Magnet status towards the CDR

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On behalf of the FCC Other Magnets Task
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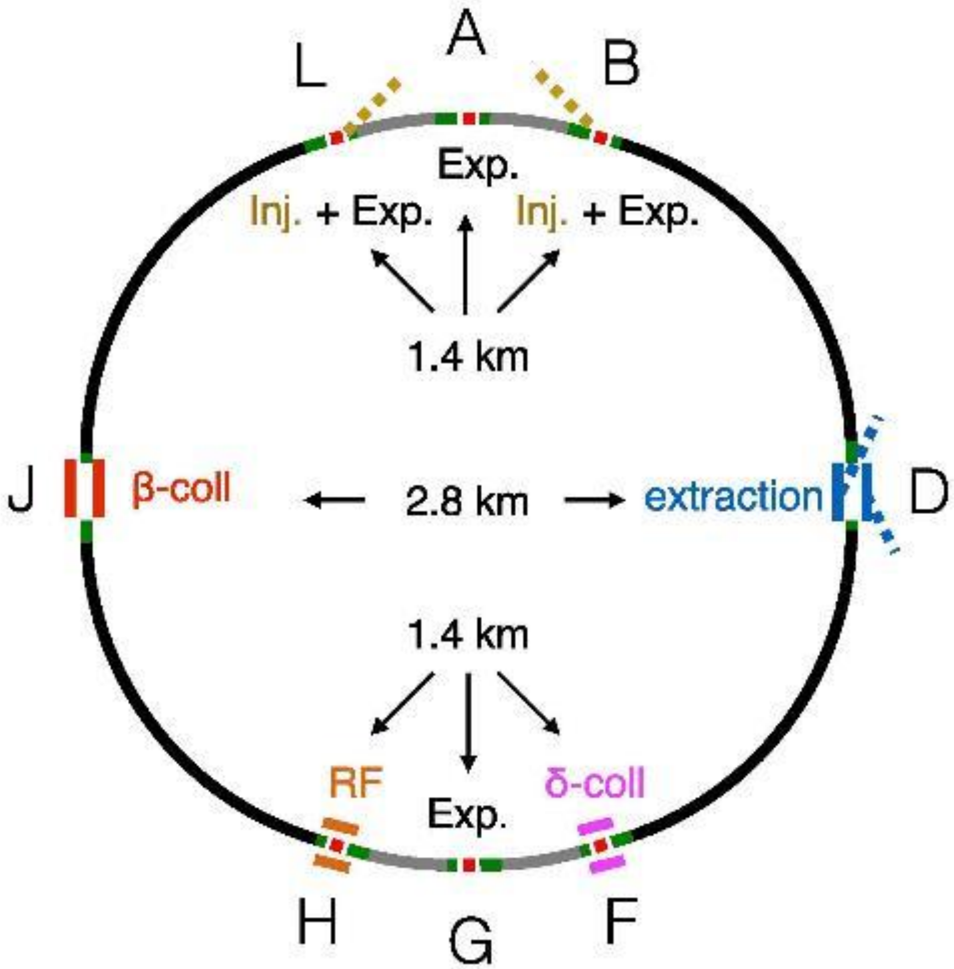
Introduction

