Other magnet parameters

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On behalf of the FCC Other Magnets Task
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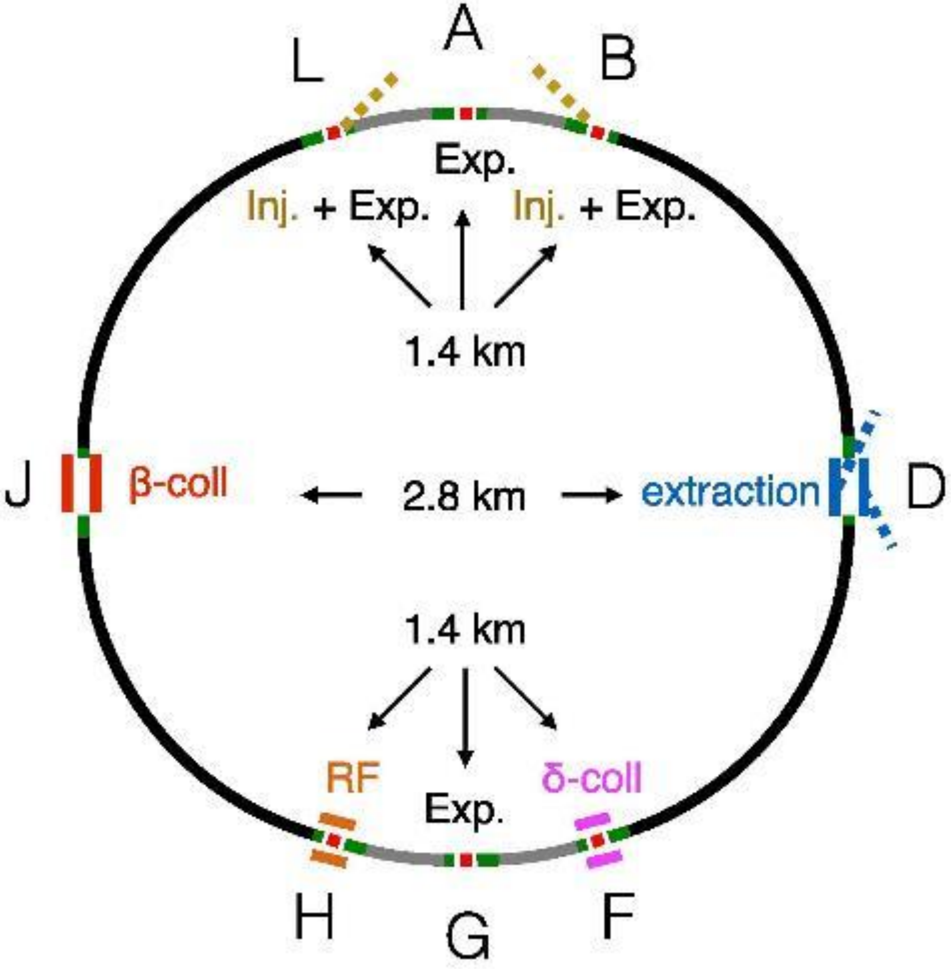
Introduction

- 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)
- For FCC we adapted the approach to select the largest possible reasonable strength but with parameters less challenging than the dipole magnets or similar challenging for the high-lumi low-β triplets
- Some designs may require further technological development

