LHC upgrade possibilities based on Nb-Ti technology

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Plan

- Introduction
- Layout and scaling to lower beta
- Magnet designs
- A hybrid Nb-Ti / Nb_3Sn approach
- Roadmap
- Conclusion

Acknowledgment

This presentation is squarely based on discussions with **Ranko Ostojic**, who is presently responsible for the insertion magnet systems at the LHC.

Also see PAC paper

R. Ostojic, N. Catalan Lasheras, G. Kirby, S. Russenschuck, "Low-b quadrupole designs for the LHC luminosity upgrade," Proc. 2005 Part. Accel. Conf. (PAC'2005), Knoxville, pp 2795-7 (available via JACoW)

Introduction

- Why we are where we are
- What we have learnt from building LHC
- Why we should consider the use of Nb-Ti
- Insertions need more than the inner triplet

Why we are where we are …

- The decision to take 70 mm as diameter for the coil aperture was based on
  - 200 μrad crossing angle
  - No beam screen
- The doubling of the crossing angle and the introduction of the beam screen led to the aperture becoming critical, and the need to increase the nominal β^* from 0.5 to 0.55 m

The coil aperture is a critical parameter

- The aperture of 70 mm figures in the "Yellow Book" (1995, nominal β*= 0.50 m, ultimate 0.25 m)
  - Long-range beam-beam effect $\rightarrow$ increase crossing angle by factor of 2
  - Electron-cloud instability $\rightarrow$ introduce beam screens
- Upgrade target remains a β* of 0.25 m (irrespective of magnet technology)
  - Piwinski parameter $\rightarrow$ luminosity increases by factor ~1.5
- Higher luminosity $\rightarrow$ greater cryogenic load
  - Impacts on choice of aperture and magnet design

Lessons learnt from building LHC

- Present low-β quadrupole design is state-of-the-art for gradient x aperture with Nb-Ti
- Field quality is better than expected
  - Probably don't need correctors for $\beta^* > 0.6$ m
- Long magnets are possible
  - Series-built 15 m dipoles, 6 m quadrupoles
- There is expertise and equipment for building small series of long magnets at CERN

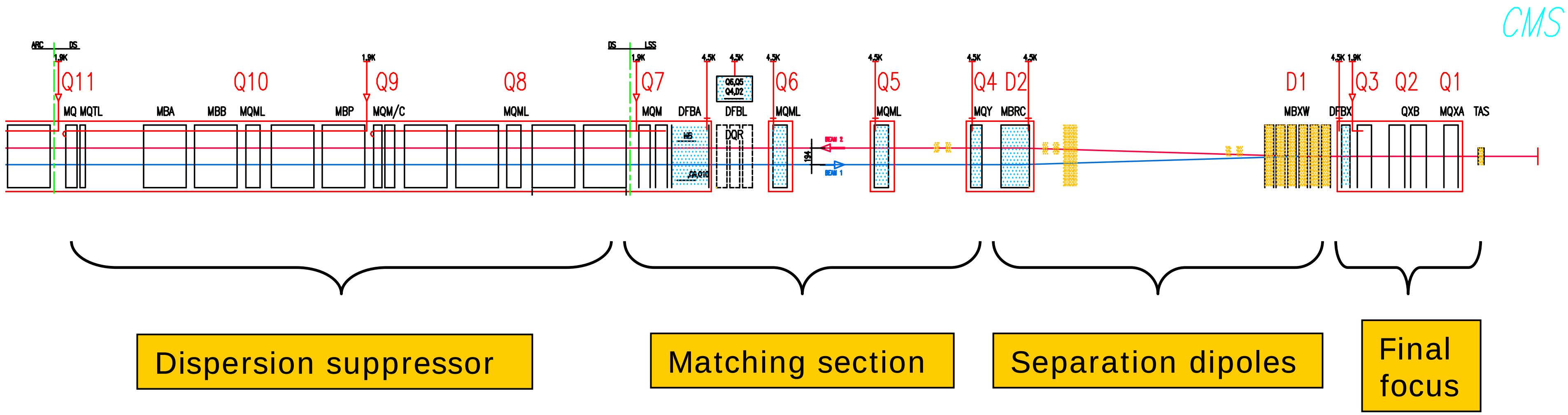
Why we should consider using Nb-Ti

- Can apply well-known technology
  - The somewhat longer and larger quadrupoles than usual are a relatively small extrapolation
- The use of Nb_3Sn (or Nb_3Al) in magnets for accelerators has yet to be demonstrated
  - This is work-in-progress that we hope pays off …
- The present day state-of-the-art is for Nb-Ti
  - If we had to build magnets today $\rightarrow$ only Nb-Ti
  - Experience needed before reliance on Nb_3Sn

