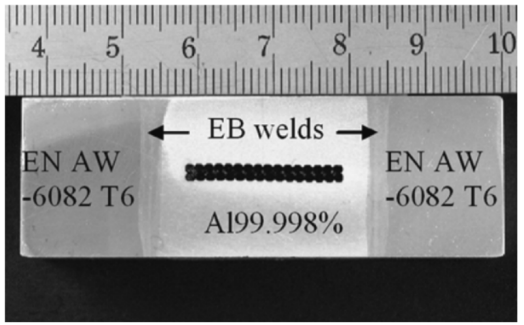
Stray field at z = 0

- The FCC-ee IDEA concept [2,3] features an ultra-transparent solenoid [4,5]
- **Optimal magnetic field distribution**:
  - Significant field where it is needed (tracker, instrumented return yoke)
  - Very little parasitic field (calorimeter)
  - Barely any stray field outside yoke
  - Minimal stored magnetic energy → **Reduced magnet system cost (> 2x)**
- **But:** Particles tunnel through magnet & vacuum vessel before reaching calorimeters → **Cold mass and vacuum vessel must be as transparent as possible**

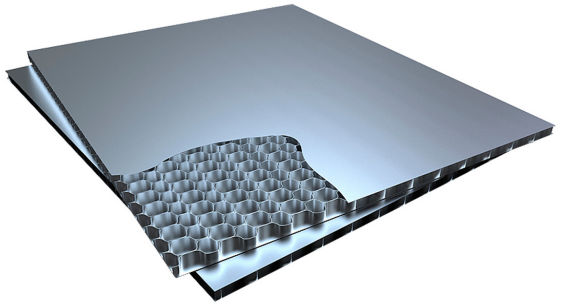
How to obtain a transparent magnet?



Design principle:
ATLAS Central Solenoid [6]



CMS High-strength aluminum-stabilized Nb-Ti conductor [8]

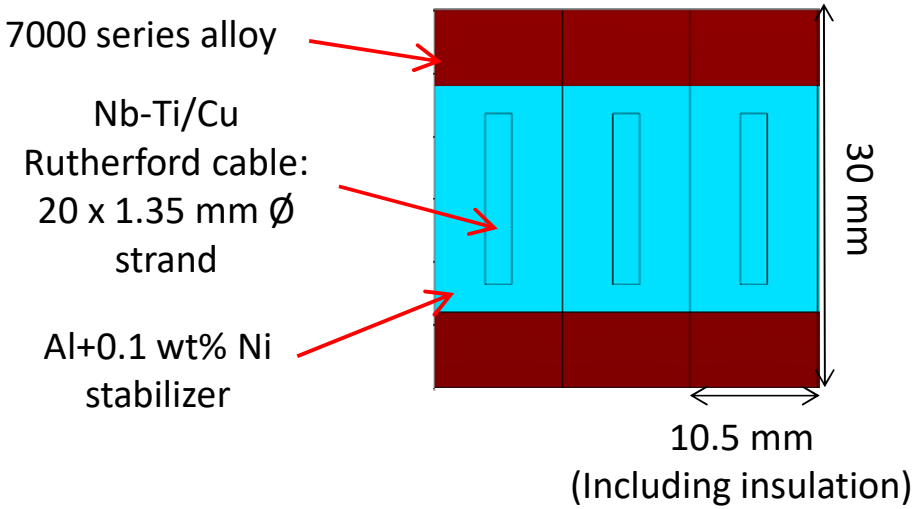


Aluminum-alloy honey-comb structure in vacuum vessel [9]

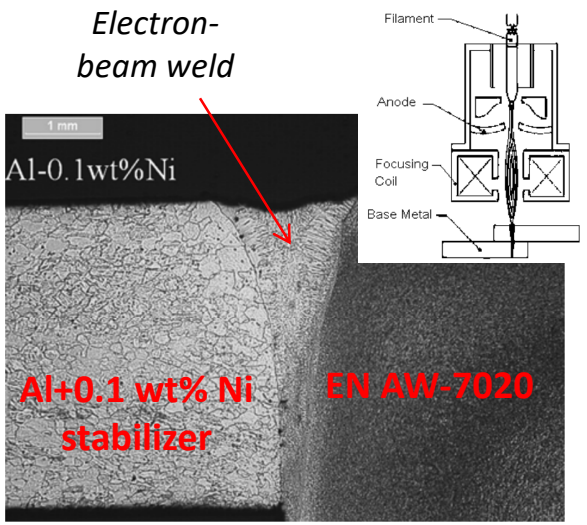
Build on top and reach beyond past research and experience [6]:

