HFM

High Field Magnets
Programme

Assumptions on FCC-hh magnets outer dimensions and cooling needs

E. Todesco

Thanks to D. Schoerling, B. Auchmann, S. Izquierdo Bermudez, L. Bottura, A. Verveij, A. Milanese

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Arc magnet dimensions historical

- Recall of values for outer diameter cold mass
  - LHC main dipole : 570 mm
  - MQXF HL-LHC quadrupole : 630 mm
  - Hypothesis considered for FCC-hh: 600 mm to 800 mm
- Magnet dimensions are related to three factors
  - Tolerable fringe field, requiring some space for iron to act as a shield
  - Space needed to allocate aperture, coil width, beam separation, mechanical structure
  - Tolerable b_2 arising from cross-talk of two apertures due to iron asymmetry
    - This can be negotiated with beam optics

- Studies in the framework of EuroCirCol network initially considered 800 mm for a 16 T operational field magnet, with 250 mm beam separation

- 800 mm is the RMM diameter (16 T magnet) (but with single aperture and very large coil width)

TABLE I
COMMON STARTING PARAMETERS FOR THE MAGNET OPTIMIZATION

Dipole field at aperture	16	T
Aperture diameter	50	mm
Reference radius	17	mm
Beam-to-beam distance	250	mm
Outer diameter	800	mm
Cryostat outer diameter	1000	mm
Operating margin (nominal current is 90% on loadline)	≥10	%
Nominal current	≥9000	A
Working temperature	4.2	K
Cable insulation thickness	0.15	mm per conductor face
Inter-layer insulation thickness	0.5	mm
Minimum ground insulation thickness	2	mm
X-section multipoles (geometric)	A few 10^{-4}	units at reference radius
Overall coil length	14	m
Peak temperature	350	K (quench at 105% of nominal current)
Peak voltage to ground	2000	V (quench at 105% of nominal current)
Peak inter-turn voltage	100	V (quench at 105% of nominal current)
Protection circuit delay	10-20-30	ms

F. Toral, et al "16 T Dipole design options: Input Parameters and Evaluation Criteria" EuroCirCol-P2-WP5 (2015)

Arc magnet dimensions historical

- In 2017, beam separation reduced to 204 mm, acceptable fringe field increased to 200 mT, and magnet diameter was reduced to 600 mm
  - This was done to have the same 16 T dipole for FCC-hh installable in the LHC tunnel for HE-LHC

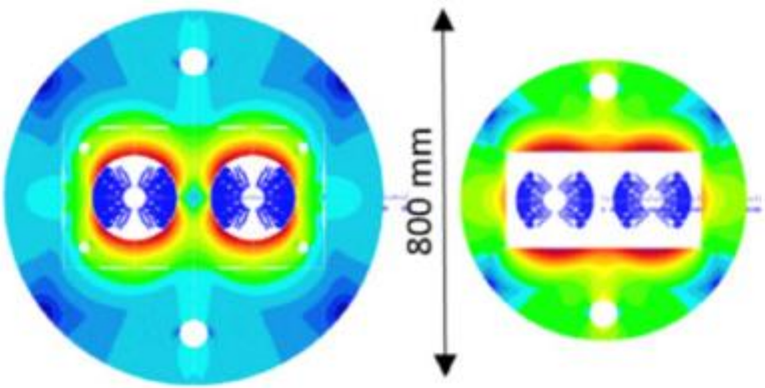


Fig. 1. Cosθ: electromagnetic cross section (left 2015, right 2017).

D. Tommasini, et al, IEEE TAS 28 (2018) 4001305

- In 2019, the parameters are fixed to 800 mm outer dimension, with a fringe field of 100 mT and a beam separation of 250 mm [D. Schoerling, et al, IEEE TAS 29 (2019) 4003109]
  - These are the numbers that are in the CDR [Europhys. J. 228 (2019), page 836]

Arc magnet dimensions: logistics

- There is an additional argument that should be taken into account: weight and logistics
  - Note that for a 800 mm diameter, a 14.5 m long cold mass weight is 55 tons, plus 6 of cryostat (see CDR, page 836 table 3.1)
  - A 55 tons cold mass is problematic in terms of transport – not clear to me how this is possible

    (FCC in the Netherlands?)
  - Having 10 m long dipole would fit the 40 tons, but would reduce the filling factor and the energy of the accelerator, and increase the manufacturing costs