Insertions are not only inner triplets

- The upgrade of the insertions will include intervention on, or modification of, the
  - Matching sections
  - Beam separation equipment
- This is not trivial !
  - Will require studies, tests (+ people)
  - Will require new separation dipoles
  - May require other new magnets

LHC insertion magnet system



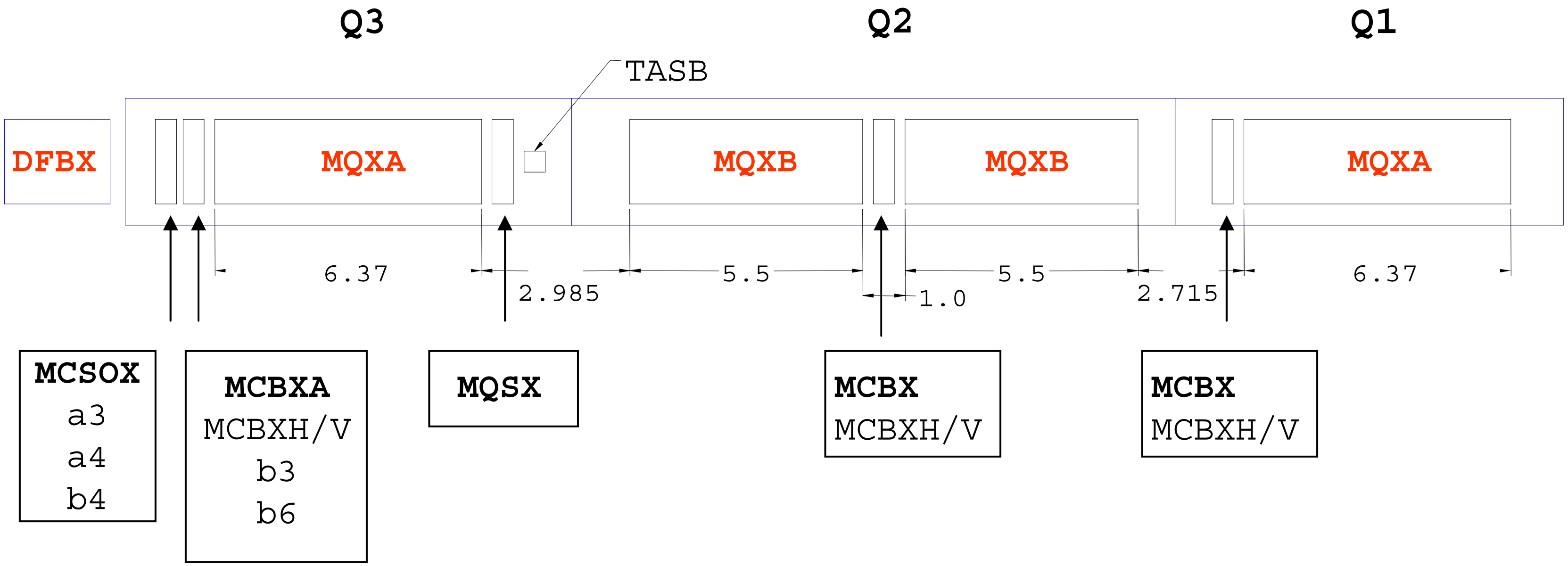
154 superconducting magnets:

- 102 quadrupoles cooled at 1.9 K, with gradients of 200 T/m
- 52 dipoles and quadrupoles cooled at 4.5 K, with fields of 4 T and gradients of 160 T/m

Layout and scaling to lower beta

- Triplet layout is similar to the present one
- Aperture according to latest definition
- « Quality factor » used is the ratio β_{peak}/β^*
- Layouts are indicative – not yet optimized

The present LHC low-β triplet



LHC low-β triplets

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Limits of present LHC triplets