Length: 97.75 km



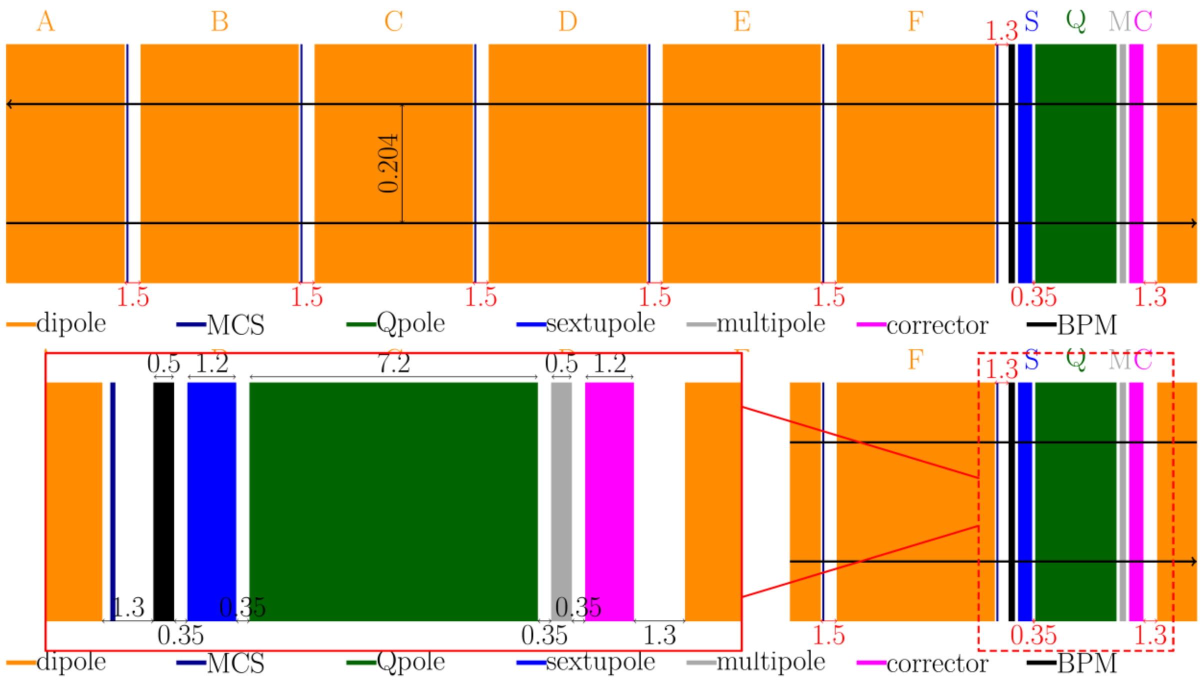
Arc lattice magnets

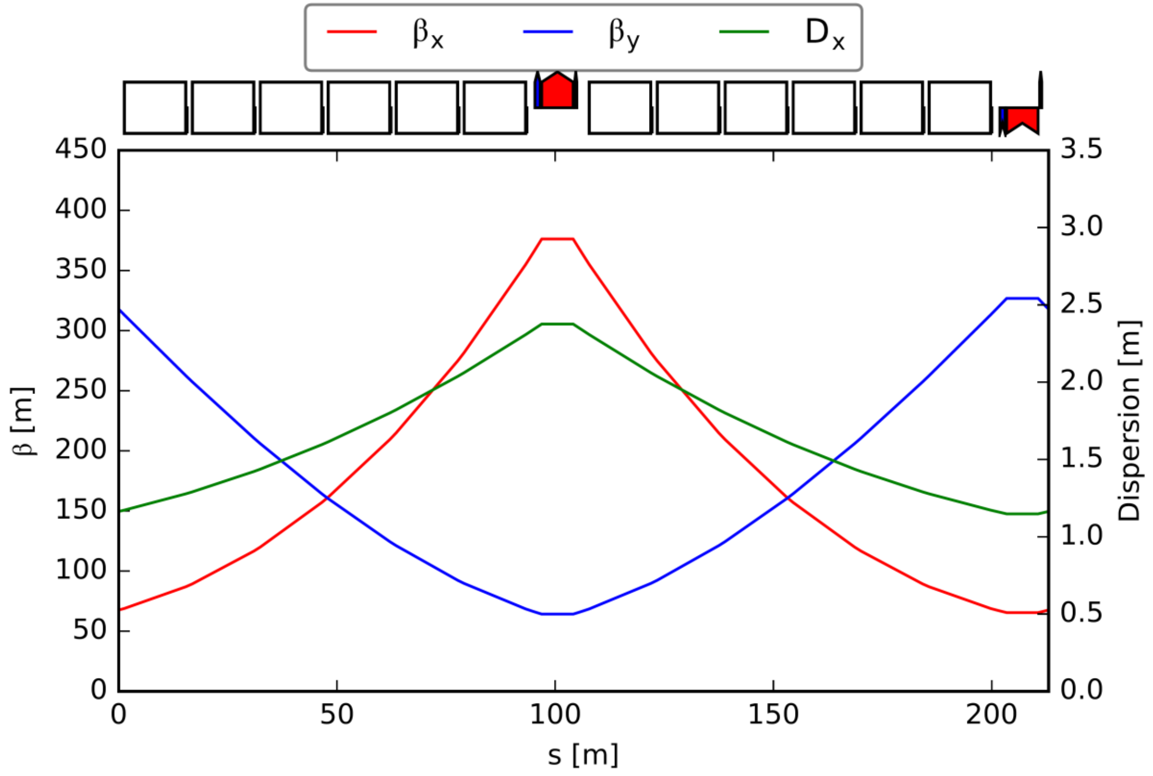
- FODO cell length is 213 m (90 deg phase advance, 12 dipoles and 2 short straight sections)
- The aperture in all arc magnets is 50 mm
- Each arc begins and ends with a dispersion suppressor (DIS)
- The aim was to increase the filling factor as much as possible, that means to provide ‘other’ magnets with as high as reasonable possible field strength

