EuroCircol – The Cosine-theta Configuration:

Electromagnetic Design

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EuroCirCol A key to New Physics

INFN Istituto Nazionale di Fisica Nucleare

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Outline:

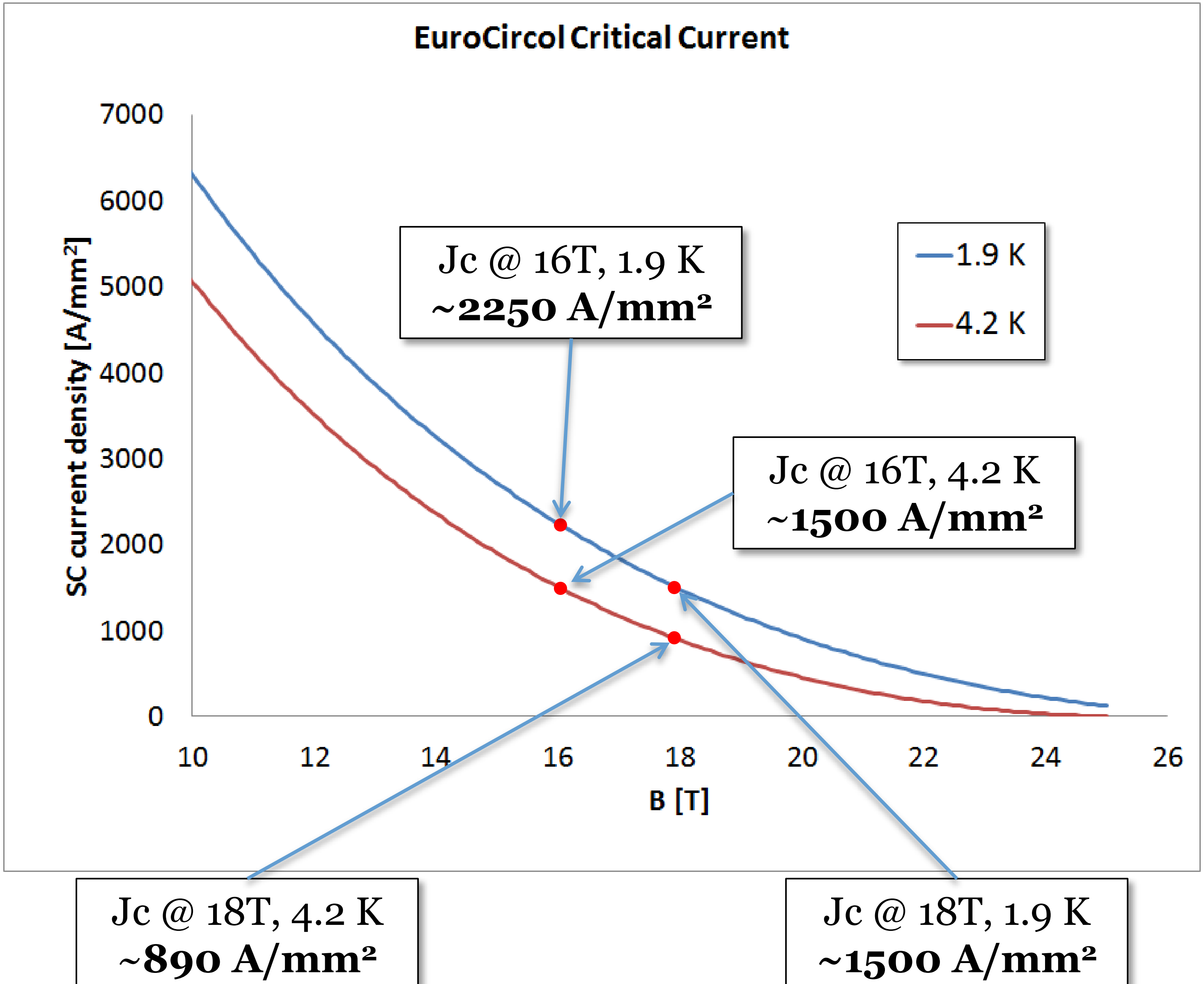
1. Main design parameters
2. Magnetic design
3. Protection
4. Some considerations
5. Conclusions

