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DESIGN ISSUES IN A 130 MM APERTURE TRIPLET

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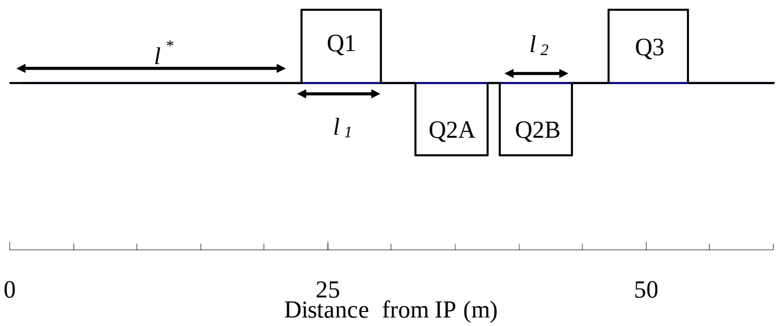
CONTENTS

- Motivations for a 130 mm aperture triplet
- 130 mm aperture quadrupoles in Nb-Ti
- 130 mm aperture quadrupoles in Nb_3Sn
- Conclusions

MOTIVATIONS FOR A 130 MM APERTURE

- Proposed LHC triplet lay-out for getting β^*=0.25 (the "symmetric" solution, LHC Project Report 1000)
  - A stretched version of the present lay-out
  - The same aperture and cross-section in Q1-Q3
    - To minimize cost of model, prototypes and spares, maximize interchangeability
  - Different lengths of Q1-Q3 and Q2 but the same current
    - To minimize cost of power supply, simplify powering schemes
  - We require β^*=0.25 m and additional aperture for collimation
  - We end up with
    - A=130 mm
    - G~125 T/m
    - L(Q1)=L(Q3)=9.2 m
    - L(Q2) =7.8 m
    - Total triplet length 35 m
      - with gaps, 40 m



Motivations for a 130 mm aperture

- The study presented in LHC PR 1000 presents a parametric study of solutions having [E. Todesco, J. P. Koutchouk, CARE workshop Valencia06]
  - Triplet length from 25 to 40 m
  - Triplet aperture from 90 to 150 mm

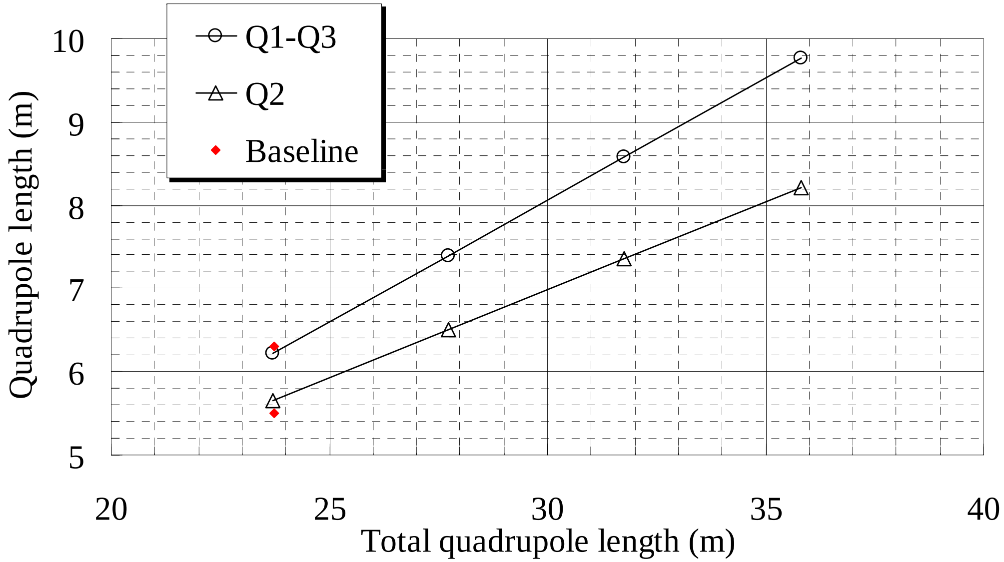
- Main features of the semi-analytical approach
  - It is not a simple scaling
  - It is not a simplified analytical model of the optics
  - Triplet optics from IP to Q4 is exact, approximate matching is done
  - Four cases are computed, and then results are fit
  - Obtained solutions proved to be rather close to exactly matched solutions with MAD [R. De Maria, LIUWG meeting, October 2007]

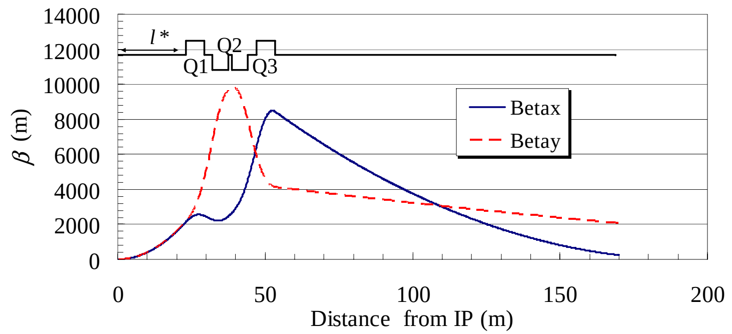
  - A completely analytical approach on simplified model has been recently developed [R. De Maria, *Phys. Rev. STAB* **10** (2007)]