PERMISSIBLE MAXIMUM WEIGHTS OF LORRIES IN EUROPE (in tonnes)							
Country	*Weight per non-drive axle*	*Weight per drive axle*	*Lorry 2 axles*	*Lorry 3 axles*	*Road Train 4 axles*	*Road Train 5 axles and +*	*Articulated Vehicle 5 axles and +*
Albania	10	11.5 (1)	18	26 (2,3)	36	40	44
Armenia	10	10	18	22	36 (4)	36 (4)	36 (4)
Austria	10	11.5	18	26	36	40 (5)	40 (5)
Azerbaijan	10	10	18	24	36	42	44
Belarus	10	10 / 11.5	18 / 20	25	38 / 40	40 / 42	42 / 44
Belgium	10	12	19 (6)	26 (6)	39 (7,8,9)	44 (10,11,12,13,14)	44 (10,14,15)
Bosnia-Herzegovina	10	11.5	18	25 / 26	36 / 38	40 / 42	42 / 44 (16,17)
Bulgaria	10	11.5	18	26 (2)	36	40	40
Croatia	10	11.5	18	25 (18)	36	40	40 (5)
Czech Republic	10	11.5	18	26 (2)	32	48	48
Denmark (19)	10	11.5	18	24 (20)	38	44 (21)	44 (21)
Estonia	10	11.5	18	26 (2)	36 (22)	40 (23)	40 (23,24)
Finland (25)	10	11.5	18	28 (2)	36	44 (26)	44 (26)
France	12 (27)	12 (27)	19	26	38 (28)	40 / 44 (29)	40 / 44 (29)
Georgia	10	11.5	18	25 / 26 (30)	36	40	40 / 42 (16) (17)
Germany	10	11.5	18 (31)	26 (31)	36	40 (32)	40 (32)
Greece	7 / 10	13	19	26	38 (33,34)	40 / 42 (35)	40 / 42 (24)
Hungary	10 (36)	11.5 (36)	18 (37)	25 (38)	36 (39)	40	40 / 42 (16) (17)
Ireland	10	11.5 (40)	18	26 (41)	36 (42)	42 (2,43,44,45)	44 (45,46,47,48)
Italy	12	12	18	26 (2)	40	44	44
Latvia	10	11.5	18	25 / 26 (30)	36	40	40 (24,49)
Liechtenstein	10	11.5	18	26 (2)	36	40	40
Lithuania	10	11.5	18	25 (18,50,51)	36	40 (49)	40 (24)
Luxembourg	10	12 (52)	19	26	44	44	44
Malta	10	11.5	18	25	36	40	40 (53)
Moldova	10	11.5	18	25 (18)	36	40	40 (53)
Montenegro	10	11.5	18	26 (54)	36	40	40 (53)
Netherlands (19)	10	11.5	21.5	21.5-30.5 (55)	40	50	50
North Macedonia	10	11.5	18	25	36 (22)	40	40
Norway (19,56)	10	11.5	19	26 (57)	39	46-50 (58)	46-50 (59)
Poland	10	11.5	18	26 (2)	36	40	40
Portugal (19)	10 (60)	12	19	26	37 (61)	44 (60)	44 (62)
Romania	10	11.5	18	25 / 26 (30)	36	40	40 / 42 (16) (17)
Russia	10	10 (63)	18	25 (64)	36 (28)	40 (65)	40 (65)
Serbia	10	11.5	18 (66)	25 (18,67)	36 (68)	40	40 / 42 (16) (17)
Slovakia	10	11.5	18	26 (2)	40	40	40
Slovenia	10	11.5	18	25 (18,50)	36	40	40 / 44 (16,69)
Spain	10	11.5	18	25 (18)	36 (68)	40	42 (49) / 44 (24)
Sweden	10	11.5	18	25 / 28 (30)	38	40 (70)	44 (53)
Switzerland	10	11.5	18	26 (71)	36	40	40
Turkey	10	11.5	18	25 (72)	36 (28,73)	40	40 (74)
Ukraine	11	11	16 (75)	22 (76)	38 (77)	40 (77)	40 (77)
United Kingdom	10	11.5	18	26 (78)	36 (79)	40 / 44 (80)	40 / 44 (80)

S. Spielberg, et al, "Duel" Universal Television (1971)

Arc magnet dimensions: the new targets for Nb_3Sn

- In the past four years, the indication of lowering the operational field of the FCC-hh dipole has become more and more evident
  - US-MDP considered 15 T as a target field for FNAL program
  - 12 T magnet was introduced in the HFM program
  - The last few tesla are very expensive in terms of conductor, see [D. Schoerling, et al, IEEE TAS 27 (2017) 4003105]
- Since 2024 the HFM mandate explicitly includes a target of 14 T for Nb_3Sn operational field (see https://indico.cern.ch/event/1377966/)
  - Since 800 mm diameter were proposed for the 16 T case, it will be fine 14 T (weight issue still to be clarified, maybe 700 mm would be more appropriate
  - For 800 mm diameter cold mass, 1220 mm diameter cryostat was proposed [FCC-hh CDR, Europhys. J. 228 (2019), page 835 Fig 3.1]

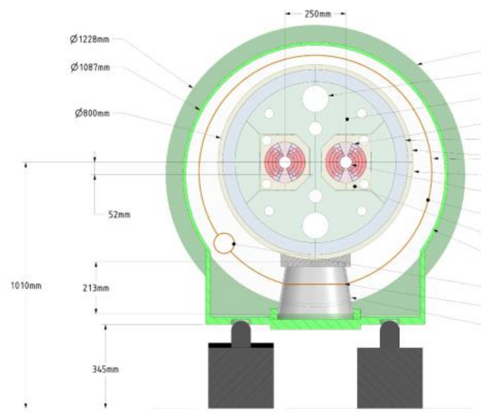


Fig. 3.1. Main dipole cross-section.