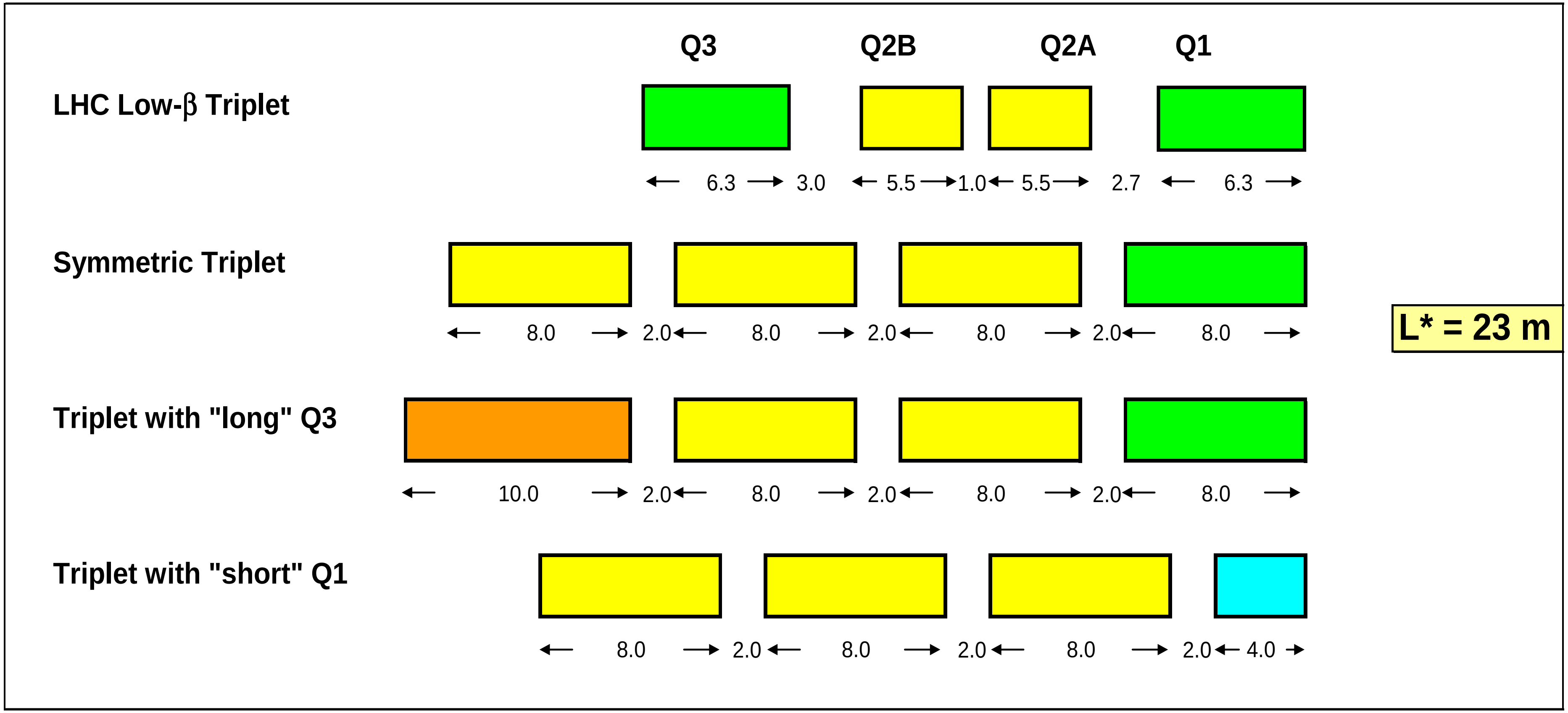
- Aperture

  70 mm coil

  63 mm beam tube

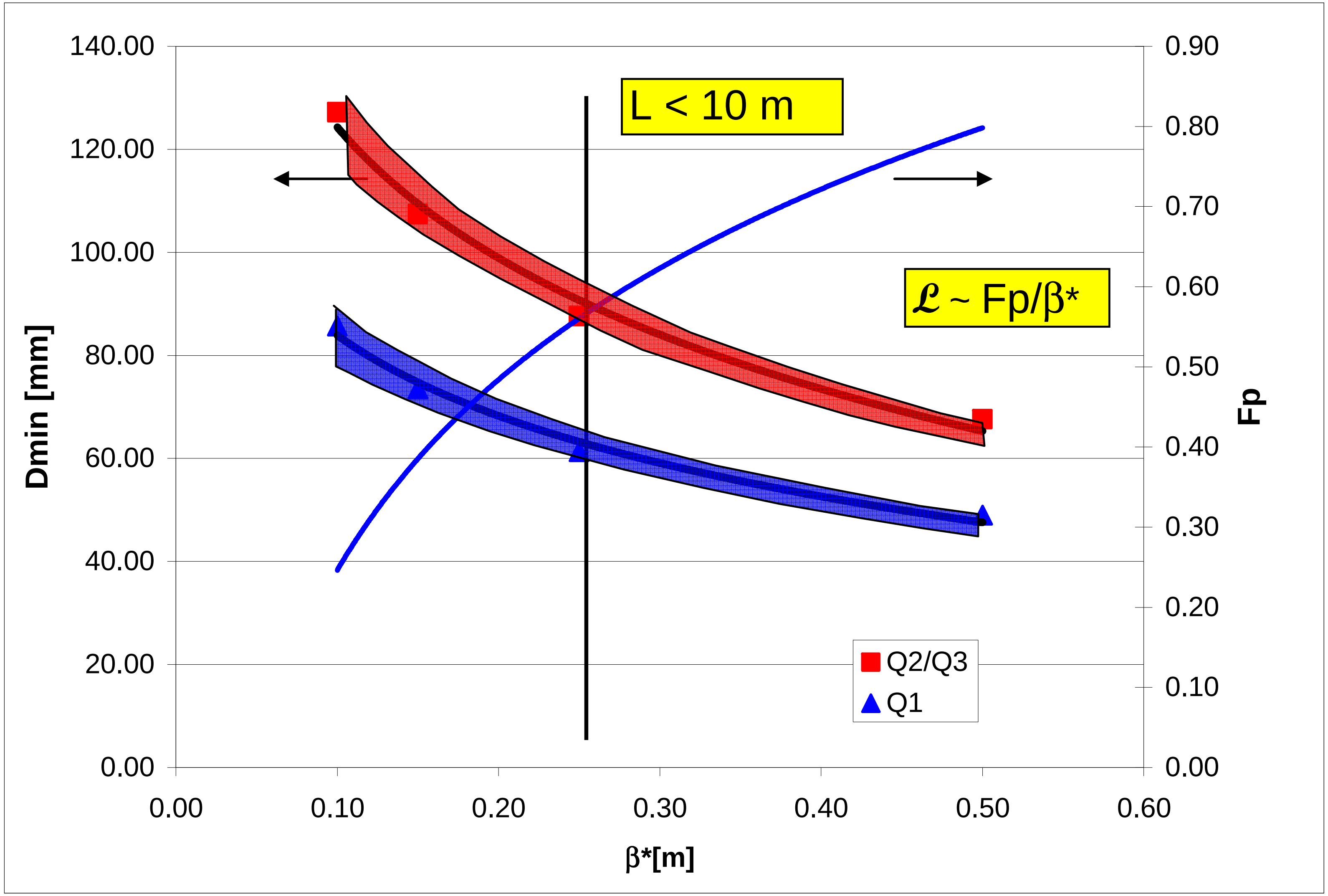
  60 mm beam screen → **β*** = 0.55 m
- Gradient
  - 215 T/m → operational 205 T/m
- Field quality
  - Excellent, no need for correctors down to β* ~ 0.6 m
- Peak power density
  - 12 mW/cm^3 → $\mathcal{L}$ = 3 10^{34}
- Total cooling power
  - 420 W at 1.9 K → $\mathcal{L}$ = 3 10^{34}

Example quadrupole-first layouts



The aperture and length of the quadrupoles can be optimized according to their position in the triplet