Motivations for a 130 mm aperture

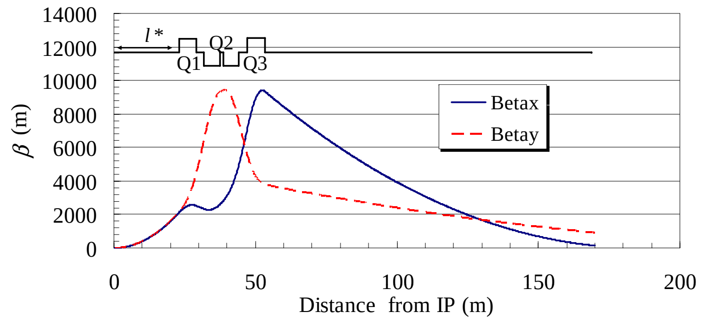
- How to fix the relative lengths of Q1-Q3 and Q2
  - For each total quadrupole length there is a combination of lengths that gives equal beta function in the two planes
  - We compute four cases, and then we fit

[E. Todesco, J. P. Koutchouk, Valencia06]





Nominal triplet l1=5.50 m l2=6.37 m

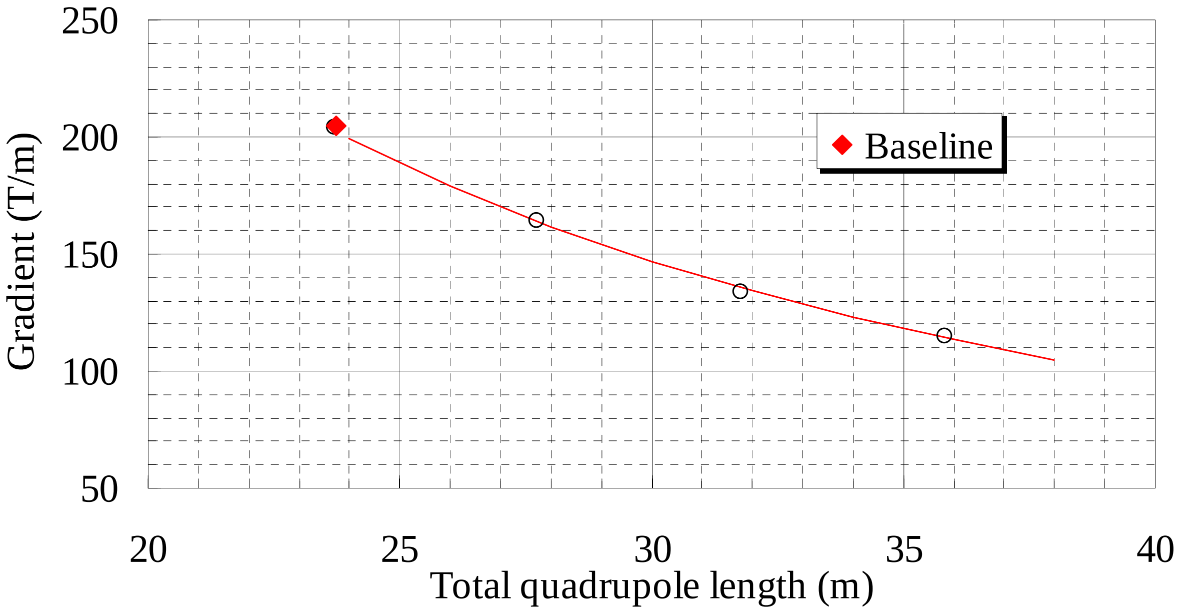


Triplet l1=5.64 m l2=6.22 m

MOTIVATIONS FOR A 130 MM APERTURE

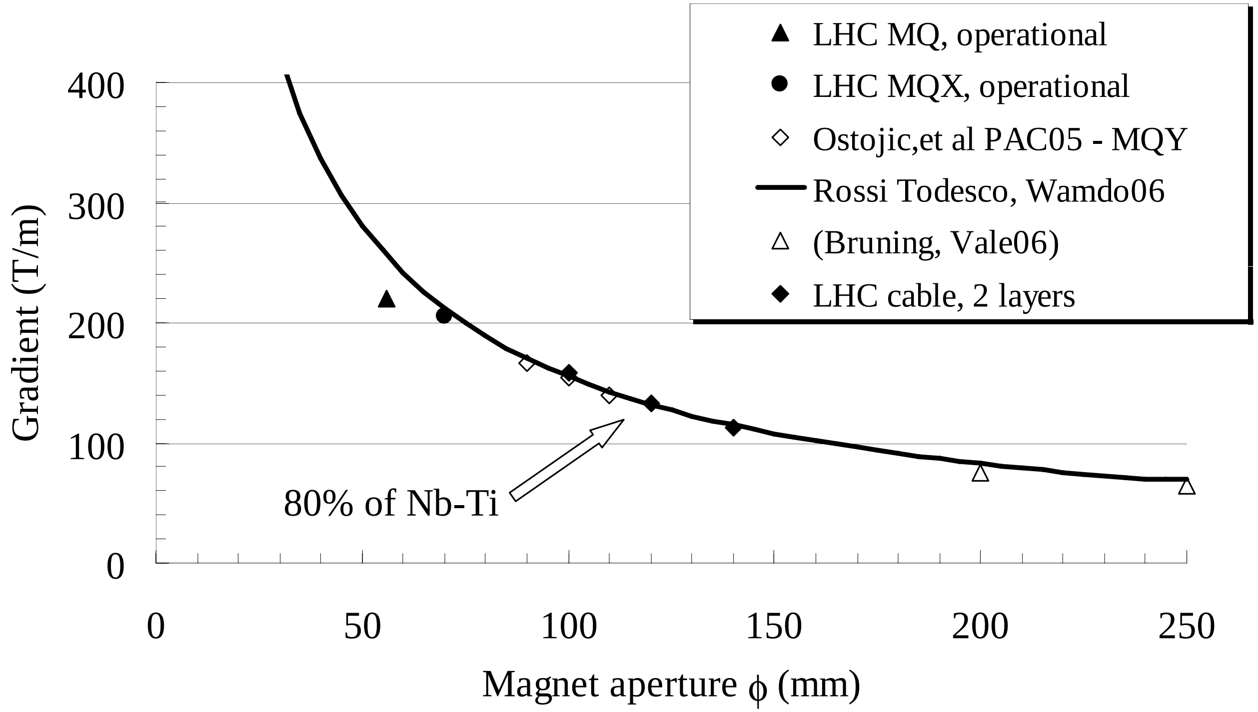
- How to fix the gradient
