Low Gradient Triplet Magnets

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with transparencies from Ranko Ostojic
CERN

- motivation:

-alternative solution to Nb_3Sn ➔ known magnet technology
➔ comparative studies
➔ shorter development time
➔ synergy with IR magnet
rescue facility

Low Gradient Triplet Magnets

- Introduction
  - general considerations
  - time scale and targets for upgrade scenarios
  - limits of the nominal LHC IR layout

- Layout from LUMI'05 and conclusions for future studies

- Optimization and study goals
  - large aperture
  - modular magnet design
  - minimize β-max inside triplet magnets

General Considerations for LHC IR Upgrade

- time scale: (POFPA June 2006)

➔ NbTi triplet magnet lifetime is estimated at 700 fb^{-1}

➔ time scale for LHC detector upgrade is estimated at 300 fb^{-1}

assuming $L = 10^{34}\ cm^{-2}sec^{-1}$ after 1 year; 200 d/y; 50% efficiency

➔ triplet magnets require upgrade after 9 years -> end 2016 run

➔ inner tracker requires upgrade after 4 years -> end 2011 run

➔ synchronize IR upgrade with other major construction interventions in the LHC (e.g. experiment upgrades)

➔ plan for an IR upgrade scenario in several phases

General Considerations for LHC IR Upgrade

- provide infrastructure for NbTi magnet repair / maintenance

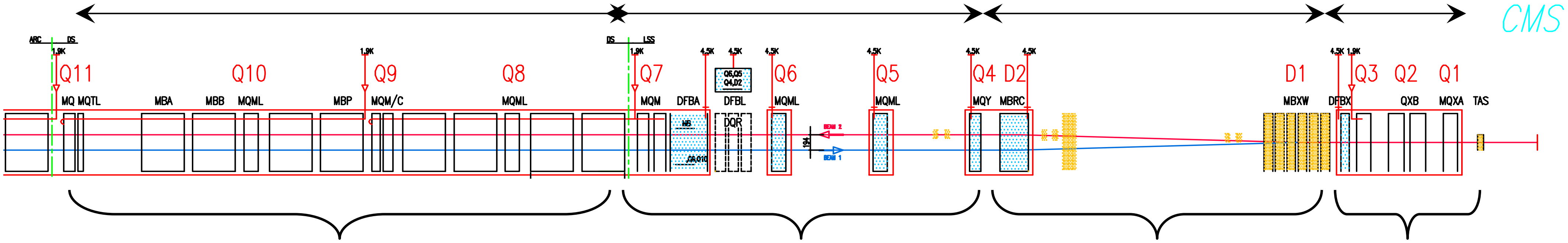
  ➔ LHC IR upgrade studies based on NbTi technology provide synergy with LHC magnet repair and consolidation efforts

- actual performance limits will only be identified with LHC operation: (aperture; heat load and quench limits; beam-beam; chromatic aberrations). Larger aperture will help in all cases but choice of implementation depends on type of problem:

  ➔ keep all technical options alive and prepare a staged upgrade scenarios

Introduction: the nominal LHC IR layout

ca. 170 m ca. 100 m ca. 100 m ca. 35 m



Dispersion suppressor

Matching section

Separation dipoles

Final focus

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

For the LHC upgrade studies we assume that MS; Separation dipoles and final focus system can be modified

Introduction: existing LHC magnet classes

1 MB – class (MB, MQ, MQM)

(8.5 T, Nb-Ti cable at 1.9 K; μ-channel polyimide insulation)

1b. MQX- class (MQXA, MQXB)

(8.5 T; Nb-Ti cable at 1.9 K; closed-channel polyimide insulation)

2. MQY- class (MQM, MQY)

(5 T; Nb-Ti cable at 4.5 K; μ-channel polyimide insulation)

3. RHIC – class (D1, D2, D3, D4)

(4 T; Nb-Ti cable at 4.5 K; closed-channel polyimide insulation)

4. MQTL – class (MQTL, MCBX and all correctors)

(3 T; Nb-Ti wire at 4.5 K; impregnated coil)

5. Normal conducting magnets (MBW, MBWX, MQW)

(1.4 T; normal conducting; impregnated coil)

Introduction: limits of nominal LHC IR magnets

- 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 → $\mathcal{L} = 3\ 10^{34}$

Ranko Ostojic
LTC May 2006

Introduction: upgrade options for LHC IR magnets

- The present matching quadrupoles are state-of-the-art Nb-Ti quadrupoles which operate at 4.5 K.
  - The upgrade of the matching sections should in the first place focus on modifying the cooling scheme and operating the magnets at 1.9 K.
  - In case larger apertures are required, new magnets could be built as extensions of existing designs.
- The 4 T-class separation dipoles should be replaced with higher field magnets cooled at 1.9 K.
- The MQTL-class should be replaced by magnets more resistant to high radiation environment.

