Field quality, correctors and filling factor in the arcs

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With contributions from L. Bottura, P. Hagen, D. Tommasini, R. Garcia Tomas, D. Schulte

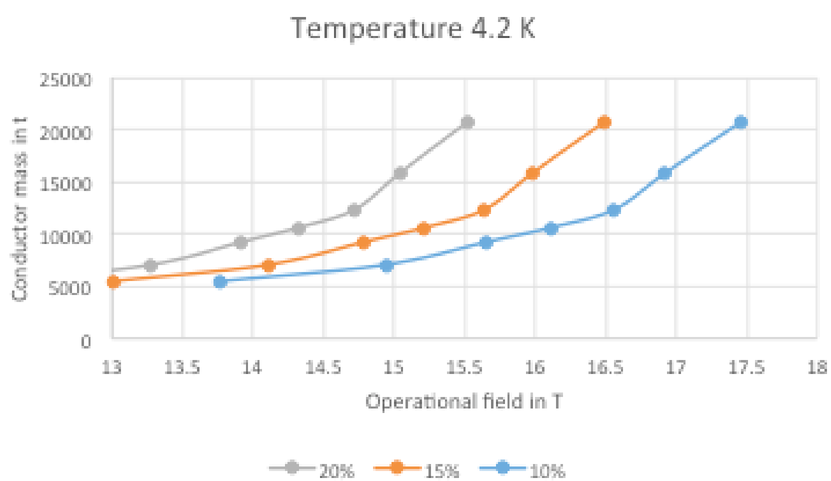
CONTENTS

- Correctors needed in the arc
  - Do we have some correctors whose length becomes very long?
  - Do we have to launch special R&D ?
- Field quality targets [B. Dalena talk, this conference]
  - Feedback from tracking
  - What are we aiming at? How much more difficult than LHC?
    [E. Todesco et al., "The LHC field model at 6.5 TeV" IEEE Trans. Appl. Supercond. 2016]
- Review of interconnection
  - Did we take reasonable hypothesis?

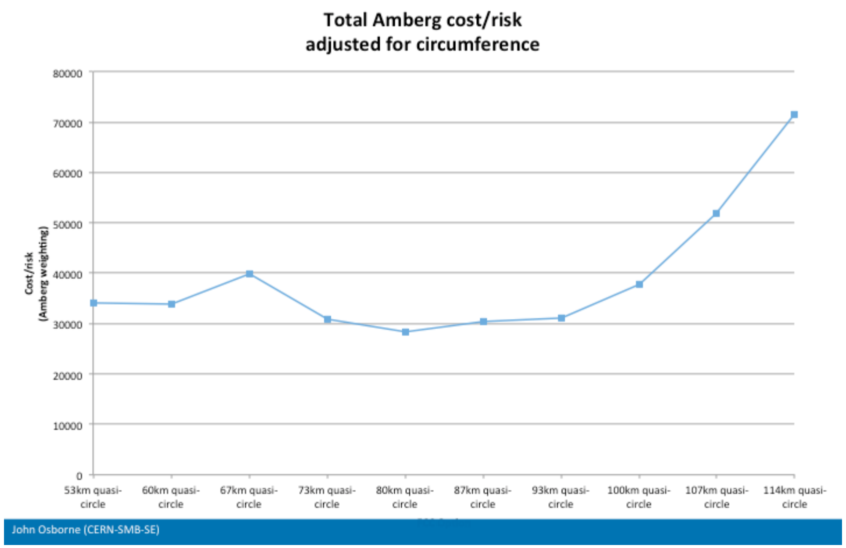
- General goal
  - See all ways to increase the filling factor in the cell (fraction of the cell covered by dipolar field)
    - Today we are at 80%, we should aim at 85%
    - Cell semilength is 100 m, so every meter per half cell is 1% and can be useful

CONTENTS

- The magnet at 16 T is at the Nb_3Sn wall
  - 1 T less would give lbeneficial relax on magnet design (stress, size, protection) and cost (quantity of superconductor) [see talks from D. Tommasini, F. Toral, P. Vedrine, T. Salmi, V. Marinozzi, R. Gupta, Q. Xu, A Verweij, D. Schoerling]
- The tunnel size is already close to the 100 km wall
  - Larger size becomes problematic [talk from J. Osborne]