- On the other hand, <u>I would exclude magnet diameters larger than 800 mm</u> (and this is the information that is needed today)
  - The issue of the weight for 1000 mm diameter cold mass would become too challenging

Cooling

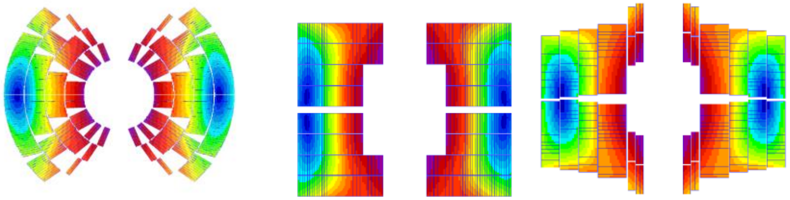
- The main components of the cooling requirements are
  - Static losses due to cryostat (in the cold mass and in the beam screen)
  - Hysteresis losses, ramp rate losses in the superconductor (in the magnet cold mass)
  - Hysteresis losses, ramp rate losses in the yoke (in the magnet cold mass) – much smaller
  - Synchrotron radiation and beam losses (mainly intercepted by the beam screen at higher temperature than the cold mass)
    - Remember that synchrotron radiation is not negligible in FCC-hh , and scales with E^4, therefore 20% energy reduction from 100 to 80 TeV means halving the heat load due to synchrotron radiation

Cooling targets for Nb_3Sn

- Targets for cooling considered operational temperature of 1.9 K, and are given in [D. Schoerling, et al, IEEE TAS 29 (2019) 4003109]
  - Static losses are estimated at 0.5 W/m at 1.9 K and 10 W/m at 50 K
  - A target has been set at 5 kJ/m per ramp (total 140 kJ per cycle for a 14 m long magnet) – source is [S. Izquierdo Bermudez, November 2017, presentation at EuroCirCol https://indico.cern.ch/event/679654/] – see following slides

Hysteresis losses for Nb_3Sn

- Hysteresis losses in the superconductor are the dominating source
  - For Nb_3Sn, they mainly depend on the filament size – with present HL-LHC technology (diameter of 50 µm) losses are order of 20 kJ/m per cycle (10 kJ/m per ramp, i.e. twice the target)
  - To be compared to 0.5 kJ/m in the LHC dipoles
  - Hysteresis losses are found to weakly depend on magnet design



Coil geometry		Cos-theta	Block	Common Coil
Deff	µm	50	50	50
Xi	--	1	1	1
I1	Inom (50 TeV)	11060	10465	16100
I2	Ireset	100	100	100
I3	Iinj (3.3 TeV)	729.96	690.69	1062.6
I4	Inom (50 TeV)	11060	10465	16100
AC-loss (2 Ap)	J/m	18330	19603	23489
AC-loss/Asc	J/m_3	4728455	4633384	4776274

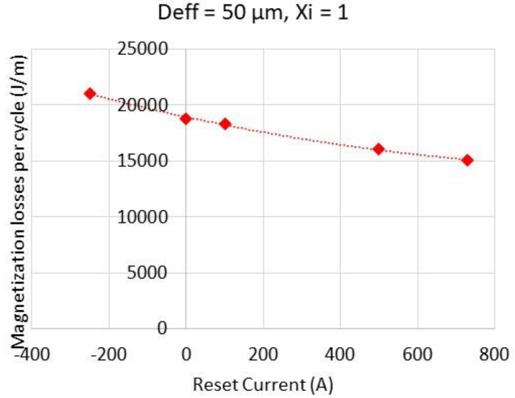
Talk given by S. Izquierdo Bermudez, November 2017, EuroCirCol meeting
https://indico.cern.ch/event/679654/

Hysteresis losses for Nb_3Sn

- The main dependence of hysteresis losses is on filament size
  - A reduction of D_{eff} from 50 µm to 20 µm can halve these losses – this is the reason for setting a target of 5 kJ/m for ramp
  - Pinning with internal oxidation also allows to reduce magnetization