1.1 Main design parameters

Constraints for the magnet design	
Bore inner diameter	50 mm
Beam distance	250 mm
Bore nominal field	16 T
Operating temperature	4.2 K → 1.9 K
Operation point on the load line	90 %
Maximum strand number per cable	40
Cable insulation thickness	0.15 mm
Cu/NCu	≥1
Field harmonics (geometric/saturation)	≤3/10 units
Peak temperature (105 % of operating current)	350 K
Yoke outer radius	400 mm
Maximum voltage to ground	2 kV

- Magnetic design for a **double aperture** magnet
- Mechanical design for a **single aperture** magnet

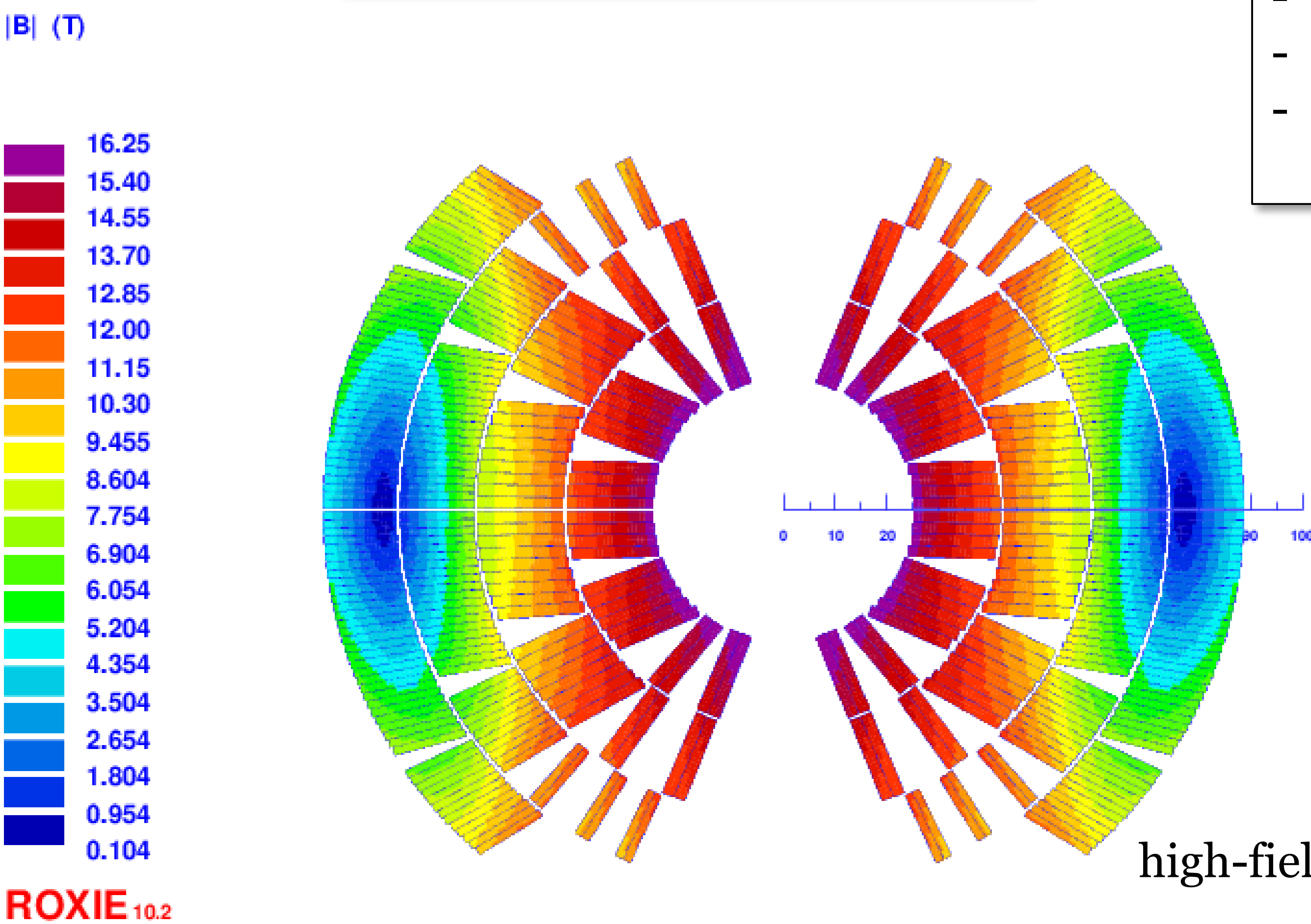
1.2 Main design parameters



B peak
16.3 T (with strand "self-field")