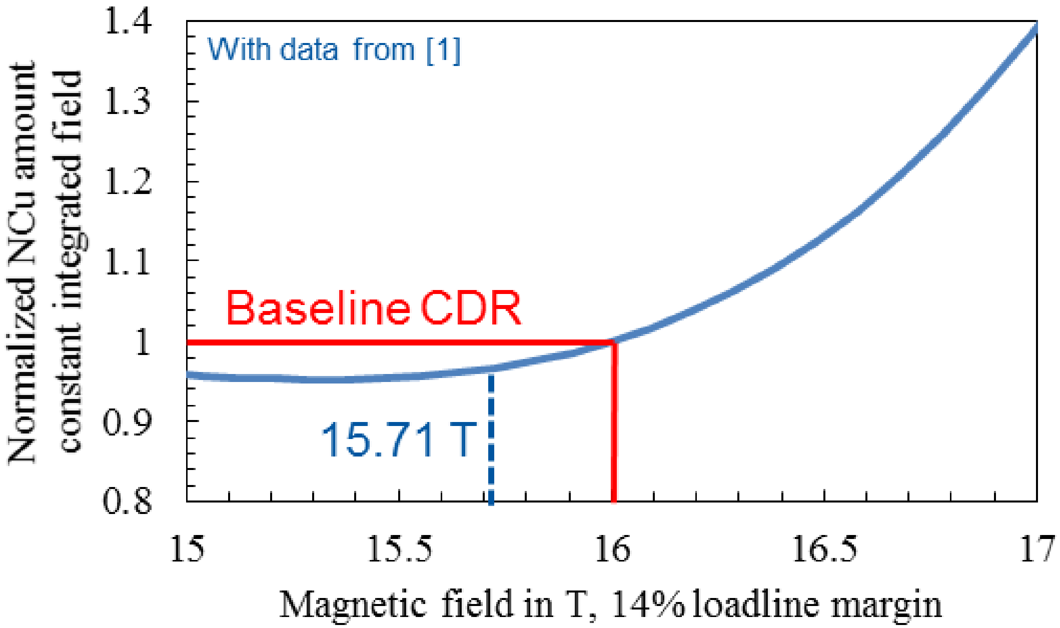
- The lattice design for 50 TeV beam energy is driven by the required integrated dipole field (1 MTm) and the length of the tunnel (~100 km)
- We assume that the cell length is fixed. Therefore, if the length of a magnet is changed, the length and the field amplitude of the dipole magnets have to be adapted such that the integrated field over the arc cell remains the same
- For the other magnets, in certain cases, we have the choice between different technologies (HTS, Nb_3Sn, Nb-Ti, normal-conducting)
- Distance between magnets is assumed to be as in LHC (→agreement during FCC week 1.5 m between dipoles, ΔB = +0.16 T)

Length: 97.75 km



Arc design – principles for magnet selection

- Currently the baseline dipole field is 16 T. The latest lattice design requires an operating field of 15.71 T. The available field amplitude margin might be used to increase the dipole margin, reduce the cost and complexity of the dipoles or, partially, to increase the length of some of the other magnets to decrease their cost and complexity
- We note that the choice of the field amplitude of the dipole magnets has a considerable impact on the magnet cost, conductor mass and complexity



[1] D. Schoerling et al., *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. No. 4003105

Arc magnets - Quadrupoles

- The MQ requires around 15-20 times less conductor than the dipole magnets
- An addendum to the MoU with CEA is currently under preparation for performing a conceptual design report of the MQ
- An arc design with 60 deg cells would require 30% less quadrupole strength. In case this space is filled with dipoles the amplitude of the dipole field could be reduced by -0.31 T (proposal of E. Todesco, Rome 2016; beam might be less stable, to be clarified)
- Alignment target values to be established
- For a MQ design with an operating current of ~20 kA and 20% margin a 2-layer MQ design might be within reach (see presentation of C. Lorin)

Number of units	750
G in T/m	381
$\int G\,dl$ in T	2286
L in m	6
Aperture in mm	50

MQ	Nb_3Sn (14%)	Nb_3Sn (20%), 2-layer	Nb-Ti (20%)	Baseline
Gradient	400 T/m	360 T/m	250 T/m	381 T/m
Δ Dipole field	-0.05 T	+0.06 T	+0.56 T	0

Arc magnets – Lattice sextupoles

- The strength of the lattice sextupole magnet is under discussion. The current baseline allows to reach the baseline β^* at the HL IRs of 0.3 m.
- Larger sextupole strength is required to go to lower values (20 % larger sextupole strength yields 30% smaller β^*) → under discussion