Magnet type	Distance (m)	Remarks
MB-MB	1.5	May be longer if stronger MCS required
MB-SSS	1.3	Does not include BPMs
MQ-Other	0.35	Other magnetic elements in SSS
Other-Other	0.35	

Magnet type	Number	Max. Strength	Length	SC material	LHC nominal strength (56 mm aperture)	LHC nominal strength scaled to 50 mm aperture
Main Dipole (MB)	4668	16 T	14.1 m	Nb_3Sn	8.33 T	8.33 T
Main Quadrupole (MQ)	744	360 T/m	7.2 m	Nb_3Sn	223 T/m	250 T/m
Trim Quadrupole (MQT)	120	220 T/m	0.5 m	Nb-Ti	123 T/m	140 T/m
Skew Quadrupole (MQS)	96	220 T/m	0.5 m	Nb-Ti	123 T/m	140 T/m
Main Sextupole (MS)	696	7000 T/m^2	1.2 m	Nb-Ti	4430 T/m^2	5560 T/m^2
Main Octupole (MO)	480	200,000 T/m^3	0.5 m	Nb-Ti	63,000 T/m^3	90,000 T/m^3
Sextupole Corrector (MCS)	9336	3000 T/m^2	0.11 m	Nb-Ti	1630 T/m^2 (58 mm)	2200 T/m^2
Dipole Corrector (MCB)	792	4 T	1.2 m	Nb-Ti	3 T	3 T
DIS Trim Quadrupole (MQTL)	48	220 T/m	2.0 m	Nb-Ti	129 T/m	145 T/m
DIS Quadrupole (MQDA)	48	360 T/m	9.7 m	Nb_3Sn	129 T/m	145 T/m

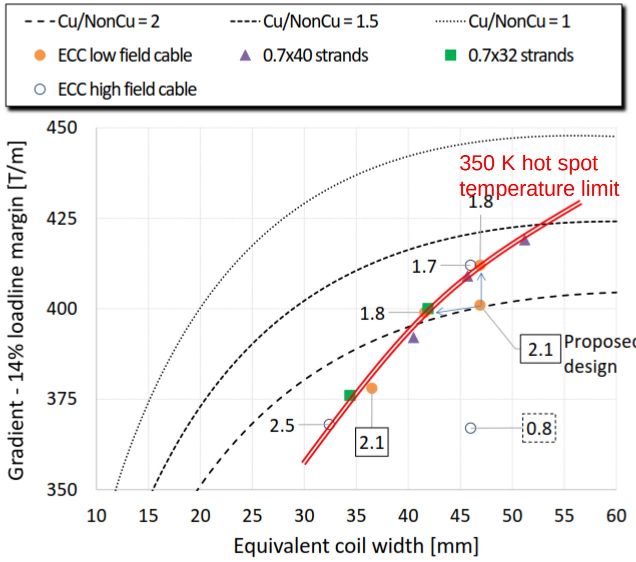
Arc lattice magnets





FCC-hh MQ

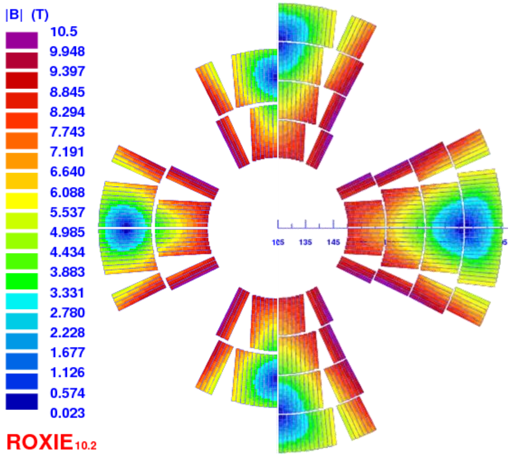
- MQ (designed by CEA) was started as 400 T/m quadrupole [1] and a four layer design. After discussions a 2-layer design is proposed with ~20% LL.
- Challenges of this design: cable with large aspect ratio (51 strands, 0.7 mm), nominal current ~20 kA