Main characteristics:

- 2 double-pancakes
- 2 conductor size
- Splitting of pole blocks to decrease peak-field



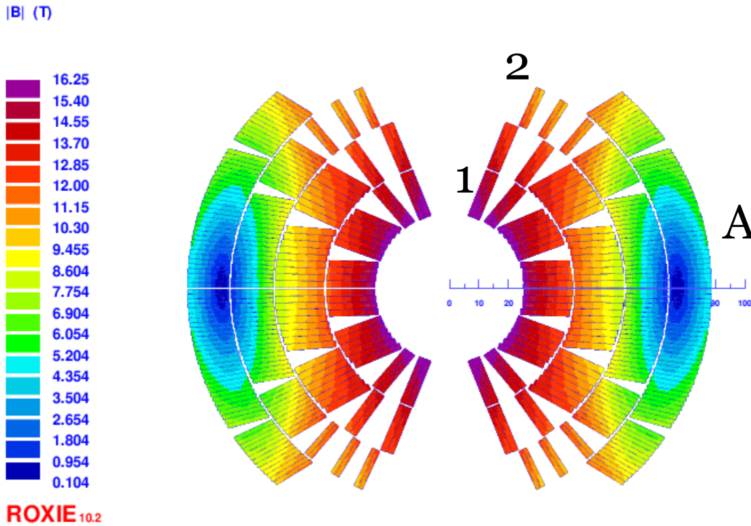
Turn number:

high-field cond.: Layer 1: 14; Layer 2: 21

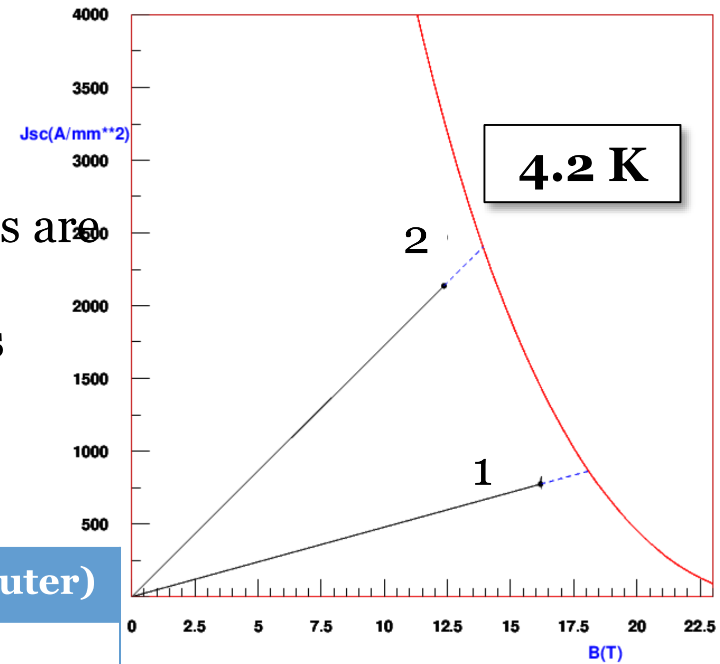
low-field cond.: Layer 3: 37; Layer 4: 43

Tot: 230/ap.