- **Aluminum-based** cold mass and vacuum vessel (Radiation length X_0 = 89 mm, nuclear interaction length λ = 397 mm [7])
- High-strength aluminum-stabilized Nb-Ti superconducting conductor [8] → **High stress-tolerance gives reduced cold-mass thickness**
- Optimized vacuum vessel [9] → **Smart mechanics for reduced vacuum-vessel thickness**

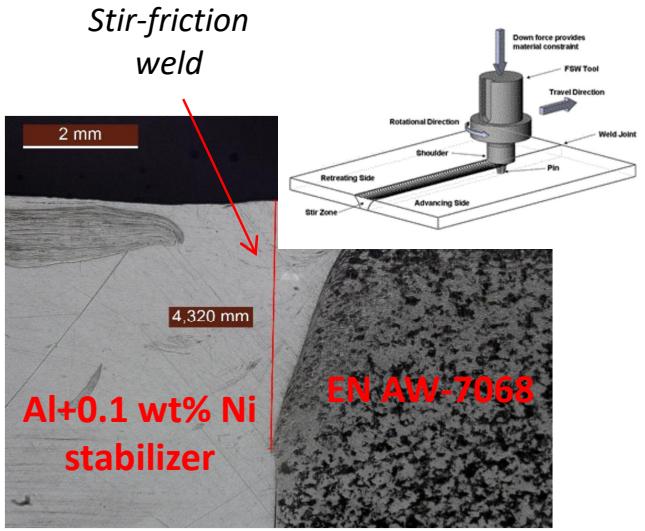
High-strength conductor development



Proposed conductor for FCC-ee



Welding technique #1: Electron-beam welding [11,12]



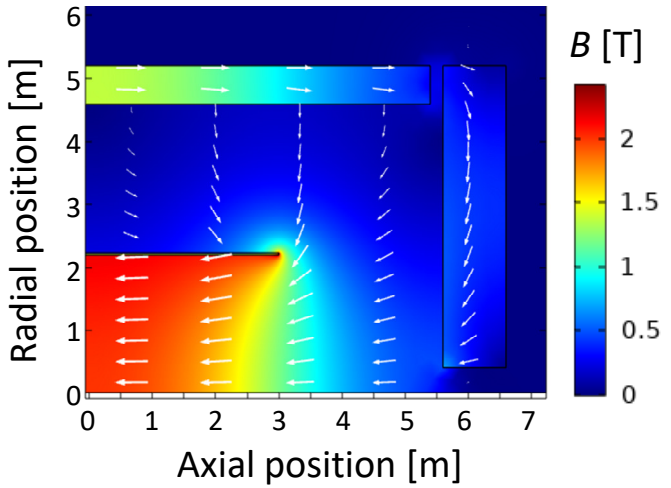
Welding technique #2: Stir-friction welding [12]

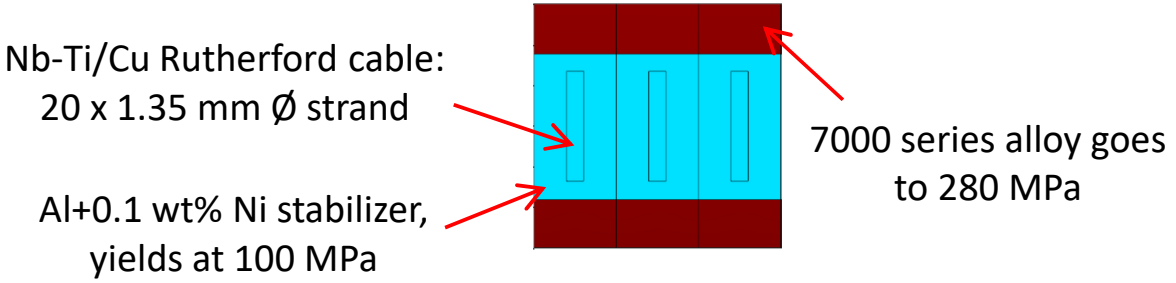
High-strength conductor:

- Same principle as CMS conductor [8] but stronger alloys: Nickel-doped aluminum instead of pure aluminum [6,10], 7000 series aluminum-alloy instead of 6000 series [11]
- **Test-samples fabricated** using two different welding techniques, to be measured:
  - Electron-beam welding [11,12]
  - Stir-friction welding [12]

FCC-ee magnet design

Property	Value
Magnetic field in center [T]	2
Cold mass length [m]	6
Cold mass thickness [mm]	30
Stored magnetic energy [MJ]	160
Cold mass volume [m³]	2.5
Cold mass [t]	7.7
Energy density [kJ/kg]	21
Operating current [kA]	20
Iron yoke mass [kt]	2.9





Magnet properties:

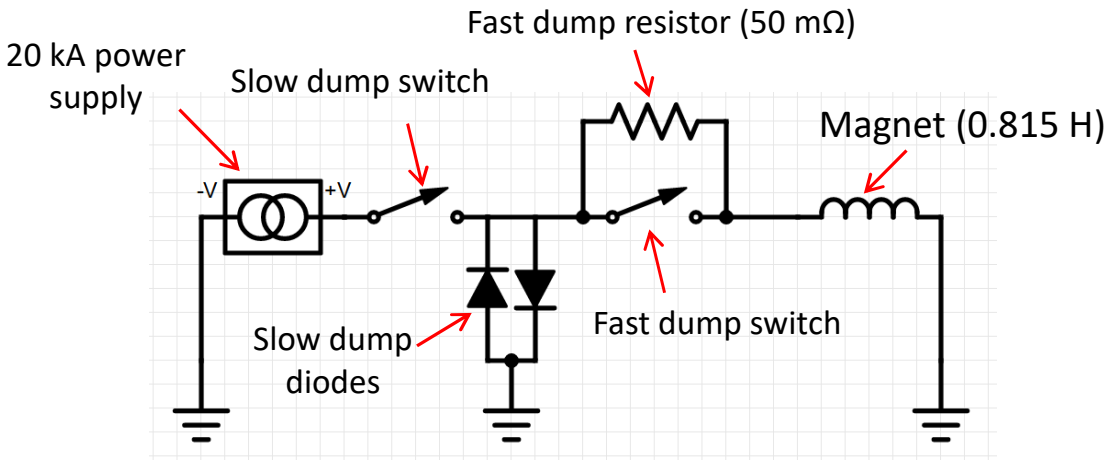
- **2 T over 4 m free bore, 6 meter length** gives 160 MJ
- Cold mass volume: 2.5 m^3, weight: 7700 kg

Conductor in the magnet:

- Conductor: 77% Aluminum, 5% Copper, 5% Nb-Ti, 13% G10
- Current sharing temperature at peak field (3.2 T): 6.5 K
- Peak stress in the conductor: 280 MPa
- **Energy density: 21 kJ/kg** → Challenging, but very valuable to have!

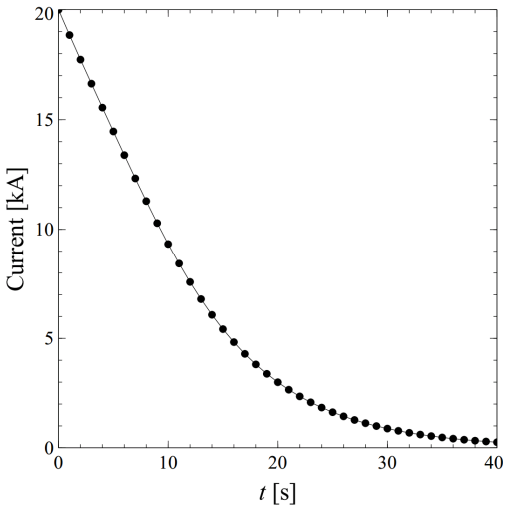
Cold mass transparency: **$0.46 \times X_0$, $0.09 \times \lambda$**

Quench protection

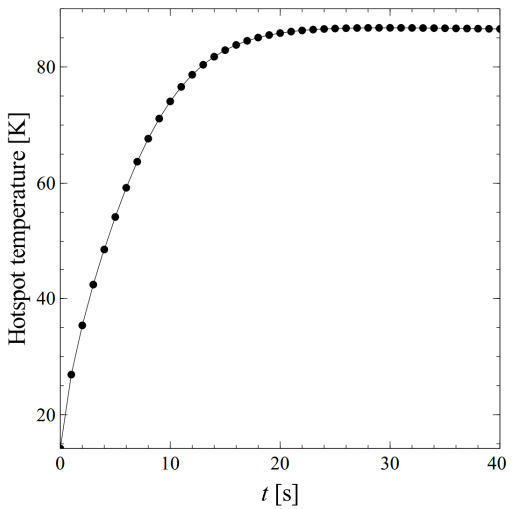


Powering + Protection circuit

Failure case	Hotspot temperature [K]
Nominal quench protection	90
Without heaters	150
Without energy extraction	120
No heaters, no extraction	**> 500**