Number of units	744
G in T/m	360
$\int G\,dl$ in T	2592
L in m	7.2
Aperture in mm	50

See presentation C. Lorin

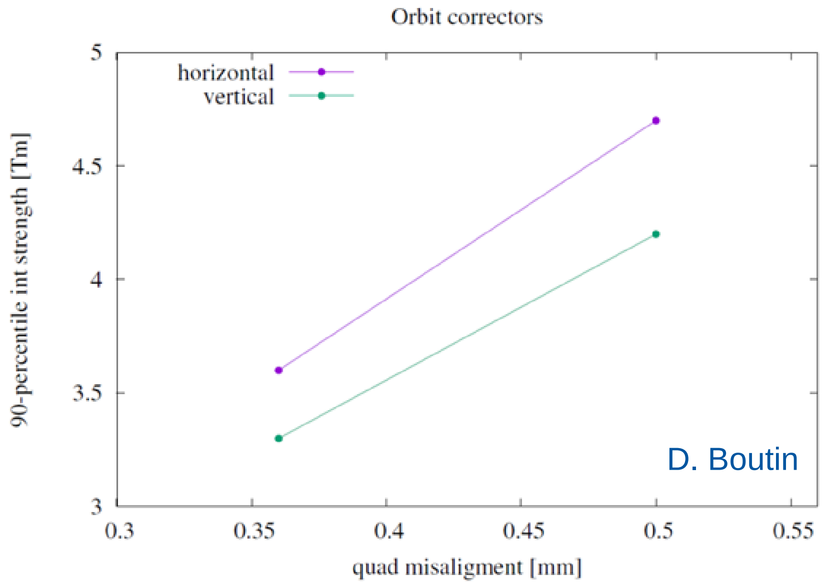
MQ	Nb_3Sn (14%)	Nb_3Sn (20%), 2-layer	Nb-Ti (20%)
Gradient	400 T/m	360 T/m	250 T/m
Δ Dipole field	-0.1	0	+0.6



[1] C. Lorin, Design of a Nb_3Sn 400 T/m quadrupole for the Future Circular Collider, IEEE Transaction on Applied Superconductivity, DOI: 10.1109/TASC.2018.2797945

FCC-hh correctors

- The required strength of the corrector magnets depends mainly on the random dipolar error in the dipoles (here b_1 = 10 units) and on the alignment tolerances of the MQs
- The chosen maximum bore field allows for low current (<200 A) designs with Nb-Ti



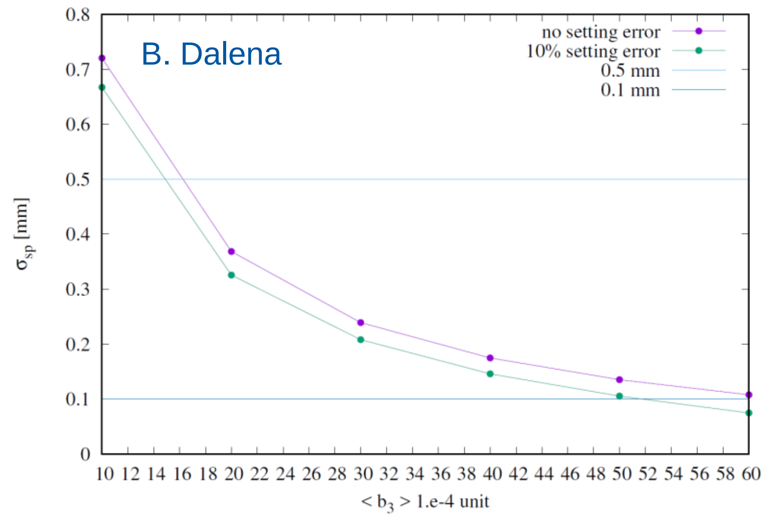
Target values for FCC quadrupole alignment (all considered sources, 1σ values)