  - This depends on matching conditions
  - We require to have in Q4 "similar" beta functions to the nominal
  - We find an empirical fit of the four cases

$$G = \frac{1}{f l_q^{\,2} + h l_q}$$



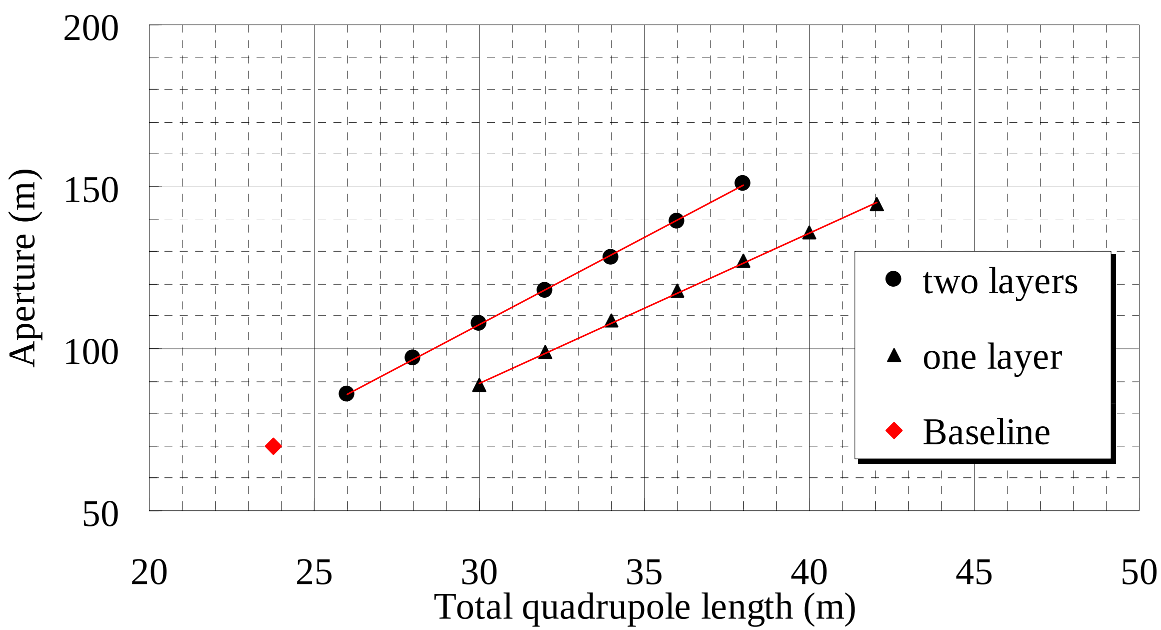
MOTIVATIONS FOR A 130 MM APERTURE

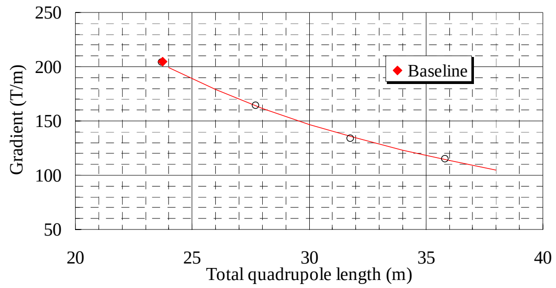
- What a Nb-Ti quadrupole can give as gradient vs aperture
  - We computed three lay-outs with 2 layers of the LHC MB cable, of apertures 100, 120, 140 mm – agreement with the semi-analytical formula [L. Rossi, E. Todesco, *Phys. Rev. STAB* **9** (2006) 102401]