Coil aperture and β*



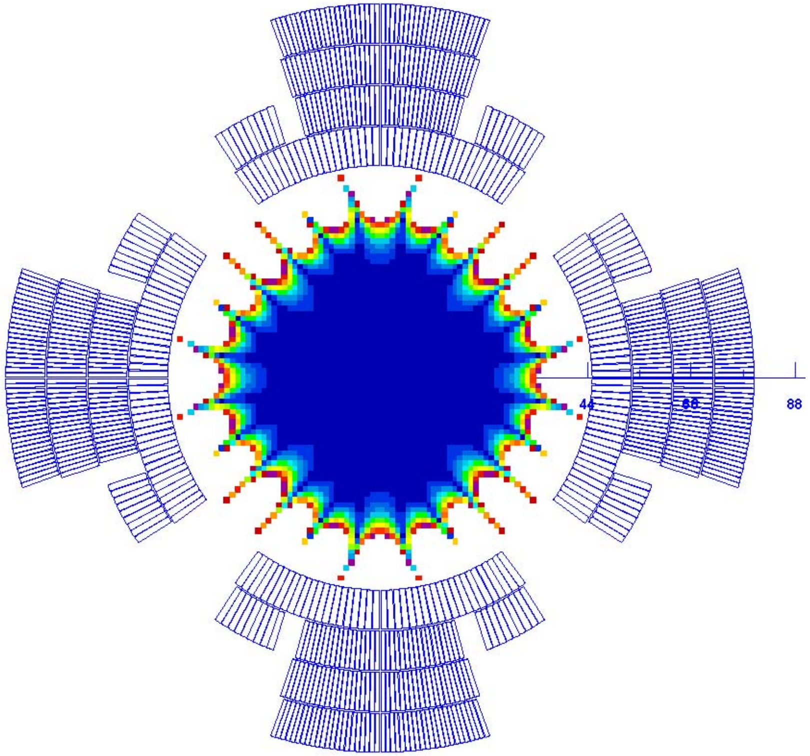
Use of aperture

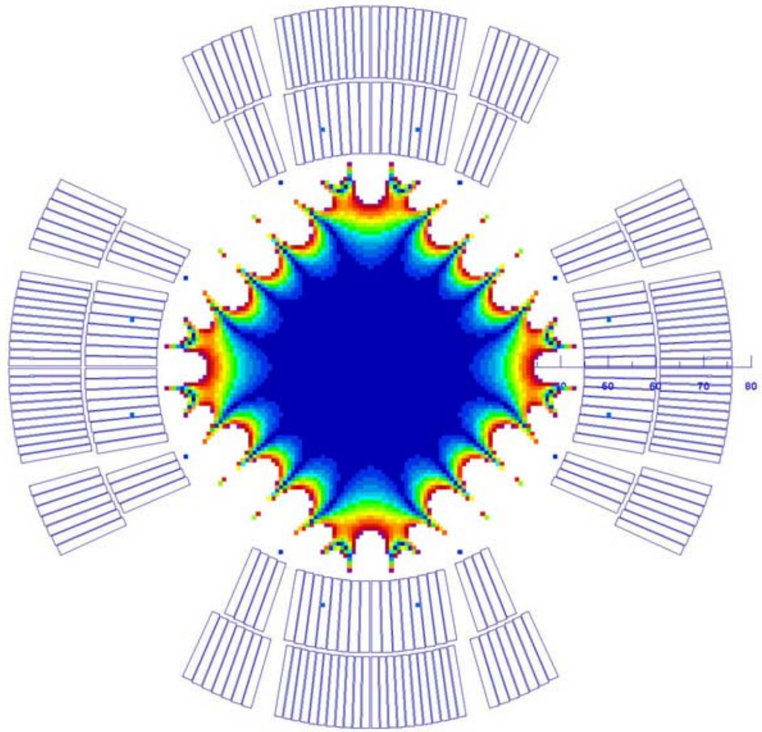
- Increase the aperture to reduce heat loads (both peak and total);
- Profit from better field quality to reduce the number of multipole correctors and introduce stronger orbit correctors;
- Decrease β^* to complement other ways of increasing luminosity.