	Units	Fiducialisation	Alignment error at installation	Alignment error and movement 4 years after installation	$\sqrt{\sum_{i=1}^{n} x_i^2}$ at installation	$\sqrt{\sum_{i=1}^{n} x_i^2}$ 4 years after installation
Transversal	mm	0.2	0.1	0.5	0.22	0.54
Vertical	mm	0.2	0.1	0.3	0.22	0.36
Roll	mrad	0.1	0.1	0.3	0.14	0.32
Pitch	mrad	0.1	0.03	0.15	0.10	0.18
Yaw	mrad	0.1	0.03	0.1	0.10	0.14

Number of units	792
B in T	4
$\int B\,dl$ in Tm	4.8
L in m	1.2
Aperture in mm	50

FCC-hh sextupole spool pieces

- Up to b_3 = 4 units at collision and 60 units at injection (3.3 TeV) can be corrected with the proposed spool pieces
- To limit 'β-beating' at injection to the same value as created by the random dipole b_2 component (in FCC 5%, in LHC 2.6%), the maximum allowed MCS alignment error depends on the required correction strength (currently the b_3 error at injection in the dipoles is around 60 units)
- The alignment error of the spool pieces is a function of: (a) the alignment error of the MCS within the cryo-magnet assembly (in LHC this alignment was $\pm$0.5 mm) and (b) the alignment error of the cryo-magnet in the tunnel (in LHC after realignment $\pm$ 0.12mm, see presentation of D. Missiaen)$\rightarrow$ We assume that an alignment error of $\pm$0.5 mm is within reach for FCC without new developments
- Such an alignment error would require to reduce the b_3 field errors in the dipoles to around ~10 units (requires the compensation of persistent current induced multipole errors, under study)
- Other correctors b_4, b_5 are not needed for DA; a_3 correctors might be needed (few per arc, LHC: 4)



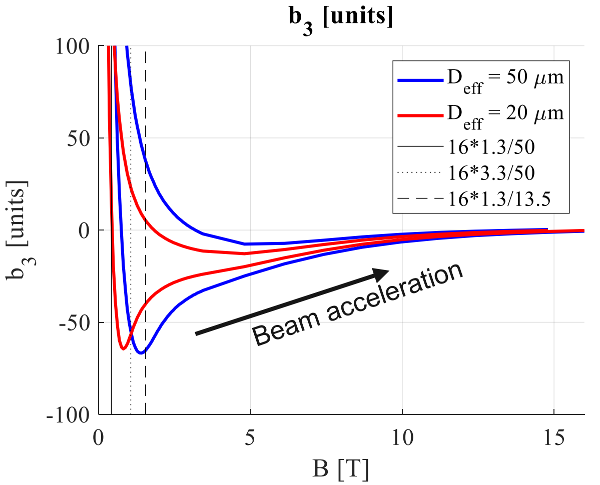
Number of units	9336
S in T/m^2	3000
$\int S\, dl$ in T/m	330
L in m	0.11
Aperture in mm	50

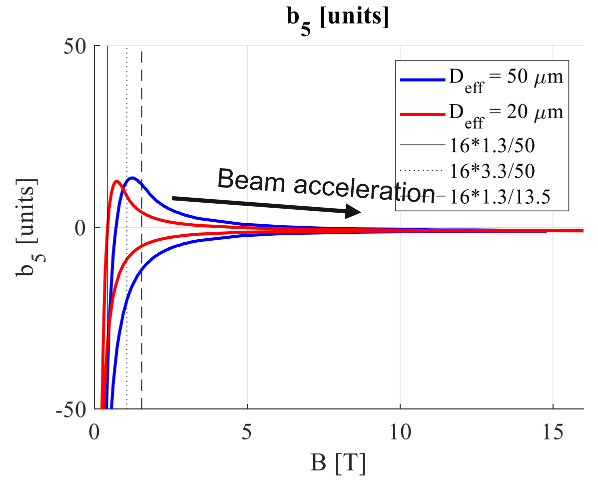
Field quality table for 3.3 TeV (LHC injection, 1.1 T)