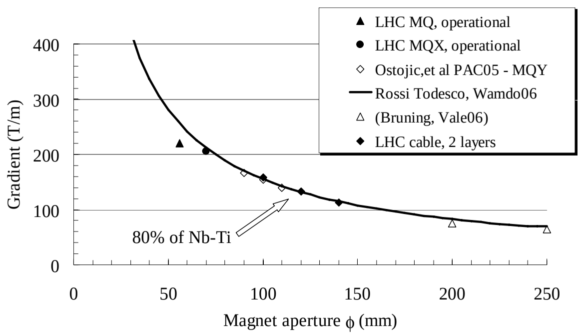


MOTIVATIONS FOR A 130 MM APERTURE

- We can now have aperture vs quadrupole length
  - With two layers Nb-Ti we can build focusing triplet of 30 m, 110 mm aperture – or 34 m, 130 mm aperture







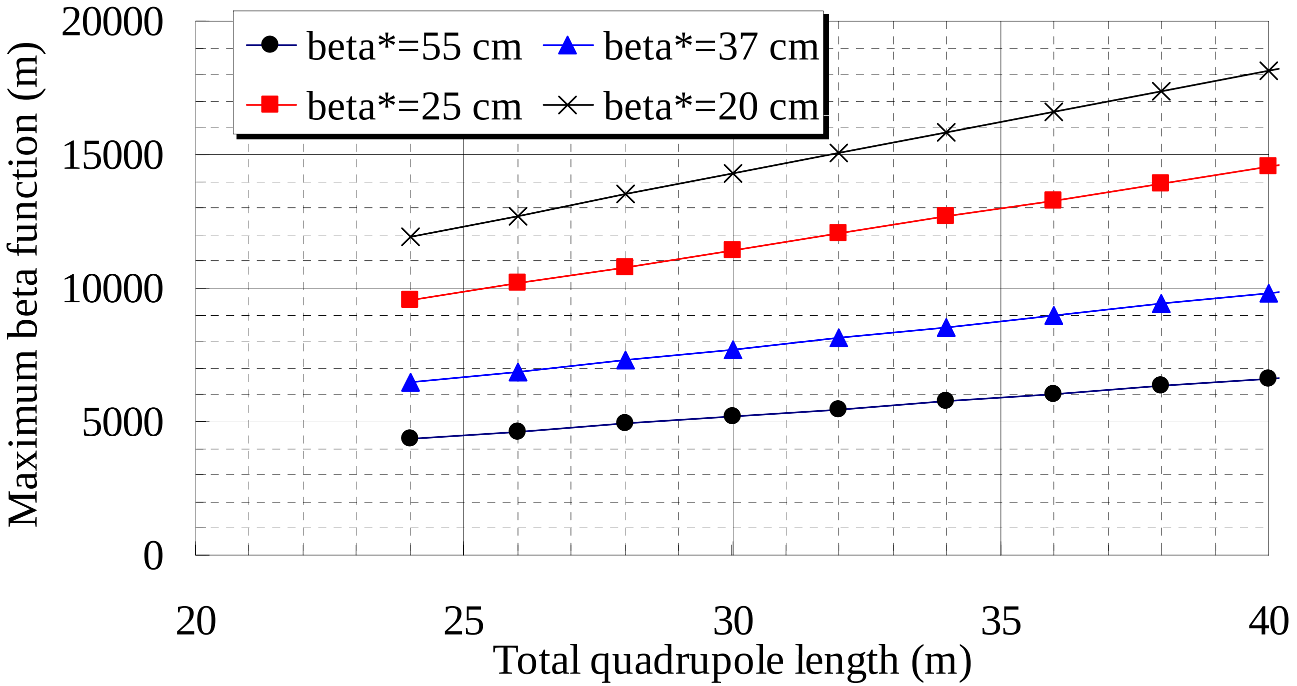
MOTIVATIONS FOR A 130 MM APERTURE

- Longer triplet will give larger beta functions !
  - Larger, but not terribly larger … we find a fit as

$$\beta_{max} = \frac{l^{*2} + a l_q}{\beta^*}$$

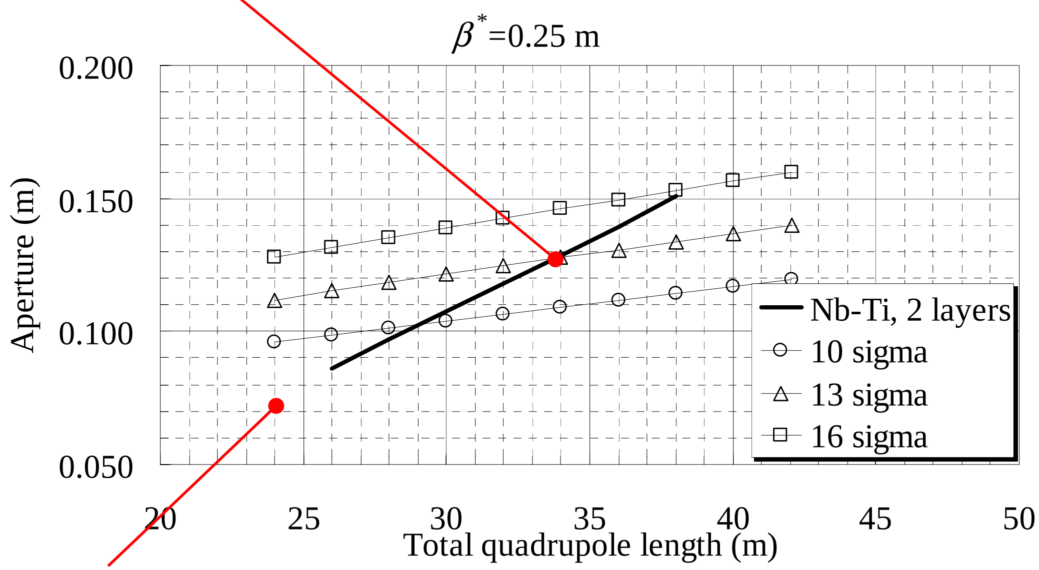
a~77.5 m (where β^* is the beta in the IP)