Current discharge, nominal protection

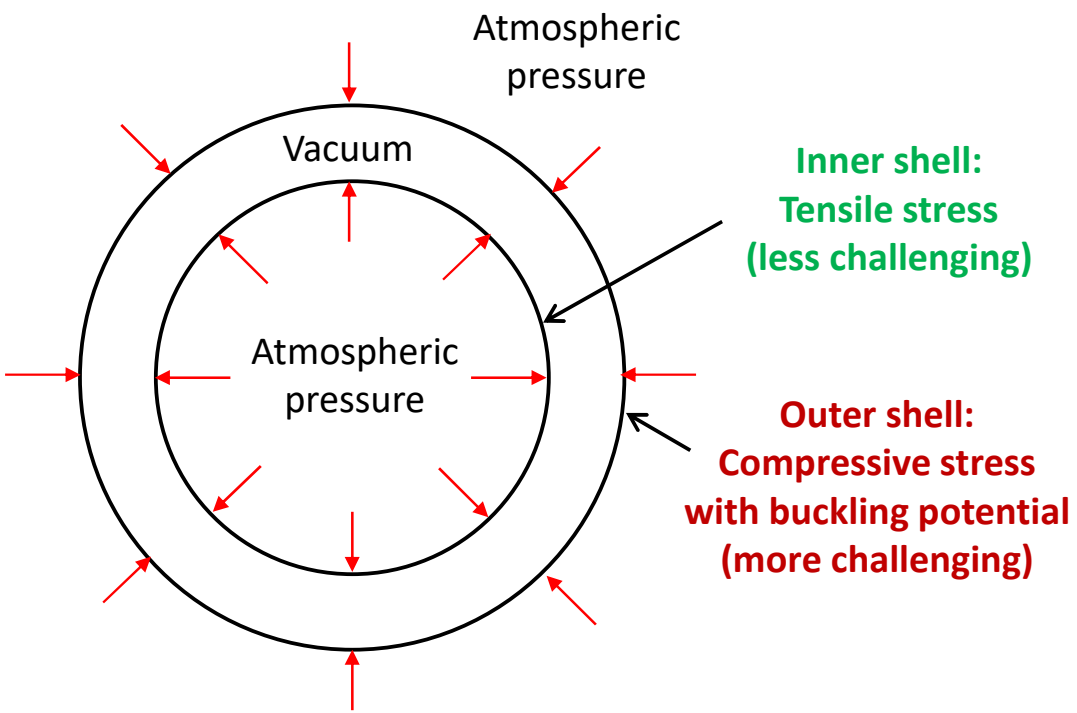


Hotspot temperature, nominal protection

In case of quench (Calculated with Quench 2.7 [13])

- Magnet protection: Quench heaters and energy extraction
- $V_{\text{Extractor,Max}}$ = 1000 V → 77% extraction of stored magnetic energy
- Further scope for improvement: Axial aluminum strips, for cooling and quench propagation
- Quench detection and protection will be designed in a redundant manner
- **Magnet is protected, except for most extreme failure scenario**

Vacuum vessel transparency



Component	(Effective) thickness [mm]
Inner shell	1.3
50 K inner thermal shield	0.35
50 K outer thermal shield	0.35
Outer shell (honey-comb)	4.0
Total	**6.0**

Vacuum vessel thickness, aluminum alloy with honey-comb structure

Outer shell reinforcement options [9]

Vacuum vessel challenge, what are the limits?

- Outer shell more challenging than inner shell: Compressive stress with potential to buckle
- Honey-comb structure found most optimal to prevent buckling [9]
- With aluminum-alloy Al-5083-O: 6 mm thickness in total, gives **$0.07 \times X_0$, $0.013 \times \lambda$**

What is next?