Number of units	718
S in T/m^2	7184
$\int S\,\mathrm{d}l$ in T/m	8621
L in m	1.2
Aperture in mm	50

MS, see [1]	Nb_3Sn (20%)	Nb-Ti (20%)	Baseline	Nb-Ti (20%) 20% larger L
Strength	9300 T/m^2	7800 T/m^2	7184 T/m^2	7800 T/m^2
Integrated Strength	8621 T/m	8621 T/m	8621 T/m	10,345 T/m
Δ Dipole field	-0.05 T	-0.02 T	0	+0.02 T

[1] D. Schoerling, FCC-hh magnet-beam dynamics coordination meeting 02, Conceptual sextupole and octupole design:

Arc magnets – Landau octupoles

Number of units	750
S in T/m^3	160,650
$\int S\,\mathrm{d}l$ in T/m^2	54,410
L in m	0.32
Aperture in mm	50

- The required strength of the Landau octupole magnets is under discussion
- More dynamic aperture studies are required to understand the required strength. A safety factor of ~2 might need to be added (alternatives are being studied) → under discussion

MO, see [1]	Nb_3Sn (20%)	Nb-Ti (20%)	Baseline	Nb-Ti (20%) 200% larger L
Strength	270,000 T/m^3	220,000 T/m^3	160,065 T/m^3	220,000 T/m^3
Integrated Strength	54,410	54,410	54,410	108,820
Δ Dipole field	-0.02 T	-0.02 T	0	+0.03 T

[1] D. Schoerling, FCC-hh magnet-beam dynamics coordination meeting 02, Conceptual sextupole and octupole design:

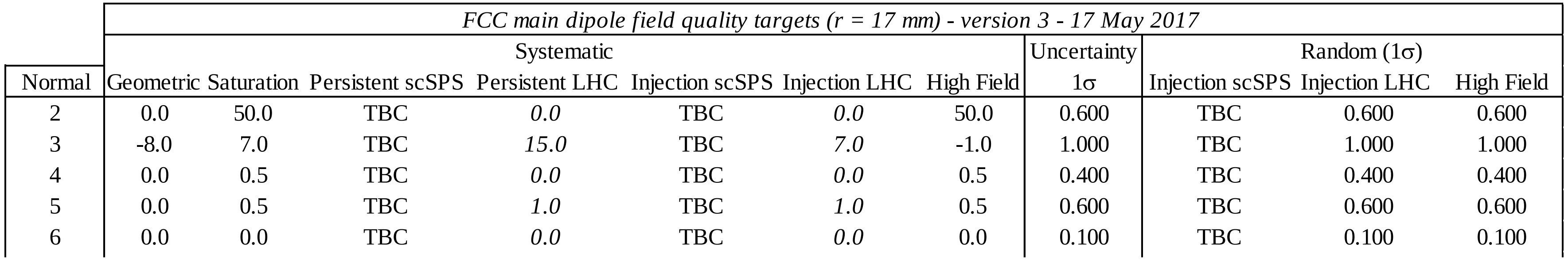
Arc magnets – Short Straight Sections

- In LHC a total of 40 different types of cold-mass assemblies, 10 types of Short Straight Section (SSS) cryostats and 61 different SSS types are installed!
- For FCC-hh we try to standardize the MQ + corrector cryostat assembly as much as possible
- The composition is as follows:
  - Skew quadrupole: strength depends on correction scheme, G = 140 T/m
  - Trim quadrupole (every 6th MQ): integrated field is 1.5% of one MQ (trim over 6-7 MQ: ~50 A, 1 MQ: 300 A)
  - Quadrupole
  - Sextupole
  - Dipole corrector (H/V, nested): 4 Tm, Dipole field strength 3 T, length 1.3 m
  - Octupoles
  - All other multipoles (skew sextupoles & octupoles, etc.) depend on correction scheme (still to be defined by WP2) → need to be integrated in special SSS