Magnet designs

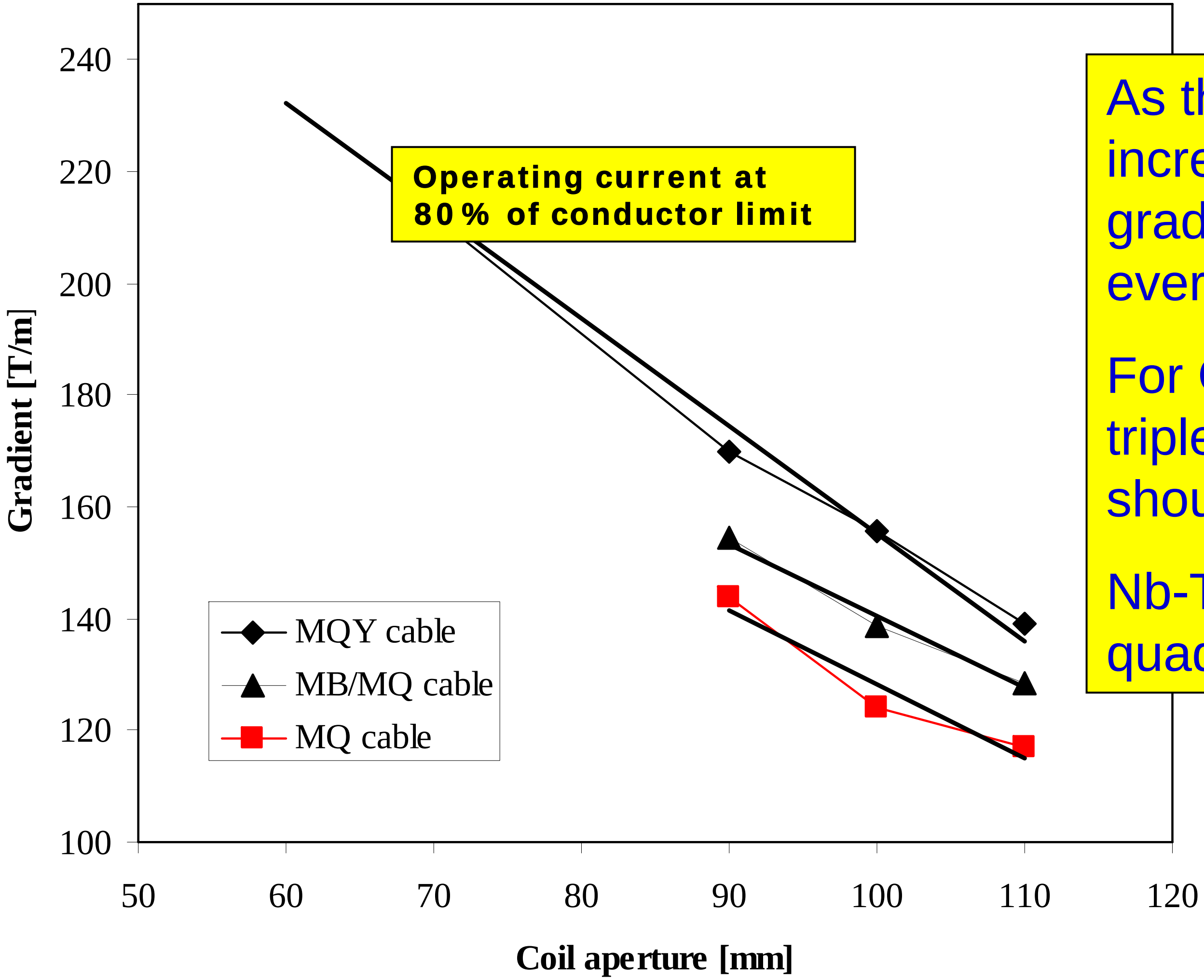
- There is experience with 2- and 4-layer coil designs that give good field quality
- Larger aperture => more efficient design
- Magnet protection is understood
- Probably don’t require multipole correctors
  - Could include stronger dipole correctors
- Outer transverse dimensions can be such that magnets fit into the present cross-section

Large aperture quadrupole coils based on existing LHC cables





Large aperture quadrupoles



As the quadrupole aperture increases, the operating gradient falls by 20 T/m for every 10 mm of coil aperture

For GL similar to the present triplet, quadrupole lengths should increase by 20-30%

Nb-Ti technology is proven for quadrupoles up to 12 m long

Hybrid Nb-Ti / Nb_3Sn approach

- Q1 is the key
  - Smaller β => requires smaller aperture
- Consider making Q1 using Nb_3Sn
  - Would be shorter than Nb-Ti version
  - Only four such magnets, 4 m long, to supply
- Short Q1 improves efficiency of insertion
  - Provides β_{peak}/β^* = that in present scheme !