[E. Todesco, J. P. Koutchouk, Valencia06]



Motivations for a 130 mm aperture

- β^*, β_{max} and the triplet length determine the aperture needs
  - 10 σ: the nominal $\phi = \phi_0 + \chi\phi_1\sqrt{\beta_{\max}} + \phi_2 \frac{l^* + l_t}{\sqrt{\beta^*}} + \phi_3 \frac{(l^* + l_t)^{3/2}}{\sqrt{\beta^*}} \sqrt{N_b k_b}$
  - 13 σ: reduces the collimator impedance, and allowing a nominal beam intensity [E. Metral, et al., PAC07, R.W. Assman LIUWG October 2007]
  - We chose 130 mm aperture quadrupole, giving a triplet length of 34 m (without gaps)



  - This is our baseline today

CONTENTS

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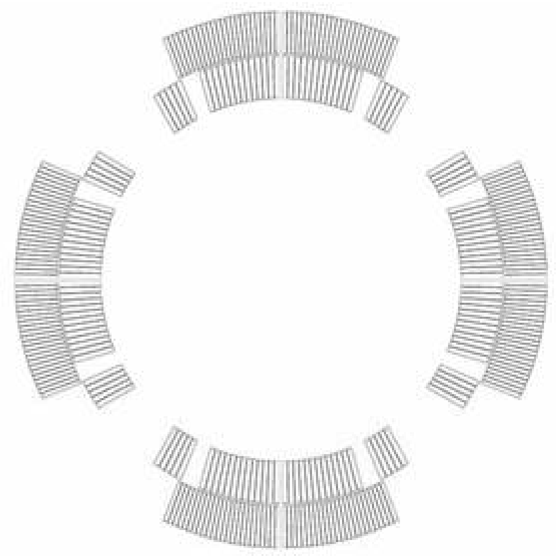
130 mm Nb-Ti Quadrupole

- MQXC: operational gradient of 124 T/m
  - 20% operational margin
- Operational current 12.5 kA
- Coil: two layers, with grading (27%), using the LHC MB inner and outer layer respectively
- Peak field 8.4 T (in between MQXA and MQXB)
  - Cable needed to wind one dipole unit length is enough

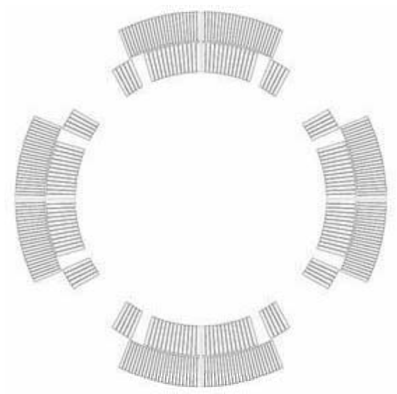
		Inner layer		Outer layer	
	length (m)	n turns (per pole)	pole length (m)	n turns (per pole)	length (m)
MQXC	9.2	18	331	26	478
MQXC	7.8	18	281	26	406
MB	14.3	15	429	25	715



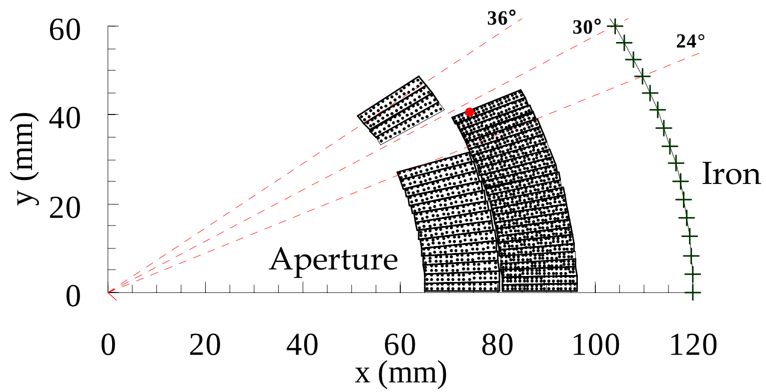
130 mm aperture coil lay-out

130 mm Nb-Ti quadrupoles – field quality

- Field quality is critical at nominal field – optimization includes iron saturation, persistent currents not an issue
- Coil design based on:
  - Inner layer: two blocks with [24°,30°,36°] lay-out – this kills b_6 b_{10}
  - Outer layer: one block at 60° - this kills b_6 (b_{10} not affected by outer layer)
- Design multipoles at high field lower than 1 unit
  - A first iteration will be needed to fine tune field quality
  - Mid-plane shims of 0.375 mm thickness are included in the design, so that it can be varied in both directions for fine tuning



