Magnetic Design for the Superferric Multipole Magnets of the Super-FRS

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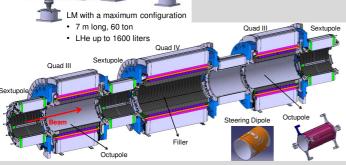
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Superconducting FRagment Separator Super-FRS) Multiplets



- · Iron dominated (cold iron)
- · Warm beam Pipe (Bore radius 192 mm)
- Design pressure of the cryostat 20 barg (PED category IV)
- DC magnets powered individually
- Self-protecting magnets
- 24 long multiplets (LMs)
- 7 short multiplets (SMs)



Design Parameters of the Main Multipole

| | Quad III | Quad IV | Sext. |
|--|---|---------|-------------------------|
| Number of magnets | 44 | 32 | 39 |
| Length of iron (mm) | 800 | 1200 | 500 |
| Pole tip radius (mm) | 250 | 250 | 237 |
| Warmbore radius (mm) | 192 | 192 | 192 |
| g _{max} (T/m, T/m ²) | 10 | 10 | 40 |
| Ramping rate(sec) | 120 | 120 | 120 |
| I _{max} (A) | 300 | 300 | 291 |
| Inductance @I max (H) | 16 | 21 | 0.88 |
| Stored Energy @I max (kJ) | 664 | 952 | 37 |
| Number of layer | 26 | 26 | 22 |
| Number of turn/layer | 48 | 48 | 11 |
| B _{Peak} in the conductor @I _{max} (T) | 4.2 | 4.2 | 1.9 |
| Magnet weight (ton) | 8 | 12 | 2.5 |
| Field Quality and ΔFQ at 190 mm | $\pm 1.0 \times 10^{-3}$, 2.0 x 10^{-3} < 0.8 * (1.2)** g _{max} | | ±5 x 10 ⁻³ , |
| | $\pm 6.0 \times 10^{-3}$, 12.0 × 10 ⁻³ > 0.8 * (1.2)** g _{max} | | 10.0 x 10 ⁻³ |

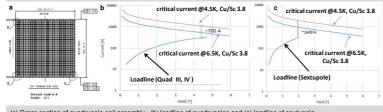
^{*:} for Quad III, **: for Quad IV

Superconducting wire

- Cu/NbTi ratio 3.5 ± 0.3 , RRR > 100
- Twist pitch < 30 mm, filament diameter < 40 μ m
- Bare conductor dimension(mm): 1.9 x 0.9 (H x W)
- Insulated conductor dimension(mm): 1.98 x 0.98 (H xW)
- Formvar insulation
- ~ 2K, ~ 700 A margin for the quadrupoles
 ~ 2K, ~ 1600 A margin for the sextupoles

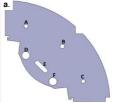
Coils assembly

- Top/bottom ground insulation: 0.8 mm NEMA G 10
- Side ground insulation: 1 mm glass epoxy
- Insulation resistance, R > 1 Gohm at 3.2 kV for the Quad IV



(a) Cross-section of quadrupole coil assembly. (b) loadline of quadrupoles and (c) loadline of sextupole

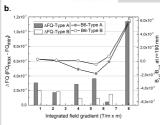
- · The initial design of sextupole meets the field quality requirement for all operating range (Δ FQ = 3 x 10⁻³ < 10.0 x 10⁻³).
- Quadrupole Design
 - Minimize B_6 and the Δ FQ* especially for $4 \sim 6.4$ T/m x m (main operating regime)
 - Type A; hyperbola pole shape + a rectangular racetrack coil
 - Type B; Type A + three holes
 - · 'A', 'B', 'C' for tie rods to lock lamination during the assembly
 - 'D', 'E', 'F' for magnetic field optimization

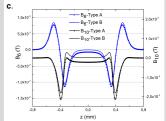


- o 3D Model and magnetic field calculation with Opera TOSCA.
- o BH curve of Thyssen M1200- 100A
- o Packing factor 98%
- o Integration length +/- 2 m

*FQ =
$$B_{mod_int}/B_{2_int} - 1$$

 Δ FQ = $FQ_{max} - FQ_{min.}$

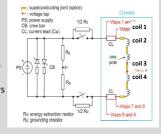




(a) Schematic of a quadrant quadrupole of Type B. (b) Δ FQ and integrated B_8 w.r.t. integrated B_2 of Quad III at various gradient levels. (c) field profiles of B_6 and B_{10} along the horizontal axis of Quad III (z) at 4 T/m x m. Quad IV has more margin than Quad III. (Δ FQ at 1.2 and 12 T/m x m is 1.35 and 9.8 x 10⁻³, respectively).

Quench Calculation

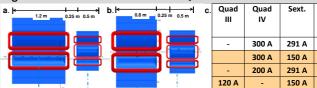
- · Model and calculation with Elektra/Quench tool of Opera
- Starting temperature 4.5 K
- Quench starts on coil 1 where B-field is max.
- Threshold differential voltage, 0.6 V
- Time delay for the breaker opening, 60 ms
- The coils are adiabatic.
- Rd= Rd1 + Rd2 = 2.8 Ohm (only for the Quads.)
- Worst case scenario for the Quad IV
- Fail to detect a guench or open the breakers
- \circ I = 330 A only for the cold test at CERN
- $T_{max} = 140 \text{ K}, V_{max} \text{ (coil to ground)} = 1600 \text{ V}$



b4 Unit w.r.t b2=1 -1.24 x 10⁻⁴

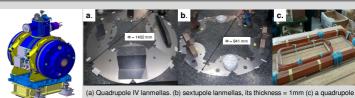
-4.24 x 10⁻⁴

Magnetic field crosstalk between the Quad. and the Sext.



(a) Schematic of the Quad IV and the Sext. in the multiplet. (b) Schematic of the Quad III and the Sext. in the multiplet. (c) the forbidden integrated harmonic b_4 when the quad. and the sext. are powered at different operating conditions. Three highlighted cases are foreseen in real Super-FRS operation. The forbidden component w.r.t B_2 should be < 4 x 10⁻⁴.

lanufacturing of the 1ST of series



(a) Quadrupole IV lanmellas. (b) sextupole lanmellas, its thickness = 1mm (c) a quadrupole and a sextupole coil-mock up. (d) current lead pair mock-up for cold test at GSI.

- 1 x Quad IV + 1 x Sext.
- 2.7 m long, 20 ton
- Up to 1200 liters of LHe
- The PRR in August 2017
- . The cold test at CERN, Q2, 2018