Roadmap

- Evaluate interest in this approach
- Optimize the layouts (hybrid and full Nb-Ti)
- Identify R&D topics
- Investigate interfaces in tunnel
- Create planning + cost estimate
- …

Some R&D topics for Nb-Ti quads

Technology and manufacturing issues are well mastered. So main magnet parameters (aperture and length) can be fixed without extensive R&D. Therefore:

- Focus R&D on magnet transparency and cooling:
  - Cable and coil insulation
  - Thermal design of the collaring and yoking structures
  - Coupling to the heat exchanger

Further comments on Nb-Ti R&D

- LHC contains several types of Nb-Ti magnets. Extensive experience exists in building magnets of different aperture and length
- proposals for the upgrade should take into account the very limited availability of spare low-β triplets and separation dipoles. This is a serious concern. The shortest route to providing new magnets is via Nb-Ti technology
- While Nb-Ti (1.9K) technology has reached its limits for large series production with the LHC main dipoles, some improvements for small series are still possible.

Conclusion

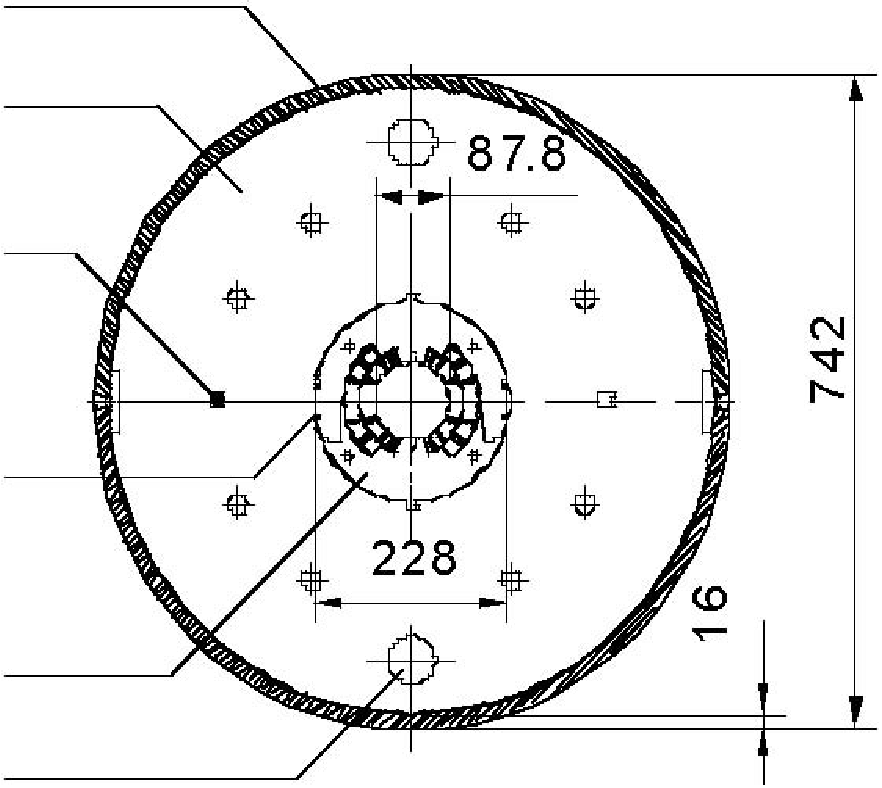
- **Development of accelerator quality Nb_3Sn magnets may take longer than expected**
- **There exists a viable route to lower β^* other than full replacement of inner triplet quadrupoles with magnets using Nb_3Sn**
- **A variant of the proposal using a single Nb_3Sn magnet per triplet could provide $\beta^* = 0.25$ m with β_{peak}/β^* = present value**

Some final comments

- It is clear that a new generation of magnets (Nb_3Sn, HTS,…) will be required at some future date for LHC upgrades. It is therefore absolutely vital to develop and demonstrate the feasibility of the new technology. *However*
- In the interest of LHC operation, we need an alternative; Nb-Ti technology can offer an intermediate solution
- The pitfalls in building Nb-Ti magnets should not be underestimated. It is not too early to start design studies
- Initial experience from operating the LHC with beam will be crucial for refining magnet parameters