2.1 Magnetic design – cross section



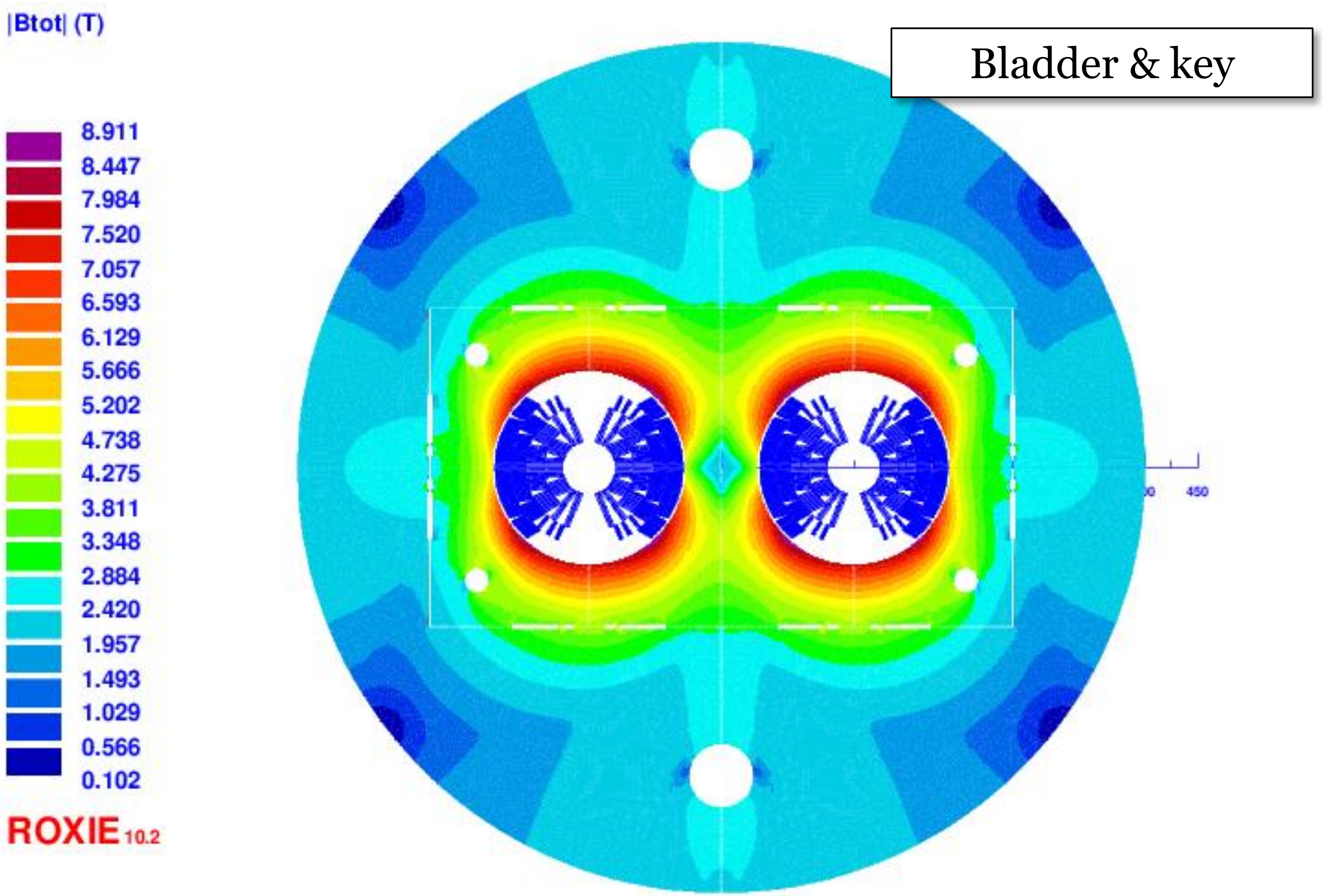
All the parameters are within the **constraints**



	Cable 1 (inner)	Cable 2 (outer)
Strand number	28	38
Strand diameter	1.1 mm	0.7 mm
Bare width	16.5 mm	14 mm
Bare inner thickness	1.892 mm	1.204 mm
Bare outer thickness	2.036 mm	1.326 mm
Insulation	0.15 mm	0.15 mm
Keystone angle	0.5°	0.5°
Cu/NCu	1.0	2.0
Operating current	**10275 A**	**10275 A**
Operating point on LL (4.2 K)	**90%**	**90%**
Operating point on LL (1.9 K)	82.0%	82.4 %

→ including the "self-field"