- Better field quality would ease machine operation
- Smaller random b_3 is required to control the chromaticity, which cannot be measured in real time during beam acceleration
- Within EuroCirCol WP5 studies to mitigate in particular b_3 have been started
- b_2 can be reduced by increasing the inter-beam distance, for example to 20 units at 250 mm

	FCC Dipole field quality version 3 - 24 Jan 2018- R_{ref}=16.7 mm. 3.3 TeV Injection								
	Systematic					Uncertainty		Random	
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field
2	-2.230	-44.610	0.000	-2.230	-46.840	0.922	0.922	0.922	0.922
3	-18.140	17.000	-38.860	-57.000	-1.140	4.000	1.351	4.000	1.351
4	-0.100	-0.930	0.100	0.000	-1.030	0.449	0.449	0.449	0.449
5	-0.690	-0.340	9.190	8.500	-1.030	1.000	0.541	1.000	0.541
6	0.000	-0.010	0.000	0.000	-0.010	0.176	0.176	0.176	0.176
7	1.610	0.140	-1.010	0.600	1.750	0.211	0.211	0.211	0.211
8	0.000	0.000	0.000	0.000	0.000	0.071	0.071	0.071	0.071
9	1.310	0.120	2.990	4.300	1.430	0.500	0.092	0.500	0.092
10	0.000	0.000	0.000	0.000	0.000	0.027	0.027	0.027	0.027
11	0.960	0.090	-0.100	0.860	1.050	0.100	0.028	0.100	0.028
12	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.009
13	-0.170	-0.020	0.170	0.000	-0.190	0.000	0.011	0.000	0.011
14	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.003
15	0.010	0.000	-0.010	0.000	0.010	0.000	0.004	0.000	0.004
Skew									
2	0.000	0.000	0.000	0.000	0.000	1.040	1.040	1.040	1.040
3	0.000	0.000	0.000	0.000	0.000	0.678	0.678	0.678	0.678
4	0.000	0.000	0.000	0.000	0.000	0.450	0.450	0.450	0.450
5	0.000	0.000	0.000	0.000	0.000	0.317	0.317	0.317	0.317
6	0.000	0.000	0.000	0.000	0.000	0.205	0.205	0.205	0.205
7	0.000	0.000	0.000	0.000	0.000	0.116	0.116	0.116	0.116
8	0.000	0.000	0.000	0.000	0.000	0.071	0.071	0.071	0.071
9	0.000	0.000	0.000	0.000	0.000	0.041	0.041	0.041	0.041
10	0.000	0.000	0.000	0.000	0.000	0.025	0.025	0.025	0.025
11	0.000	0.000	0.000	0.000	0.000	0.016	0.016	0.016	0.016
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.009
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.005
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.003
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.002

Systematic:
Injection = Geometric + Persistent
High Field/Collision = Geometric + Saturation





Lattice sextupoles and octupoles

Sextupoles:

- Used for chromaticity correction, which is mainly generated by the High-Lumi interaction points (β^* = 0.3 m).
- The strength of the lattice sextupole magnet is still under discussion. ~20% stronger sextupoles might be required to allow for a smaller β^*

Number of units	696
S in T/m^2	7000
$\int S\,\mathrm{d}l$ in T/m	8400
L in m	1.2
Aperture in mm	50

Octupoles:

- Used for Landau damping (suppression of instabilities by the spread in revolution frequencies)
- Large reduction of DA, currently under study

Number of units	480
S in T/m^3	200,000
$\int S\,\mathrm{d}l$ in T/m^2	100,000
L in m	0.5
Aperture in mm	50

Technological challenging design: 20% load line margin for impregnated Nb-Ti magnets

See presentation A. Louzguiti

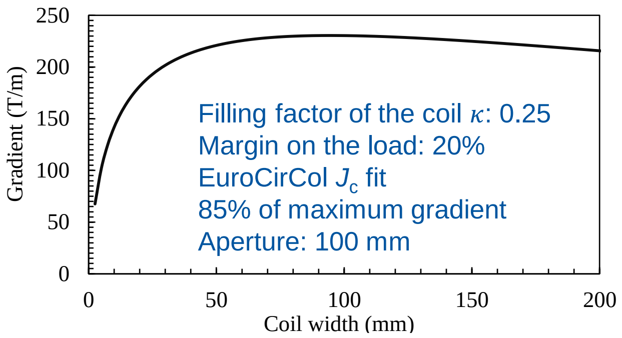
Low-β triplets overview

- At the high-luminosity IP a β^* = 0.3 m, L^* = 40 m and at the low-luminosity IP a β^* = 3 m, L^* = 25 m shall be reached
- The design criteria for the (high-luminosity) triplets is too provide the highest realistically achievable strength based on the most advanced technology one could realistically imagine to have available within the next decade