Short Straight Section (SSS), not to scale

Arc magnets – Dipole correctors

- The error table of the 16 T dipoles is being defined taking into consideration the available experience from LHC, HL-LHC and Nb_3Sn magnets [1]:
  - Persistent current field quality targets will be estimated for filament diameters of 50 μm. The random contribution will be evaluated with a J_c variation of ±10%
  - Random geometric field errors are calculated according to [2]; there is some potential of improvement?
- We propose a re-distribution of the sextupole error b_3 to injection to limit the required strength of the sextupole spool pieces:
  - $S = 2045\ \mathrm{T/m^2}$, length: 0.11 m, one circuit over each sector might be risky
  - Maximum correction capability at injection scSPS: ±55 units
  - Maximum correction capability at injection LHC: ±22 units (margin available)
  - Maximum correction capability at high field: ±1.4 units (no margin available, to be discussed)
- Discussion up to which multipole shall be corrected with spool pieces



FCC main dipole field quality targets (r = 17 mm) - version 3 - 17 May 2017

	Systematic							Uncertainty	Random (1σ)		
Normal	Geometric	Saturation	Persistent scSPS	Persistent LHC	Injection scSPS	Injection LHC	High Field	1σ	Injection scSPS	Injection LHC	High Field
2	0.0	50.0	TBC	*0.0*	TBC	*0.0*	50.0	0.600	TBC	0.600	0.600
3	-8.0	7.0	TBC	*15.0*	TBC	*7.0*	-1.0	1.000	TBC	1.000	1.000
4	0.0	0.5	TBC	*0.0*	TBC	*0.0*	0.5	0.400	TBC	0.400	0.400
5	0.0	0.5	TBC	*1.0*	TBC	*1.0*	0.5	0.600	TBC	0.600	0.600
6	0.0	0.0	TBC	*0.0*	TBC	*0.0*	0.0	0.100	TBC	0.100	0.100

[1] F. Borgnolutti et al., IEEE *Trans. Appl. Supercond.* 19 (2009), pp. 1100-1105

[2] S.I. Bermudez, Modelling of random geometric field errors, Roxie user case pdf; random displacement with RMS amplitude d = 60 μm; allowed multipoles doubled.

Magnets (matching, insertions, collimation)

- For the matching quadrupole and the quadrupoles in the dispersion suppressors we propose to adapt the same cross-section of the MQ, except where the aperture has to be increased (up to 70 mm)
- Around 156 matching quadrupoles are distributed in:
  - Dispersion suppressors (No: 96)
  - Experimental high-luminosity insertions (two alternative designs, No: 16)
  - Experimental low-luminosity insertions and injection (No: 20)
  - Injection and extraction section (No: 6)
  - β-cleaning section
  - δ-cleaning section (beam separation enlarged to 420 mm)
  - RF section (beam separation enlarged to 420 mm), apertures and beam separation under discussion (No: 8)
  - Collimation sections (No: 10)
- 48 trim quadrupoles in the 16 dispersion suppressors (8.5% of integrated field gradient of dispersion suppressor quadrupoles): Could it be trim power converters?
- Collimation insertion: same type of magnets as in LHC. Radiation load in betatron collimation region is large: Normal-conducting dipole magnets with bedstead coils are proposed [1] to reduced the dose value by one order of magnitude compared to racetrack coils

[1] M.I. Besana, 28. April 2017, FCC-hh magnet-beam dynamics coordination meeting 02