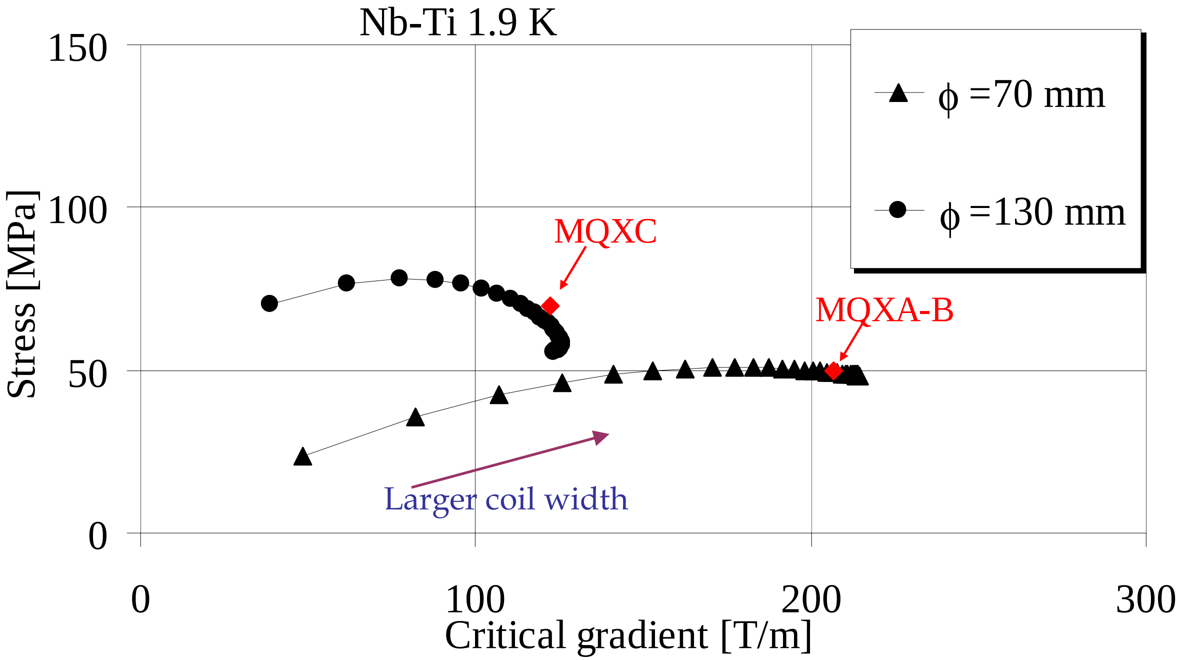
130 mm aperture coil lay-out



130 mm aperture coil lay-out, details of one eight

130 mm Nb-Ti Quadrupoles – Forces

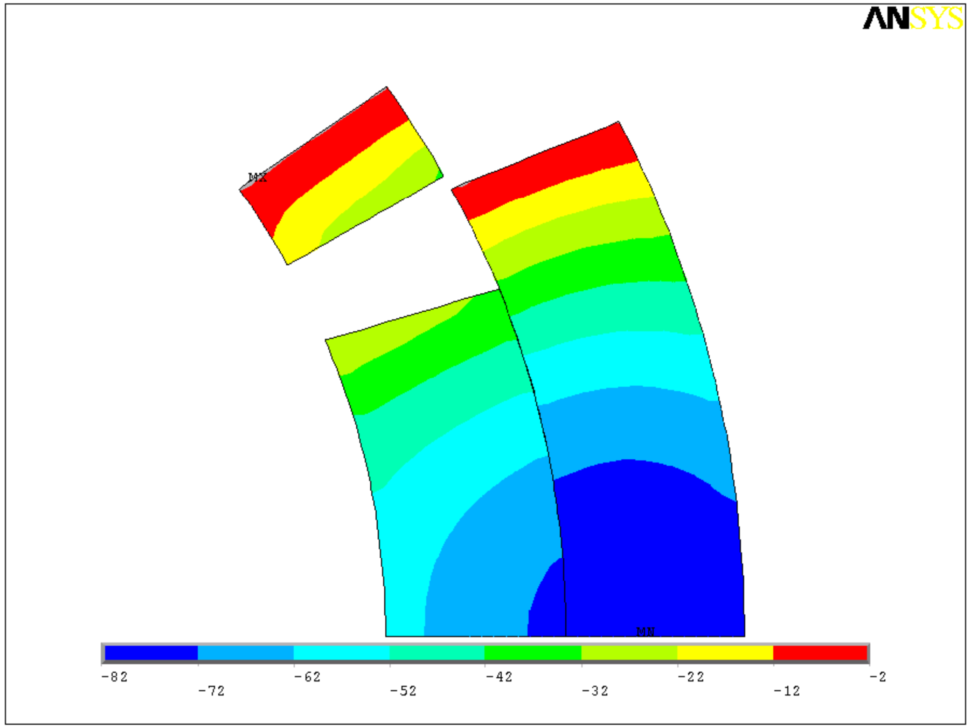
- According to analytical model [P. Fessia, F. Regis, E. Todesco, ASC06]
  - Lorentz forces induce a stress in the coil of 70 MPa, i.e. 40% more than for the MQXA-B (50 MPa)
  - Does not look so critical, but mechanical structure should be carefully designed