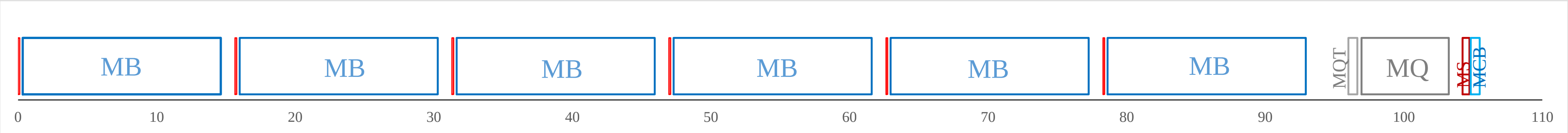


Cost vs field and margin [D. Schoerling]



FILLING FACTOR

- Filling factor definition
  - Ratio between sum of dipole magnetic lengths (over a cell) and cell length
- Present status
  - LHC: cell length 107 m, 6 dipole of 14.3 m, fill factor 80.3%
  - FCC: cell length 214 m, 12 dipoles of 14.3 m, fill factor 80.3%



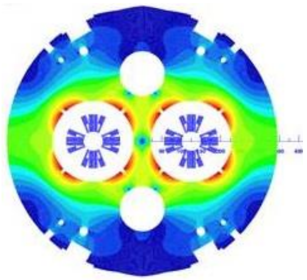
FCC cell [D. Schulte, B. Dalena]

  - Other than dipole, we have
    - Quadrupole MQ (2)
    - Orbit corrector MCB (2)
    - Tuning quadrupoles MQT (2) – sometimes they become skew quadrupole to correct coupling
    - Chromatic sextupoles MS (2) – sometimes they become skew sextupoles to correct coupling
    - Sextupole spool pieces MCS (12? 6?)

THE MAIN QUADRUPOLE

- Today requirements: 2300 T of integrated field
  - Over 50 mm with Nb-Ti you can make 250 T/m … this gives 9 m long magnet so we have to go to Nb_3Sn
  - This is also why I insisted so much on grading
- With Nb_3Sn one can reach 400 T/m

  [C. Lorin, P. Verdine this conference]
  - So we have 6 m magnet



- Integrated gradient depends on cell length *L* and phase advance

$$Gl_q = \frac{\sqrt{2}B\rho}{L}$$ for 90 degrees cell

$$Gl_q = \frac{B\rho}{L}$$ for 60 degrees cell

- Is it worth trying a 60 degrees phase advance?
  - This would give requirement of 70%, ie 1600 T m and a 4 m long magnet
  - 2 m = 2% gained!
- Or making a longer cell? Similar effect moving from 200 to 300 m
  - But larger beam size

ORBIT CORRECTORS

- LHC orbit correctors are 2.93 T magnets close to each quadrupole
  - Nb-Ti ribbon technology
    - 0.647 m long, ~2 T m requirement
    - This magnet is attached to the orbit feedback system so it should be able to act with a ramp rate of 100 s to have full field (for LHC today, 0.03 T/s)
- FCC requirement is to have 3.5 T m [B. Dalena talk, this conference]
    - With a 4 T field, we can go for a 1 m long magnet
    - Nb-Ti magnet, looks at hand
      - I would see no reason to push more to save 0.5 m
- Orbit correctors are in the shadow
  - If the requirement goes up, one should think about 6 T magnets

TUNING QUADRUPOLES

- LHC tuning quadrupoles (MQT) are individually powered small quadrupoles close to each main quadrupole
  - Nb-Ti ribbon technology
    - 123 T/m, 0.32 m long, 39 T requirement (5% of the MQ)
    - This magnet is attached to the tune feedback system – variations up to 1 T/m/s
- FCC requirement is to have 325 T (15% of the MQ) [B. Dalena talk, this conference]
    - This because it is assumed that this magnet is also used in the Dispersion Suppressor (DS) to allow optics matching
    - But 325 T would imply a 3 m long magnet – too much – or going to Nb_3Sn
      - With Nb_3Sn one could get a 1 m long magnet with 325 T/m
    - It would be wiser to have different magnets, one for the arc at 5% of the MQ and one for the DS
    - I would propose a 200 T/m over 50 mm (~6 T peak field), with 0.5 m length
- Tuning quadrupoles are in the shadow

LATTICE SEXTUPOLE

- Lattice sextupole in the LHC today (56 mm aperture)
  - Nb-Ti ribbon technology, gradient is 4430 T/m^2 (0.37 m long)
    - This gives integrated gradient of 1635 T/m requirement or equivalently 0.070 m^{-2} if normalized with the beam rigidity Bρ
  - Lattice sextupole correct chromaticity (not only from the arc)

- FCC present requirement is to have 6650 T/m requirement or equivalently 0.040 m^{-2} [B. Dalena talk, this conference]
  - Assuming the same peak field as in the LHC, over 50 mm we can give a gradient of 5560 T/m^2, so this is a ~1.2 m long object
    - There is a wish to have 15000 T/m requirement or equivalently 0.090 m^{-2}
    - This would push the sextupoles towards 3 m length

- Lattice sextupoles could be not in the shadow
  - Institutes interested in exploring HTS sextupole correctors ?