2.2 Magnetic design – iron yoke



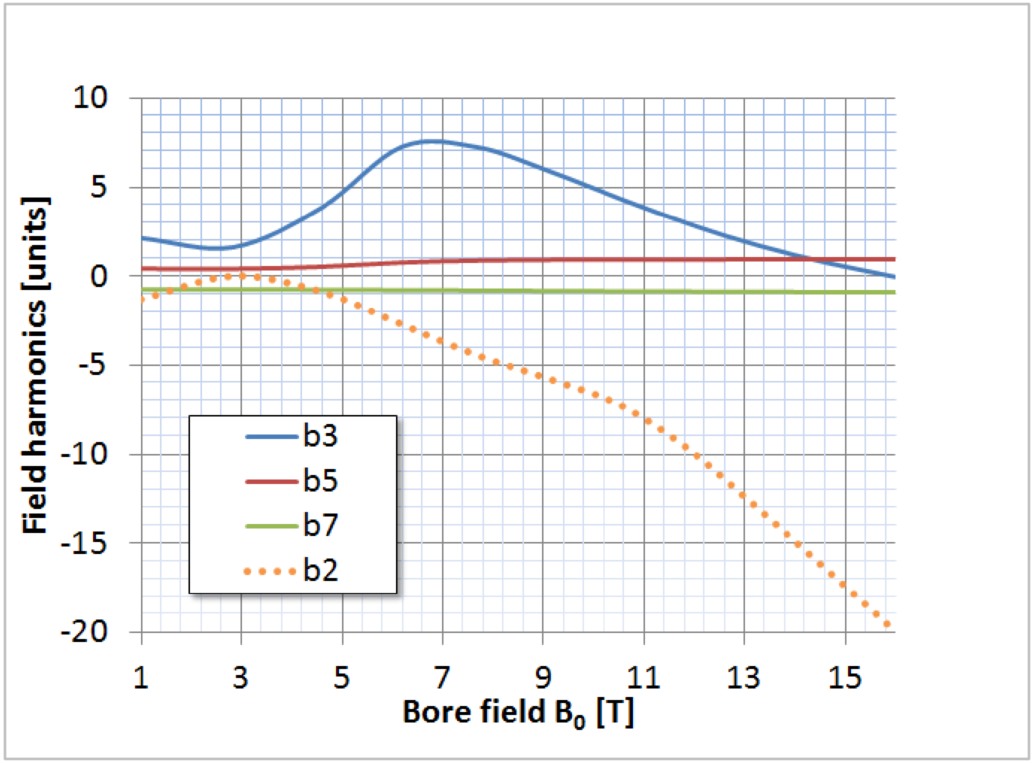
Inductance@I_{op} (1 ap)	Stored energy (1 ap)
25 mH/m	1.5 MJ/m

2.3 Magnetic design – field quality

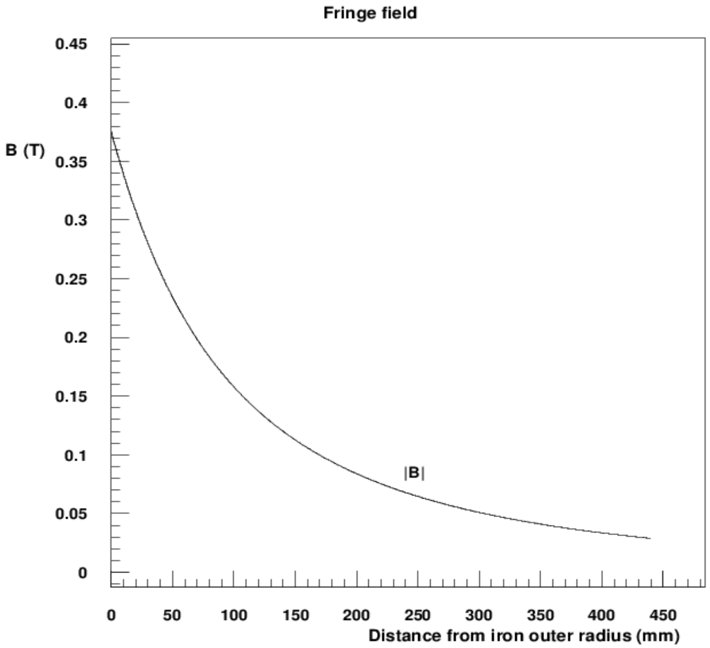
NORMAL RELATIVE MULTIPOLES @ 16 T:

b 1: 10000	b 2: -19.94	**b 3: -0.01**
b 4: -0.49	**b 5: 0.97**	b 6: -0.01
b 7: -0.87	b 8: -0.00	b 9: 0.28
b10: 0.00	b11: 0.66	b12: 0.00
b13: -0.13	b14: 0.00	b15: 0.03