Progress this year:

- Slow going (Covid-19 + end of contracts)
- Since October ‘20: Fellow (part-time) and a student* working on FCC-ee

Research questions:

- Can we find international collaborators to further develop the FCC-ee ultra-transparent solenoid?
- How does the reinforced-conductor concept compare to the conductor-in-reinforced-cylinder concept?
- Can we improve the quench behavior with quench propagation strips?
- Can we experimentally investigate the ultra-transparent magnet design with small-scale (i.e. cost-effective) prototypes?

*In-kind contribution of University of Edinburgh

Summary

Ultra-transparent solenoids for FCC:

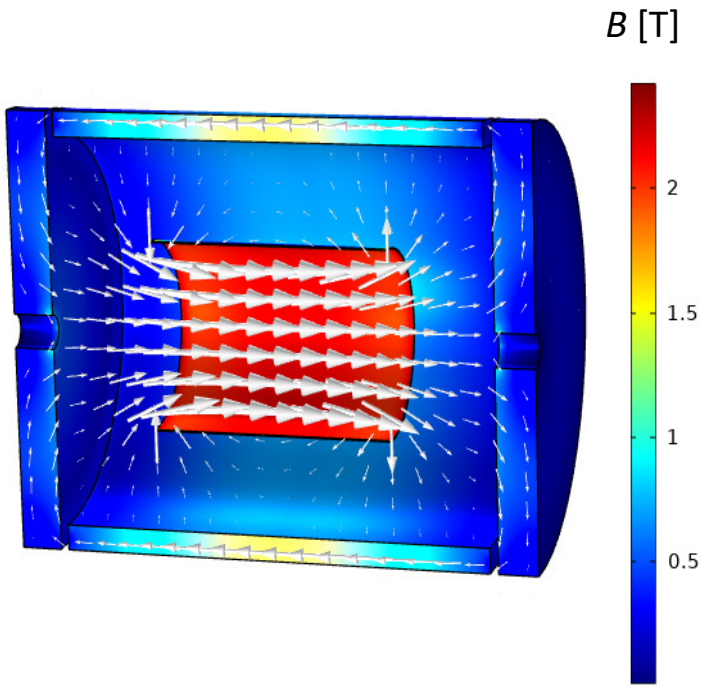
- 2 T solenoid for FCC-ee IDEA concept
- 4 T solenoid for FCC-hh (option)

FCC-ee IDEA magnet design:

- 2 T field over 4 m free bore + 6 m length
- Optimal distribution of magnetic field
- > 2x reduction in cost of magnet system expected
- **Challenge: Magnet transparency below one radiation length required**

Investigation of conceptual FCC-ee magnet concept:

- Cold mass: $0.46 \times X_0$, $0.09 \times \lambda$, with high-strength conductor
- Vacuum vessel: $0.07 \times X_0$, $0.013 \times \lambda$, with honey-comb structure
- **Very aggressive design, combined radiation length ($0.53 \times X_0$), meets the target → Promising, but experimental demonstration is needed**



No show stoppers identified, but a serious R&D program is needed to make these magnets a reality!

References

[1] M. Mentink et al. “Evolution of the Conceptual FCC-hh Baseline Detector Magnet Design”, IEEE Trans. 28, p. 4002710 (2018).

[2]. https://fcc.web.cern.ch/Pages/A-refreshing-IDEA-for-FCC-ee.aspx

[3]. M. Dam *et al.*, “FCC-ee Detector Requirements and Specific Designs”, presented at FCC week 2017

[4]. M. Mentink *et al.*, “FCC-ee, first look at detector magnet concepts”, FCC-ee 2nd Detector Requirements Workshop, 23/11/16

[5]. H. ten Kate *et al.*, “Detector Magnets for FCC-ee-eh-hh”, presented at FCC week 26/6/19

[6] A. Yamamoto *et al.*, “Design and Development of the ATLAS Central Solenoid Magnet”, IEEEE Trans. Appl. Supercond. 9, p. 852 (1999)

[7] http://pdg.lbl.gov/2009/AtomicNuclearProperties/HTML_PAGES/013.html

[8] B. Blau *et al.*, “The CMS conductor”, IEEE Trans. Appl. Supercond. 12, p. 345, (2002).

