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
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?

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
The magnet at 16 T is at the Nb\textsubscript{3}Sn wall

- 1 T less would give \textit{beneficial} relax on magnet design (stress, size, protection) and cost (quantity of superconductor) \cite{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 \cite{talk from J. Osborne]

\begin{itemize}
\item \textbf{Cost vs field and margin} \cite{[D. Schoerling]}
\end{itemize}
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%

- **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?)

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FCC cell [D. Schulte, B. Dalena]
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$_3$Sn
  - This is also why I insisted so much on grading
- With Nb$_3$Sn 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
  \[ G_{l_q} = \frac{\sqrt{2}B\rho}{L} \quad \text{for 90 degrees cell} \quad G_{l_q} = \frac{B\rho}{L} \quad \text{for 60 degrees cell} \]
- 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
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$_3$Sn
  - With Nb$_3$Sn 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/m² (0.11 m long)
    - One can make much larger gradient as in the lattice sextupole 4430 T/m²
  - 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
  - We can correct up to $\pm 6$ 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 in the LHC today (56 mm aperture)

- Nb-Ti ribbon technology
  - Gradient $63 \times 10^3 \text{ T/m}^3$ (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 $220 \times 10^3 \text{ T/m}^3$

FCC request: factor 3 to 6 larger than in the LHC [V. Kornilov talk, this conference]

- Factor 3 can be obtained with the $220 \times 10^3 \text{ T/m}^3$ 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

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FCC main dipole field quality version 0 - 28 May 2015
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)

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Systematic
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]
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$_3$Sn models 11 T and QXF: $l_{cm} - L_m \approx 950$ mm

- Very different design, aperture but similar values
- Plus 400 mm for interconnections, makes 1.35 m

Challenging but reasonable
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/m²
  - But 2.2 m longer in the worse case
- MO at $220 \times 10^3$ T/m³

There is still some space free – some meters could be recovered?

- 3 m between MQT and MB, 1 m between MQ and MS
CONCLUSION

- Orbit correctors can be critical if 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 (Nb₃Sn, 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