Stress versus gradient for quads with 70 mm and 130 mm aperture, scan over the coil width
20% operational margin on Nb-Ti short sample limit

130 mm Nb-Ti quadrupoles – forces

- Cross-check with computations using FEM model
  - MQXC: ~80 MPa
  - MQXA: ~ 70 MPa, MQXB: ~ 50 MPA



Stress in the coil due to e.m. forces in infinitely rigid structure evaluated with FEM

130 mm Nb-Ti Quadrupoles – Protection

- This MQXC is longer and larger than the previous ones
  - Inductance similar to MQY, MB, MQXA
  - Operating current similar to MB, MQ, MQXB
  - Stored energy is ~5 MJ: twice than MQXA, and 50% larger than one aperture of an MB

  - Preliminary hot spot temperature evaluations show that the order of magnitudes are similar to the MB
    - Time for firing quench heaters to avoid hot spot larger than 300 K must be not larger than 0.1 s [M. Sorbi, Qlasa code] challenging, but feasible

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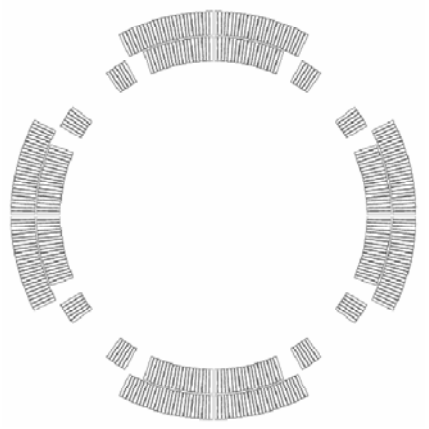
130 mm Nb_3Sn Quadrupoles - General

- Main hypothesis
  - We consider the possibility of substituting the Nb-Ti 130 mm aperture magnets with 130 mm aperture Nb_3Sn quadrupoles [proposal by L. Rossi, LARP collaboration meeting, October 2007]

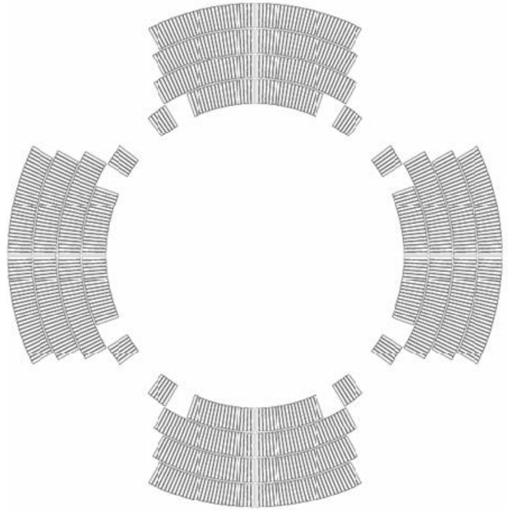
  - Constraints
    - Same powering current of Nb-Ti (12.5 kA)
    - Having a safe operational margin
    - Having a reasonable level of forces
    - Providing at least the same level of gradient
    - Satisfy the optics requirements

130 mm Nb_3Sn quadrupoles - design

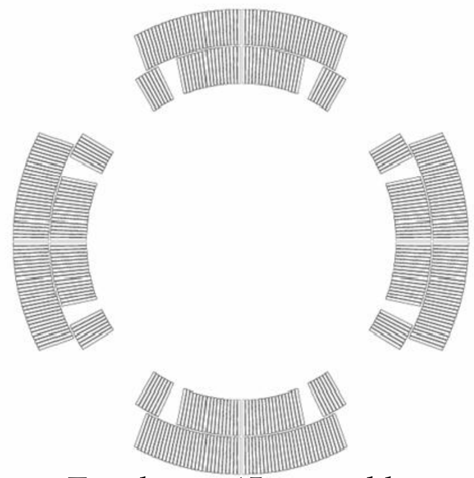
- We considered 3 designs, based on LARP strand
  - 2-4 layers with the present 10 mm width LARP cable (~TQ)
  - 2 layers with a 15 mm width cable, same strand of 0.7 mm diameter
  - Assuming 3000 A/mm^2 at 12 T, 4.2 K, 20% operational margin