- b2 optimization not performed
- Persistent currents **not** considered



Fringing field < 0.1 T at 200 mm from yoke



FCC hh ee he

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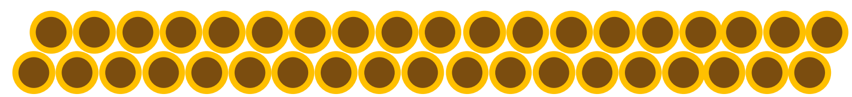
2.4 Magnetic design – strand area

High Cu content for protection reasons!

Conductor 1:
- 28 strands
- ∅ = 1.1 mm
- **Cu/NCu = 1**
- J_{cu} = 772 A/mm²
- Strand Area = 37.3 cm²/apert.
- Weight (FCC) = 4.3 ktons

Conductor 2
- 38 strands
- ∅ = 0.7 mm
- **Cu/NCu = 2.0**
- J_{cu} = 1047 A/mm²
- Strand Area= 46.8 cm²/apert.
- Weight (FCC) = 5.3 ktons



<u>COND. AREA (double ap.): = 168.1 cm²</u>

FCC-hh dipoles:

➢ **<u>COND. MASS: = 9.6 ktons</u>**

Data for FCC-hh collider	
Number of dipole units	4578
Dipole lenght	14.3 m
Conductor density	8.7 kg/dm³

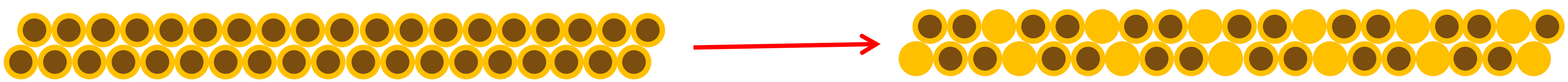
2.5 Magnetic design – strand area

- **Option to reduce cost**

Conductor 2

25 (**SC**)+13 (**Cu**) strands
- ∅ = 0.7 mm
- **Cu/NCu = 1**
- J_{cu} = 1047 A/mm²
- Strand Area (SC)= 30.7 cm²/apert.
- Strand Area (Pure Cu) = 16.0 cm²/apert.
- SC weight (FCC) = 3.50 ktons
- Pure Cu weight (FCC) = 0.75 ktons
- Pure Cu cost << SC cost

- Stability as in cable 1 (Cu/NCu = 1)
- Current diffusion time in the Cu strands to be evaluated and **compared with discharge time**
  - Zero order evaluation seems **ok** (few ms)