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Introduction: general considerations

- Maintenance and repair of insertion magnets:
  - Large number of magnets of different type means limited number of spare magnets ready for exchange.
  - A facility is planned at CERN for repair/rebuild of matching section quadrupoles.

- Particular problem: low-beta quadrupoles and separation dipoles
  - Only one spare of each type (best magnets already in the LHC).
  - As of 2006, there will be no operating facility for repair and testing of these magnets.

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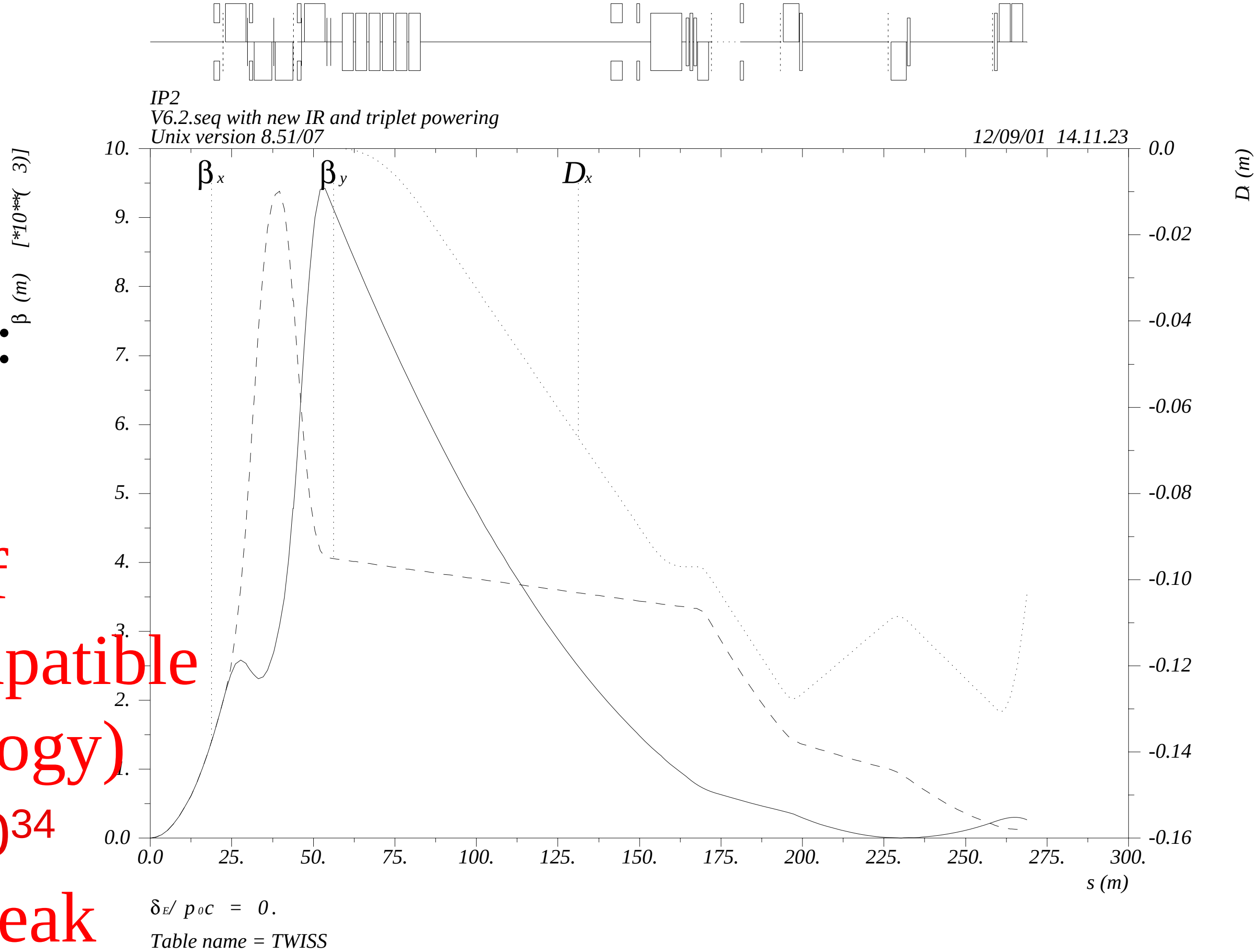
NbTi Magnet Techology: limitations