See presentation of V. Kashikhin

Low-β triplets

	Number	Strength	Length	Aperture
Q1 high lumi	4/IP	130 T/m	14.3 m	164 mm
Q2 high lumi	8/IP	105 T/m	12.5 m	210 mm
Q3 high lumi	4/IP	105 T/m	14.3 m	210 mm
Q1 low lumi	4/IP	270 T/m	10.0 m	64 mm
Q2 low lumi	4/IP	270 T/m	15.0 m	64 mm
Q3 low lumi	4/IP	270 T/m	10.0 m	64 mm



$$G_c = \frac{1}{2}\kappa s \gamma_0 \ln\left(1+\frac{w}{r}\right)\left(\sqrt{\frac{4b}{\kappa r s \lambda \gamma_0 \ln\left(1+\frac{w}{r}\right)}+1}-1\right)$$

κ	0.25
s	$4667\cdot10^6$ A/m^2
γ_0	$\sqrt{48}\cdot10^{-7}$ Tm/A
a_1	0.04
a_{-1}	0.11
b	24 T

r (mm)	w (mm)	G (T/m)	B_p (T)
36	20	249	10.2
50	25	193	11.0
60	28	166	11.3
70	33	149	11.8
80	35	133	12.1
90	38	120	12.4
100	40	110	12.6
110	43	102	12.8
120	45	94	13.0
130	48	88	13.2

CERN

High luminosity IRs

- 2 IRs (β^* = 0.3 m, L^* = 40 m)
- The separation and recombination dipoles D1 and D2 are normal-conducting, due to the large radiation
- 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
  - Radiation limit: 30 MGy (baseline) and 250 MGy (ultimate)
  - Displacement-Per-Atom (DPA) limit: $2 \cdot 10^{-3}$ (Ti-doped, limit under study)
  - 55 mm tungsten shielding (baseline) and 15 mm (ultimate) fulfil the limits (cooling, DPA, aperture, activation to be confirmed)
- Reduction of aperture for thin shielding to be evaluated

	MQXA	MQXB	MQXC	D1	D2
Number of units/IP	4	8	4	6	6
G, B	130 T/m	105 T/m	105 T/m	1.9 T	1.9 T
L	14.3 m	13.2 m	15 m	3x12.5 m	3x12.5 m
Aperture	164 mm	210 mm	210 mm	168 mm	58 mm

Low luminosity IRs

- 2 IRs (β^* = 3 m, L^* = 25 m) combined with injection region
- The separation and recombination dipoles D1 (single aperture) and D2 (double aperture) are within the 10 T range. The aperture of D1 is relatively large
- 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])

See presentation of T. Ogitsu (D1) and S. Farinon (D2)

	Q1	Q2	Q3	D1	D2
Number of units/IP	4	4	4	4	4
G, *B*	270 T/m	270 T/m	270 T/m	12 T	10 T
L	10 m	15 m	10 m	10.2 m	12.2 m
Aperture	64 mm	64 mm	64 mm	100 mm	60 mm

Magnets (matching, insertions, collimation)

- For the matching quadrupole and the quadrupoles in the dispersion suppressors the same cross-section of the MQ is used, 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)
- High- and low luminosity Q4-Q7 quadrupoles with less challenging parameters as Q1-Q3
- 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 to reduced the dose value by one order of magnitude compared to racetrack coils

Injectors SC-SPS

- Injection from LHC (3.3 TeV) is baseline; an alternative injector is under study: SC-SPS (1.3 TeV 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 on-going
- The SPS dipole magnets may be re-used in the transfer lines

See presentation of A. Kovalenko
(see session of other programs)

	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

- The parameters of the ‘other’ magnets have been specified, a technology concept has been proposed and first conceptual designs for the most challenging magnets have been established (see following talks)
- All magnets have parameters less challenging than the dipole magnets or similar challenging for the high-lumi low-β triplets
- The total amount of conductor for the other magnets is estimated to be <15% of that required for the dipoles