Coil geometry		Cos-theta	Cos-theta	Cos-theta	Cos-theta	Cos-theta	Cos-theta
Deff	µm	50 (HF)	50 (HF)	50 (HF)/20 (LF)	50 (HF)/20 (LF)	20 (HF)/20 (LF)	20 (HF)/20 (LF)
Xi	--	1	0.5	1	0.5	1	0.5
I1	Inom (50 TeV)	11060	11060	11060	11060	11060	11060
I2	Ireset	100	100	100	100	100	100
I3	Iinj (3.3 TeV)	729.96	729.96	729.96	729.96	729.96	729.96
I4	Inom (50 TeV)	11060	11060	11060	11060	11060	11060
AC-loss (2 Ap)	J/m	18330	16685	14340	12980	8026	7127

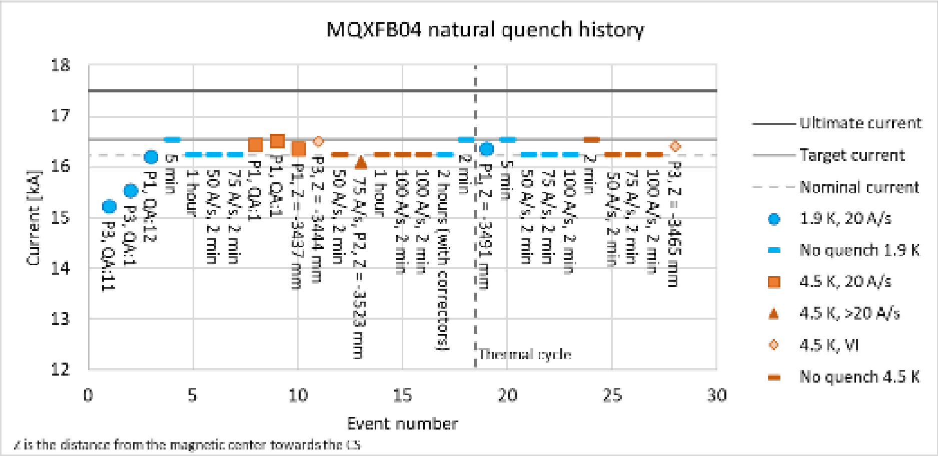
- Hysteresis losses depend on energy range since they dominate at low fields
  - In particular they depend on the reset current – this is another argument that makes a injection at 1.3 rather than 3 TeV much more challenging



Talk given by S. Izquierdo Bermudez, November 2017, EuroCirCol meeting https://indico.cern.ch/event/679654/

Cooling options

- In the CDR of FCC-hh, 16 T magnets operate at 1.9 K at 86%
- The new target for the Nb_3Sn dipole of FCC-hh of 14 T is set both at 1.9 K and at 4.5 K
  - This is achieved by setting a larger loadline margin (80%) at 1.9 K
  - Following the HL-LHC experience, where all MQXF are also able to operate at 4.5 K and nominal current



Quench performance of MQXFB04 at 1.9 K and at 4.5 K [F. Mangiarotti, S. Izquierdo Bermudez,et al.]

- Operating at 4.5 K allows to considerably save on the cooling power needed for hysteresis losses, that are in the magnet coil
  - Hysteresis losses at 4.5 K and at 1.9 K are similar, due to flux jumps, but heat is extracted at higher temperature

The HTS case

- Magnet dimension
  - For the HTS case, the target is 20 T – this relies on the possibility of significantly increasing the current density and keeping the coil mass limited (both for magnet size and for cost), and using stress management
  - Yoke size, mechanical structure, to be studied

- Cooling: Whereas for Nb_3Sn models to estimate the hysteresis losses are well established, for HTS the modeling is much less advanced and much more complicated
  - For HTS the anisotropy introduces a dependence on the magnet design
  - For HTS the contribution of hysteresis losses is much larger than in Nb_3Sn and could wipe out part or all the beneficial effects of operating at 20 K with present status of technology (not developed specifically for accelerator magnets)
  - Use of striated and twisted tapes could reduce it, but it would greatly increase the coil size
  - Physical dimension of QRL at 20 K also to be studied
  - Maximum acceptable Δt should be fixed by magnet design

Conclusions

- A maximum diameter of 800 mm can be confirmed, considering that
  - Target field for Nb_3Sn magnet has been reduced from 16 T to 14 T
  - 800 mm magnet diameter for a 14 m long magnet is already above the 40 tons
- Cooling hypothesis of the CDR of the 2019 are the latest stage of the work
  - However, the new target of 14 T at 80% at 1.9 K opens the possibility of operating the cold mass at 4.5 K
  - This would allow reducing the cooling related to hysteresis losses that is a significant part
  - Note that the present target of today for hysteresis losses (5 kJ/m per ramp) requires a technology beyond HL-LHC, i.e. smaller filaments – with HL-LHC conductor we have twice
- For HTS, many elements are still missing to draw conclusions
  - Building, testing, modelling …

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