SEXTUPOLE SPOOL PIECES

- Spool pieces in the LHC today (56 mm aperture)
  - Nb-Ti ribbon technology
    - Spool piece gradient 1630 T/m^2 (0.11 m long)
    - One can make much larger gradient as in the lattice sextupole 4430 T/m^2
  - Spool pieces corrects in the LHC a max b_3=4.35 units at 7 TeV
  - Using the same length (0.11 m) and the lattice sextupole strenght, and rescaling at 50 mm, we can obtain
    - Ie we can correct up to ±6 units of b_3 at 50 TeV – looks reasonable to me
  - We have 10 units swing of b_3, we can tentatively place -7 at injection and 3 at high field
- Sextupole spool pieces have a negligible impact on the lattice

LANDAU OCTUPOLES

- Landau octupoles in the LHC today (56 mm aperture)
  - Nb-Ti ribbon technology
    - Gradient 63×10^3 T/m^3 (0.32 m long)
    - Peak field is 1.28 T, one can make at least a factor two stronger
    - Plus the scaling with aperture from 56 to 50 mm, one can go to 220×10^3 T/m^3
- FCC request: factor 3 to 6 larger than in the LHC [V. Kornilov talk, this conference]
  - Factor 3 can be obtained with the 220×10^3 T/m^3 gradient and keeping the same length 0.32 m
    - Another factor 2 by either doubling the length or placing in the straight part of the ring
- Landau octupoles not critical

FIELD QUALITY TARGETS

- Target error table may 2015 (Version 0)
  - Uncorrected saturation, 10 units persistent
  - Most of the geometric to compensate injection
- Since then tracking has been done [B. Dalena this workshop] has been plus some new elements
  - Saturation can be compensated with iron [S. Izquierdo Bermudez]
  - Large b_3 at high field requires more sextupoles
  - Double sensitivity on chroma [R. Tomas Garcia], so with 10 units difference between inj and high field we already have 800 chroma swing during ramp

	FCC main dipole field quality version 0 - 28 May 2015								
	Systematic					Uncertainty		Random	
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field
2	0.000	0.000	0.000	0.000	0.000	0.484	0.484	0.484	0.484
3	-10.000	30.000	5.000	-5.000	20.000	0.781	0.781	0.781	0.781
4	0.000	0.000	0.000	0.000	0.000	0.065	0.065	0.065	0.065
5	-2.000	0.500	1.000	-1.000	-1.500	0.074	0.074	0.074	0.074
6	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0.009	0.009
7	1.000	0.300	-1.500	-0.500	1.300	0.016	0.016	0.016	0.016