[9] H. Da Silva *et al.*, “Ultra-thin, Radiation Length Optimized, Metallic Cryostat for a 2T, 4m bore Detector Solenoid”, presented at ICEC-ICMC, Sept. 6 (2018)

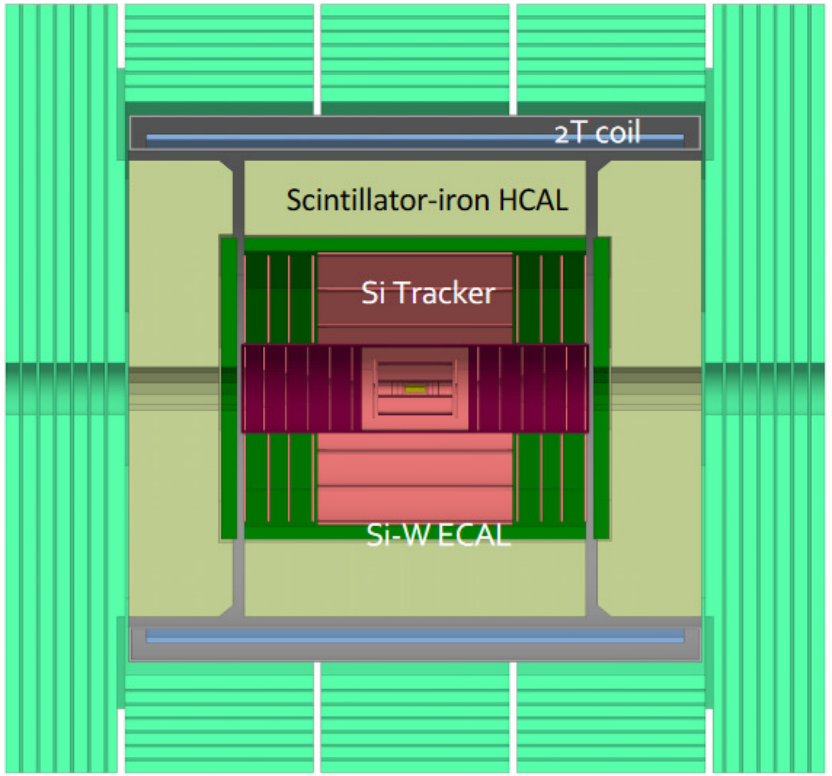
[10] K. Wada *et al.*, “High-Strength and High-RRR Al-Ni Alloy for Aluminum-Stabilized Superconductor”, IEEE Trans. Appl. Supercond. 10, p. 1012 (2000)

[11] S. Sgobba *et al.*, “Towards and Improved High Strength, High RRR CMS Conductor”, IEEE Trans. Appl. Supercond. 16, p. 521 (2006)

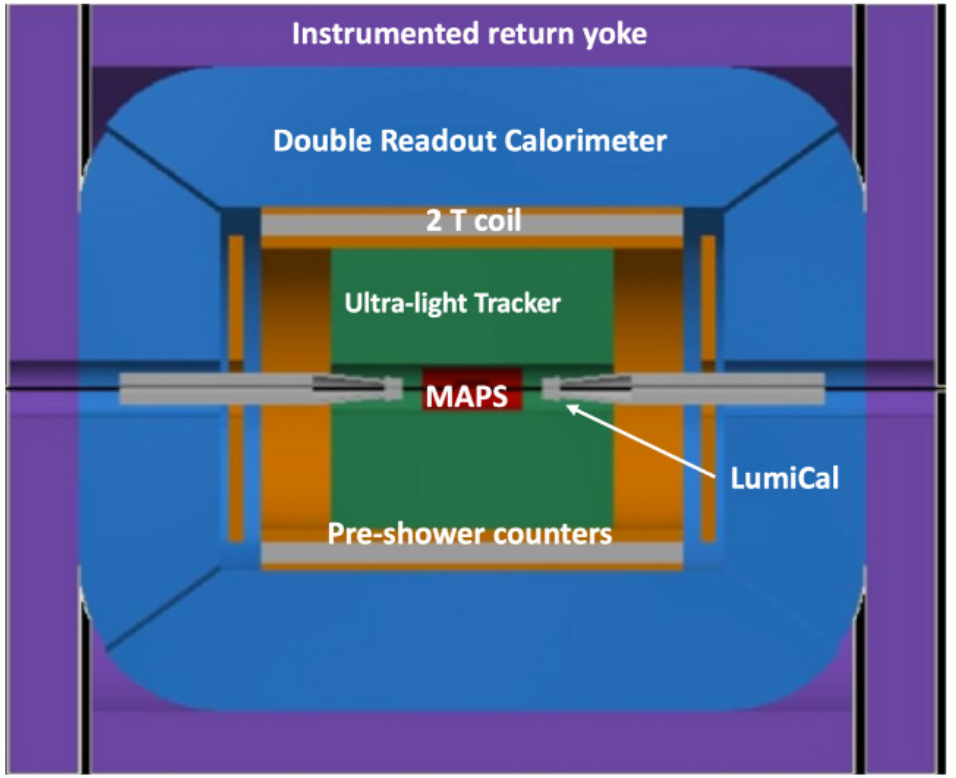
[12] T. Kulenkampff et al. “Conceptual Development of a Novel Ultra-Thin and Transparent 2 T Superconducting Detector Solenoid for the Future Circular Collider”, IEEE Trans. Appl. Supercond. 29, p. 4500405 (2019)