High luminosity IRs

- For the design of the 2 IRs (β^* = 0.3 m, L^* = 45 m) a table with the quadrupole strength limit vs aperture has been established [1]
- The separation and recombination dipoles D1 and D2 can be normal-conducting (an alternative design with 4-5 T dipole magnets to be evaluated)
- Nested H/V orbit correctors with a field of 3 T, length 1.3 m, are proposed
- Radiation and heat load limits:
    - Peak power limit: 5 mW/cm^3 (compare [2] and [3])
    - Radiation limit: 30 MGy (baseline) and 250 MGy (ultimate)
    - Displacement-Per-Atom (DPA) limit: $3.5 \cdot 10^{-3}$ (Ti-doped, limit under discussion)
    - 55 mm tungsten shielding (baseline) and 15 mm (ultimate) fulfil the limits (cooling, DPA, aperture, activation to be confirmed, see simulations [4])
- Reduction of aperture for thin shielding to be evaluated
- Alternative IR design under study (baseline to be decided)

	MQXA	MQXB	MQXC	D1	D2
Number of units	8	16	8	12	12
G, *B*	115 T/m	94 T/m	94 T/m	1.97 T	1.97 T
L	15 m	13.2 m	15 m	12.5 m	12.5 m
Aperture	190 mm	240 mm	240 mm	~200 mm	~70 mm

Aperture (mm)	G (T/m)
72	249
100	193
120	166
140	149
160	133
180	120
200	110
220	102
240	94
260	88

[1] E. Todesco in CAS-CERN Accelerator School, Erice, Italy, 24 April – 4 May 2013, CERN–2014–005 (CERN, Geneva, 2014); here was assumed: Nb$_3$Sn , 25% NCu in the coil cross-section, 20% load line margin, 15% below the maximum achievable gradient
[2] M. La China and D. Tommasini, Phys Rev STAB 11, 082401 (2008)
[3] P.P. Granieri, IEEE Trans. Appl. Supercond., Vol. 24, No. 3, June 2014;
[4] M.I. Besana, 28. April 2017, FCC-hh magnet-beam dynamics coordination meeting 02

Low luminosity IRs

- 2 IRs ($\beta^* = 3$ m, $L^* = 25$ m) combined with injection region
- The separation and recombination dipoles D1 (single aperture) and D2 (double aperture, large cross-talk due to reduced intra-beam spacing) are within the 10 T range. The aperture of D1 is relatively large (initial conceptual designs: [1] and [2])
- Nested H/V orbit correctors with a strength of 3 T, length 1.0 m are proposed
- Radiation and heat load is below the baseline limits with a 10 mm tungsten shielding (see simulations [3])

	Q1-3	D1	D2
Number of units	24	8	8
G, B	270 T/m	10 T	8 T
L	15 m	12.5 m	15 m
Aperture	64 mm	100 mm	60 mm

[1] T. Nakamoto, D1 for FCC: 6cm single aperture 12 T dipole, FCC week Washington 2015
[2] P. Fabbricatore, D2 for FCC, FCC week Washington 2015
[3] M.I. Besana, 28. April 2017, FCC-hh magnet-beam dynamics coordination meeting 02

Injectors SC-SPS

- Injection from LHC (3.3 TeV) is baseline; an alternative injector is under study: SC-SPS (1.3 TeV); see numerous talks at this workshop
- Fast ramp rate (0.35-0.5 T/s) of dipoles limits field strength to around 6 T
- A collaboration with JINR, Dubna for the development of the dipoles is under preparation
- The SPS dipole magnets may be re-used in the transfer lines

	Nb-Ti dipoles	Nb-Ti quadrupoles
Number of units	372	216
B,G	6 T	150 T/m
L	12.12 m	12.5 m
Aperture	80 mm	100 mm

Conclusion

- Most other magnets have been specified and a technology has been proposed
- Most parameters are relatively solid. However, still for a number of magnets the aperture values need to be confirmed before a conceptual magnet design can be started (triplets, several matching sections)
- A. Chancé is collecting for EuroCirCol WP2 the magnet parameters (see his talk at this workshop) to obtain a full list of all required magnets
- Conceptual magnet designs (EMAG, protection) have to be performed to verify the choices and, in case needed, to adjust and fine-tune the parameters