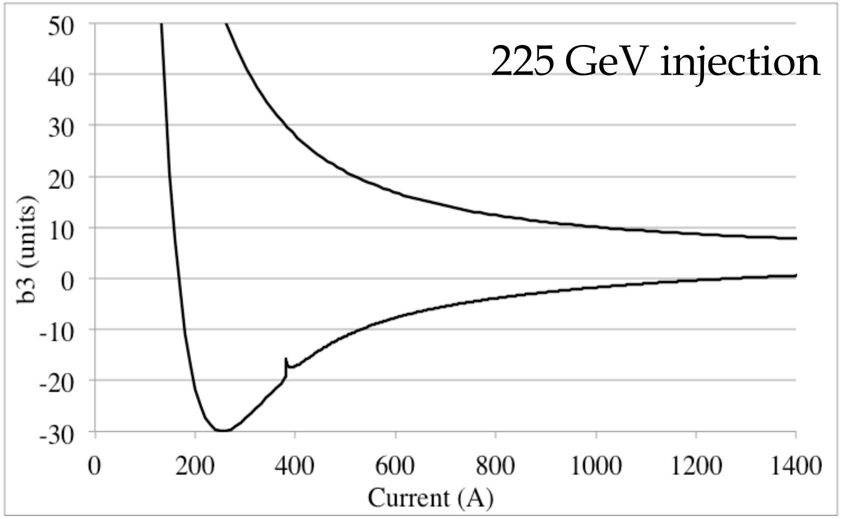
FIELD QUALITY TARGETS

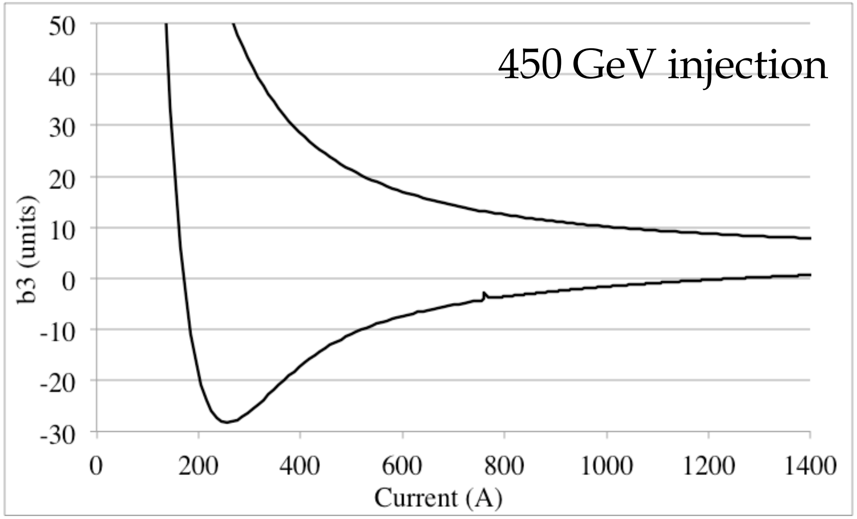
- Proposal for target error table April 2016 (Version 0)
  - Corrected saturation, 1 units left (10% error in correction)
  - Persistent current from 5 to 10 units
- Geometric partially compensates injection
  - 2/3 of the errors at injection, 1/3 at high field
- With this table we will have three times larger chromaticity change along the ramp and at decay and snapback w.r.t the LHC today
  - 50% worse magnets (7 to 10 units persistent current)
  - Factor 2 worse coming from optics (1 unit of b_3 gives 80 of chroma instead of 40)

	Systematic				
Normal	Geometric	Saturation	Persistent	Injection	High Field
2	0.000	0.000	0.000	0.000	0.000
3	-4.000	1.000	10.000	6.000	-3.000
4	0.000	0.000	0.000	0.000	0.000
5	-2.000	0.500	1.000	-1.000	-1.500
6	0.000	0.000	0.000	0.000	0.000
7	1.000	0.300	-1.500	-0.500	1.300

A CHALLENGING MD

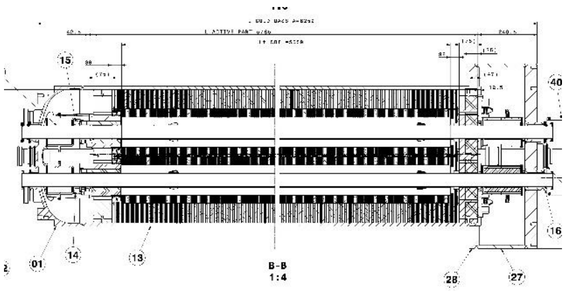
- Injection in the LHC at 225 GeV would give three times larger effects on chroma
  - This would allow to explore the proposed FCC range in the LHC
  - MD proposal under study [M. Solfaroli et al]