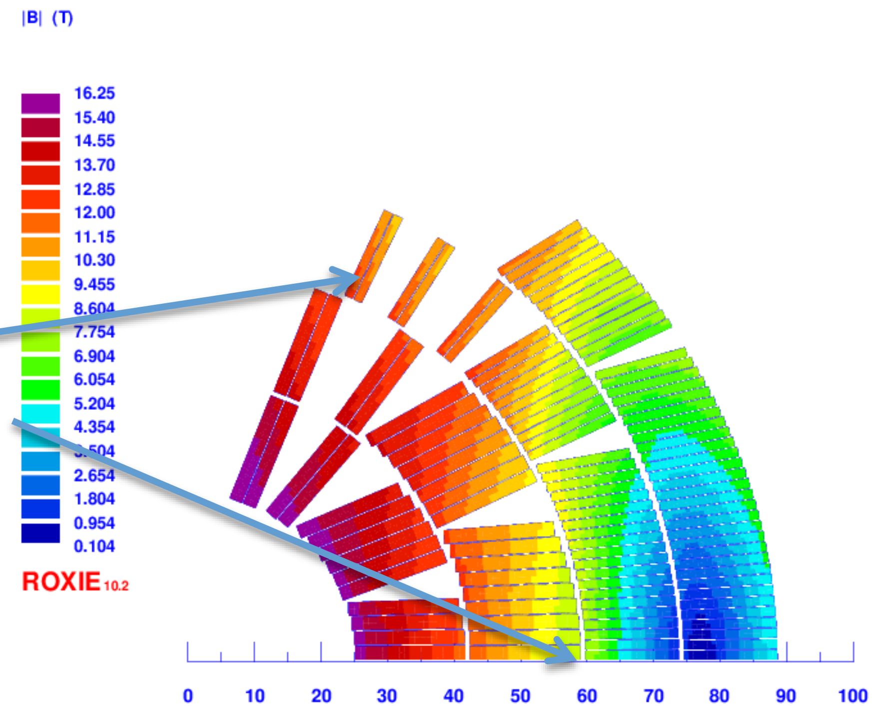
TOTAL SC STRANDS: = 9.6 → **7.8 ktons**

3.1 Protection

Simulations from **Coodi** (Tiina Salmi)

- Main assumptions:
  - **No** energy extraction
  - Quench induced in the whole magnet **40 ms** after initial quench start
  - Inductance dependence on the current
  - Material properties from **NIST**

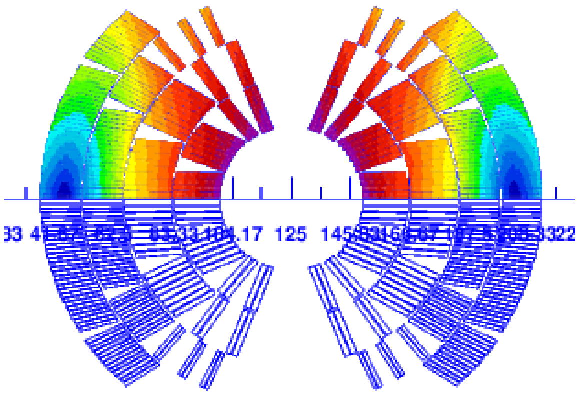
- Results (**105 %** of I_{op}):
  - Hot spot temperature: **~330 K**
  - Maximum voltage to ground: **~1400 V**



More details in the Tiina Salmi talk

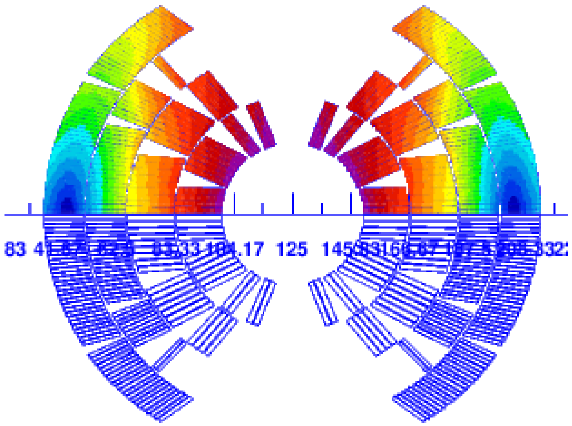
4.1 Other considerations

- Similar configurations are possible:
    - same conductor area but different turn number distribution on layers
    - possible to re-distribute the Lorentz forces or reduce number of blocks



- The minimum curvature radius of high-field conductor (∅ = 1.1 mm) is 6.3 mm (in LHC dipole is 7.3 mm with ∅ = 1.07 mm)

- The present configurations have been optimized in order to **minimize** the conductor area (inside the general constrains)



- Important limitations come from protection constrains (40 ms delay & $T_{max} < 350$ K ⇒ Cu/NCu = 2.0 L.F. cond.)

5.1 Conclusions

- The presented 16 T cosine-theta **accomplishes** the **Eurocircol** design constraints
  - Operating point on the load-line is **90%** at 4.2 K → **82% at 1.9 K**
  - Good **field quality**
  - Hot spot temperature **330 K** @ 105% I_{op}

- **cosine-theta advantage**: less conductor area, less costs
  - 168.1 cm² (total 9.6 ktons) → 136.0 cm² (total **7.8 ktons**)

5.2 Critical aspects

- Maximum voltage during discharge (see section on protection study). Possible cure:
  - Decrease turn number and increase current (both decreasing the margin and increasing the conductor strands n. to > 40)

  - Increase the subdivision of the layers to better mix **high field** region (resistive) with **low field** region (inductive) → increase the number double pancake