Thank you for your attention

Best Nb-Ti magnet yet



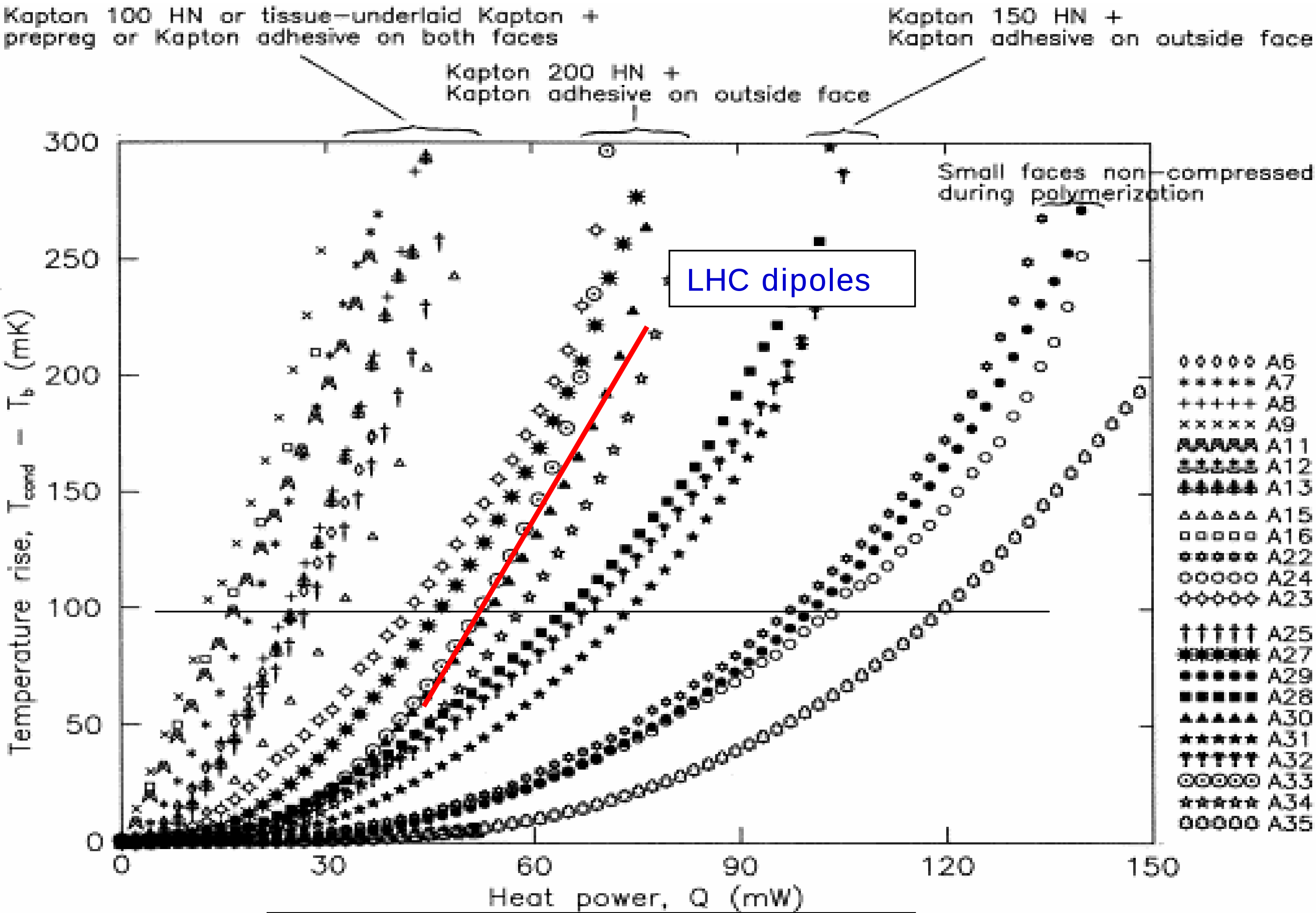
FRESCA, 10 T, 88 mm

D. Leroy et al., 1999

Characteristics of LHC cables

Cable parameters	MQY	MQ	MB
Width [mm]	8.3	15.10	15.10
Mid-thickness [mm]	0.84/ 1.28	1.48	1.90
Critical current, Ic [A] @ 9 T, 1.9K	5070/ 9110	12960	13750
dIc/dB [A/T]	1350/ 2550	3650	4800

Cable cooling



C. Meuris et al, 1999