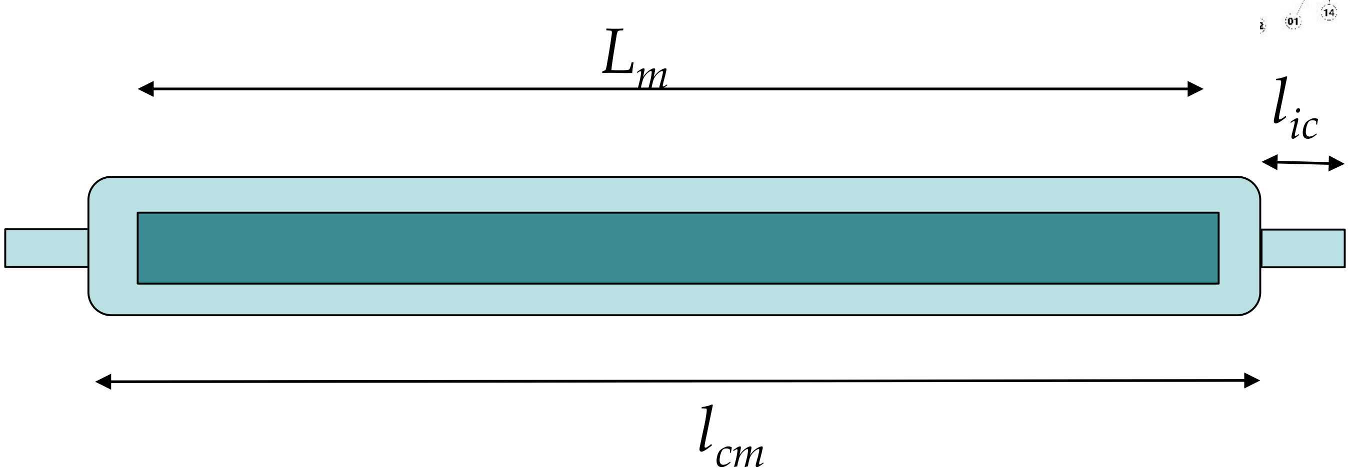


INTERCONNECTIONS & CO

- First guess distance between magnetic lengths: 1.36 m
  - L_m: magnetic length (seen by optic files)
  - l_{cm}: physical length of the cold mass (tank with He at 1.9 K)
  - l_{IC}: length interconnections between cold masses
  - Experience from first Nb_3Sn models 11 T and QXF: l_{cm}-L_m~950 mm
    - Very different design, aperture but similar values
    - Plus 400 mm for interconnections, makes 1.35 m



  - Challenging but reasonable



MINOR CHANGES PROPOSED

- Proposed changes
  - MCB at 4 T
    - 0.23 m longer
  - MQT at 200 T/m but reduced force
    - 0.07 m shorter
  - MS at 5560 T/m^2
    - But 2.2 m longer in the worse case
  - MO at 220×10^3 T/m^3
- There is still some space free – some meters could be recovered?
  - 3 m between MQT and MB, 1 m between MQ and MS

LHC					
Aperture	Length	field/gradient	peak field	int field	int field
(mm)	(m)	T, T/m, T/m2	(T)	Tm , T , T/m	T m
56	14.3	8.33	8.7	119	119
56	3.150	210	6.76	662	11.2
56	0.320	123	4.13	39	0.7
56	0.647	2.93	3.52	2	1.9
56	0.369	4430	*3.47*	1635	0.5
56	0.11	1630	*1.28*	179	0.05

	FCC present					
	Aperture	Length	field/gradient	peak field	int field	int field
	(mm)	(m)	T, T/m, T/m2	(T)	Tm , T , T/m	T m
MB	50	14.3	16	16.5	229	229
MQ	50	6.29	370	10.64	2327	39.6
MQT	50	0.65	500	15.00	325	5.5
MCB	50	0.65	3	3.60	2	1.9
MS	50	0.50	13100	*8.19*	6550	1.9
MCS	50	0.11	4430	*2.77*	487	0.14

	FCC update					
	Aperture	Length	field/gradient	peak field	int field	int field
	(mm)	(m)	T, T/m, T/m2	(T)	Tm , T , T/m	T m
MB	50	14.3	16	16.5	229	229
MQ	50	5.82	400	11.50	2327	39.6
MQT	50	**0.58**	**200**	**6.00**	**116**	**2.0**
MCB	50	**0.88**	**4.0**	**4.50**	**3.5**	**3.5**
MS	50	**2.70**	**5557**	**3.47**	**15000**	**4.3**
MCS	50	0.11	4430	2.77	487	0.14

CONCLUSION

- Orbit correctors can be critical is strength goes above 4 T m
  - A 4 T magnet is ok
- Tuning quadrupoles in the cell should have limited requirements to limit their length to 0.58 m
  - So different (longer ?) magnets for the DS
- Lattice sextupole are long (3 m)
  - Larger gradient could be interesting to save 1-2 m … Nb3Sn makes sense ?
- Spool pieces are negligible (0.11 m as today)
  - This allows 6 units correction of b_3
  - Iteration on FQ to have -6 units of b_3 at injection and 3 at high field
- Distance between magnetic lengths are tight but fine

- An MD to check the possibility of correcting the chromaticity swing of 800 units would be welcome (3 times larger effects than today in the LHC)

IDEAS

- From the optics
  - Reducing quadrupole length with 60° phase advance or going to longer cell would save another 2%
  - Making the cell tighter and recovering up to 3 m ? (3%)
- From the magnets
  - Developing much stronger sextupoles (Nb_3Sn, HTS ?) would allow saving 2%
  - Putting two 15 m long magnets in the same cold mass
    - HL LHC experience with Q1/Q3: 350 mm minimum between cold mass, so 1 m saved per 30 m (3%)
    - Incredibly long cold mass of 30 m, 3% gain – does it makes sense? Probably not
  - Nothing to gain on the spools, tuning quad or orbit correctors

- I think we have the possibility of issuing a new optics with 85% filling factor and 16-ε T dipoles, with ε → 1