Two layers 10 mm cable:
G_{ss}=183 T/m
G_{op}=147 T/m and I_{op}=11.0 kA



Four layers 10 mm cable:
G_{ss}=216 T/m
G_{op}=173 T/m and I_{op}=7.6 kA

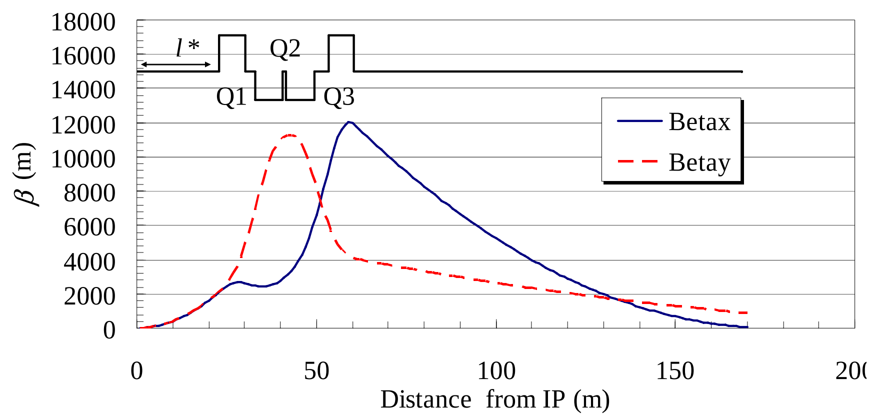


Two layers 15 mm cable:
G_{ss}=200 T/m
G_{op}=160 T/m and I_{op}=13.1 kA

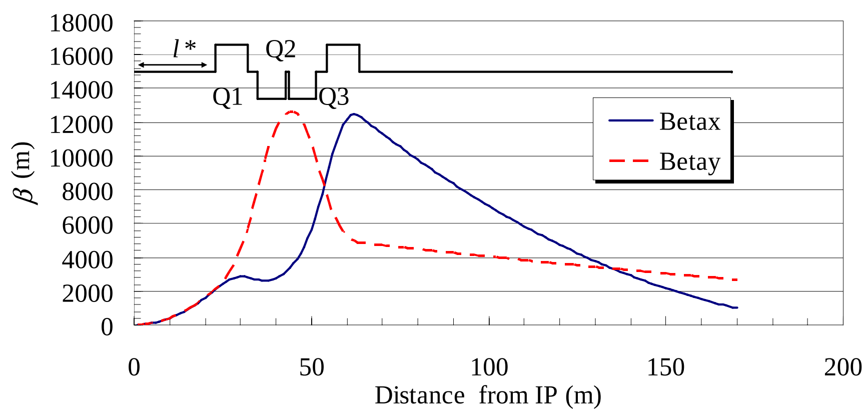
- The 15 mm cable is the only one that can bear the 12.5 kA current

Sketch of a mixed triplet for the upgrade

- Same lay-out as for the Nb-Ti triplet, but Q1-Q3 replaced by Nb_3Sn quadrupoles 7.2 m long
  - Operating at 160 T/m, at 20% margin, in series with Q2a-Q2b,
  - Q2 in the same position and with the same lengths in the "Nb-Ti only" lay-out
    - Small trim on the current (4% larger) than in the Nb-Ti only option
    - a small gain in the maximal beta function (~5%)



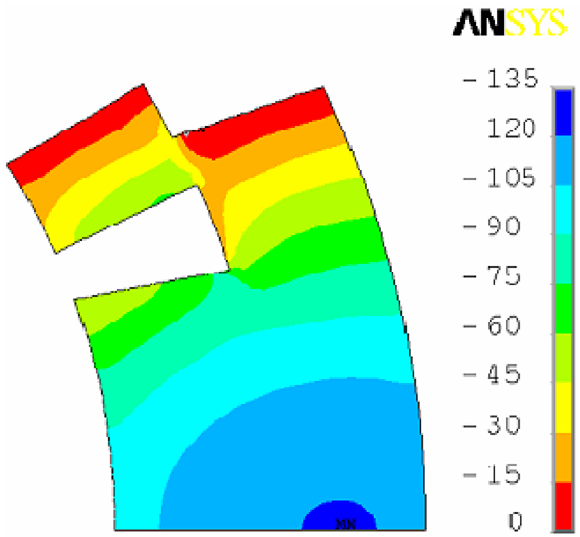
Optical functions in the sketch of a lay-out with Nb_3Sn (Q1,Q3) and Nb-Ti (Q2) quadrupoles



Optical functions in the sketch of a lay-out with Nb-Ti only quadrupoles

130 mm Nb_3Sn quadrupoles - forces

- At operational values (20% margin from short sample) peak stress due to e.m. forces is large (120 MPa), but within 150 MPa
  - with a model in an infinitely rigid structure – more analysis should be done with the real structure
    - 2 layers 15 mm has ~10% less stress than the 10 mm cable designs



Stress due to e.m. forces evaluated with ANSYS, infinitely rigid structure

130 MM Nb_3Sn QUADRUPOLES

- Please note that at short sample the stress is $(25\%)^2$=56% larger
  - The magnet can go up to ~200 MPa
  - It cannot be powered at the short sample !!
    - It could be a nice destructive test to find out the stress (strain) limits in Nb_3Sn in a short model

- Temperature margin
  - With the mixed lay-out, Nb_3Sn has 4.7 K temperature margin with respect to 2.1 of Nb-Ti

CONCLUSIONS

- We outlined the motivations to go for a 130 mm aperture in a Nb-Ti LHC triplet
  - β^*=0.25 m with 3 σ clearance for collimation

- We discussed a conceptual design of the Nb-Ti magnet
  - Field quality, stresses, protection

- We considered the possibility of replacing Q1-Q3 with Nb_3Sn magnets
  - Not possible with the present 10 mm cable
  - With 15 mm cable could be viable, with margin and stresses within limits
  - Optics seems viable, should be validated by exact matching
  - It would give a more than a factor 2 in temperature margin (and would be the first test of Nb_3Sn in operational conditions)