[13] Van Nugteren, “Quench Simulation Code for Solenoids”, Tech. Rep. CERN, (2011)

Extra slides 1/3



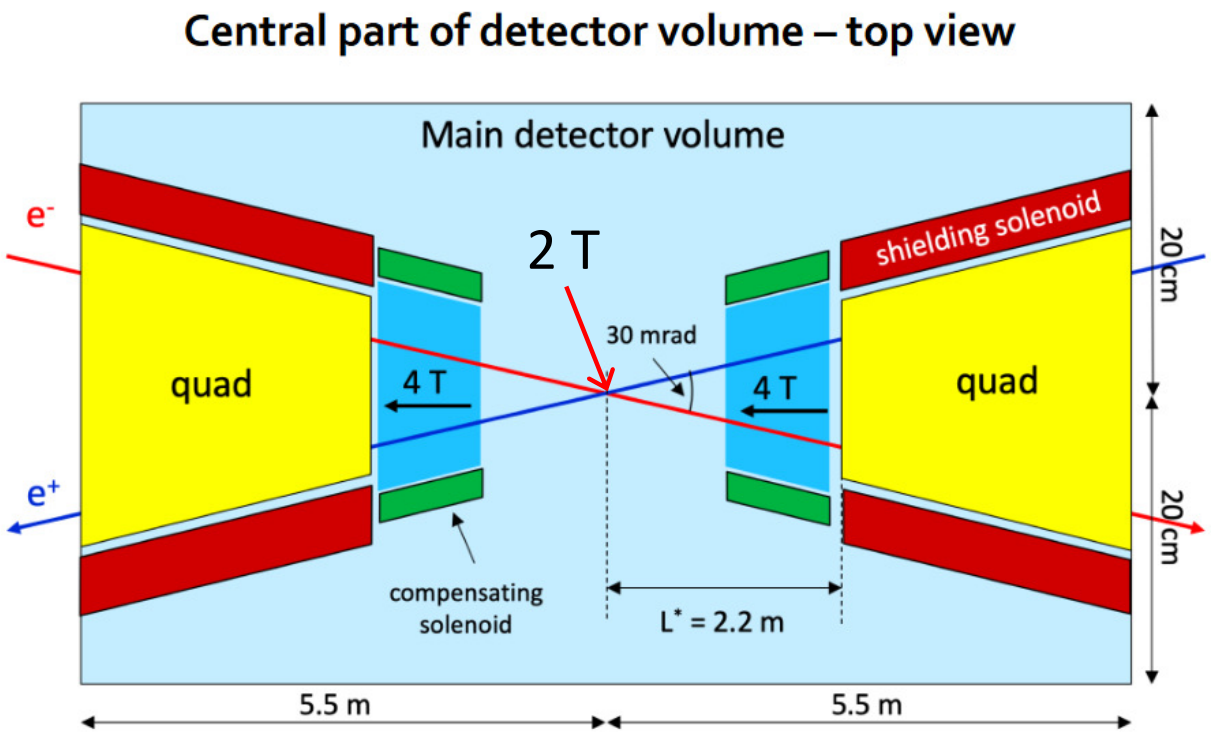
FCC-ee CLD concept



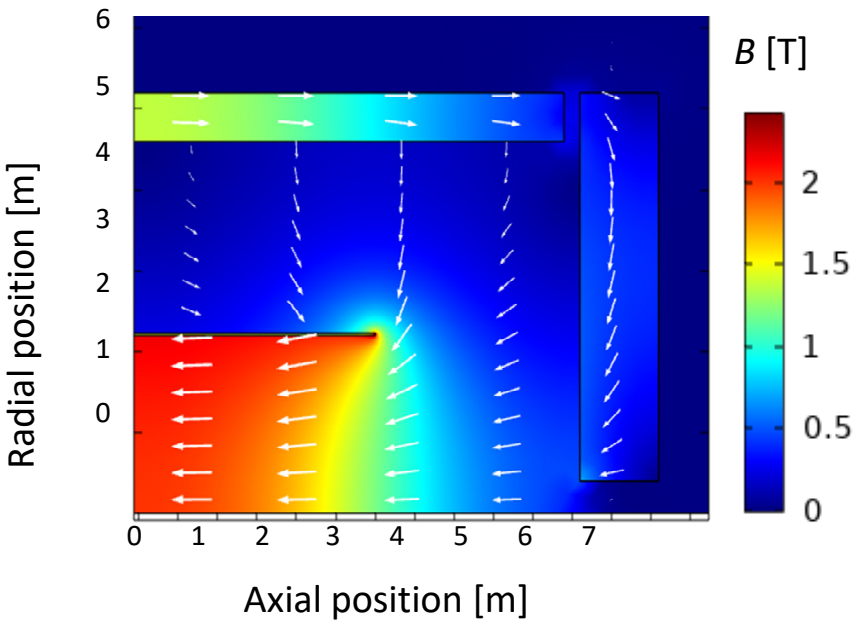
FCC-ee IDEA concept

Source: M. Dam – FCC-ee: The Experimental Challenge, 4th FCC Physics and Experiments Workshop, 10/11/20

Extra slides 2/3



MDI magnets for FCC-ee



Magnetic field map for ultra-transparent solenoid

Source: M. Dam – FCC-ee: The Experimental Challenge, 4th FCC Physics and Experiments Workshop, 10/11/20

Extra slides 3/3

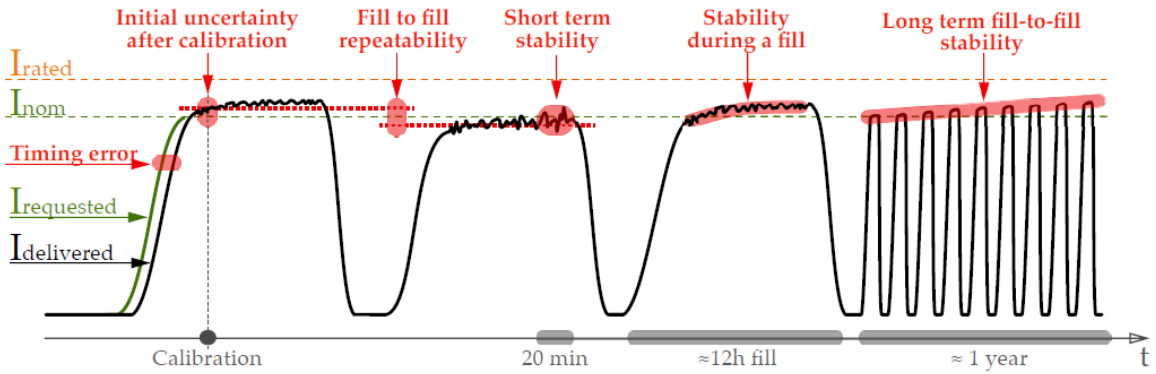


Table 6: Uncertainty specifications for the different classes of PCs installed in LHC (classes 1 to 4) and possibly available for future upgrades (class 0). The values are based on actual measurements and estimations [15, 21], and represent a single PC.

PC class:	0	1	2	3	4
Setting resolution [ppm]	0.5	0.5	1	1	1
Initial uncertainty after cal. [2×r.m.s. ppm]	2	2	5	10	20
Linearity [|.| max ppm]	2	2	5	10	10
Stability during a fill (12 h) [|.| max ppm]	1	2	5	10	20
Short term stability (20 min) [2×r.m.s. ppm]	0.2	0.4	1	2	5
Noise (0.1-500 Hz) [2×r.m.s. ppm]	3	5	10	15	25
Fill-to-fill repeatability [2×r.m.s. ppm]	0.5	1	2	5	10
Long term fill-to-fill stability [|.| max ppm]	10	10	20	50	100

CERN power converter stability specification

Source: D. Gamba, CERN-ACC-2017-0101