🟩 nominal layout:

$\beta^* = 0.25$ + x-ing
+ L^* of 23 m ➔
90 mm coil diameter:



➔ gradient of 215 T/m requires peak field of > 10 T at coil (incompatible with NbTi technology)

➔ heat load for ℒ = 3 10^{34} exceeds acceptable peak power density for nominal magnet design ➔ no simple scaling

NbTi Magnet Techology: Strong Points

- Technology and manufacturing issues are well mastered.
- Relatively easy extension of main magnet parameters (aperture and length) without extensive R&D.
- Focus R&D on magnet "transparency":
  - ❑ Cable and coil insulation
  - ❑ Thermal design of the collaring and yoking structures
  - ❑ Coupling to the heat exchanger

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NbTi Magnet Techology: Potentials

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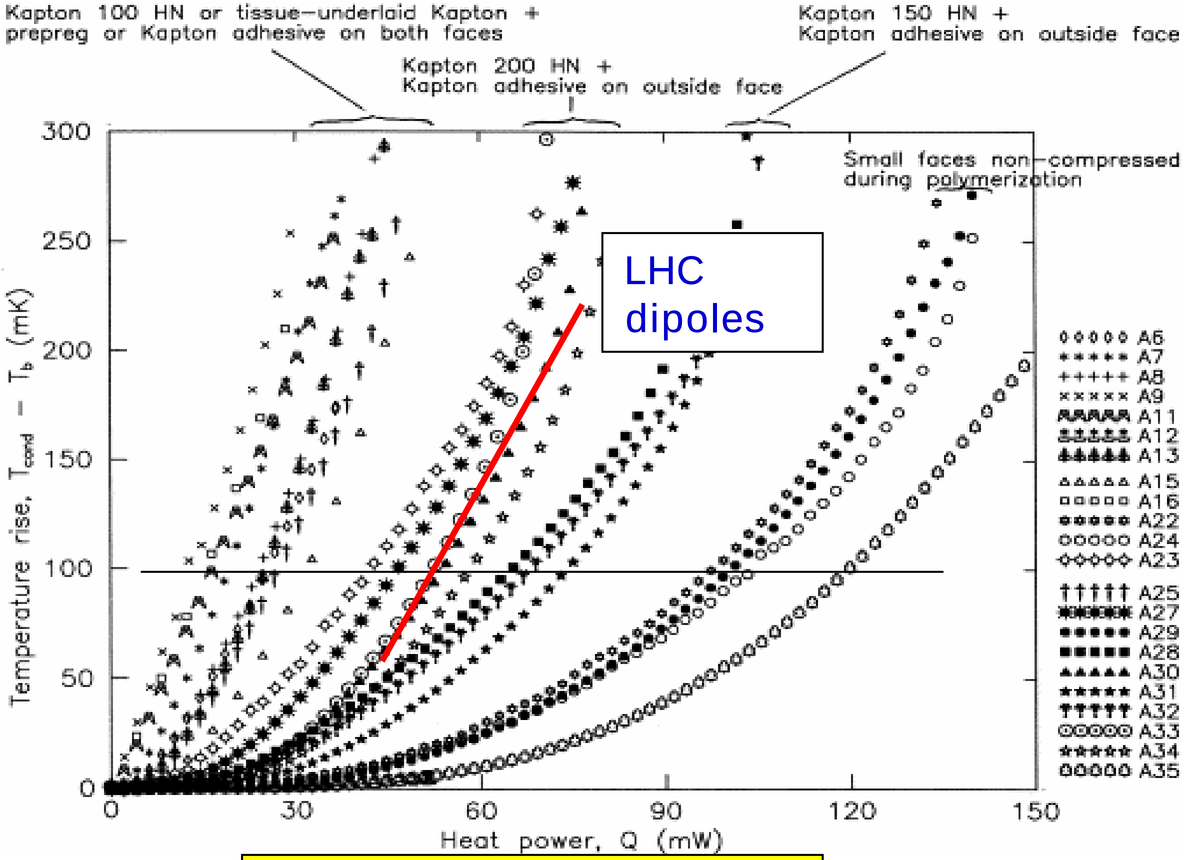
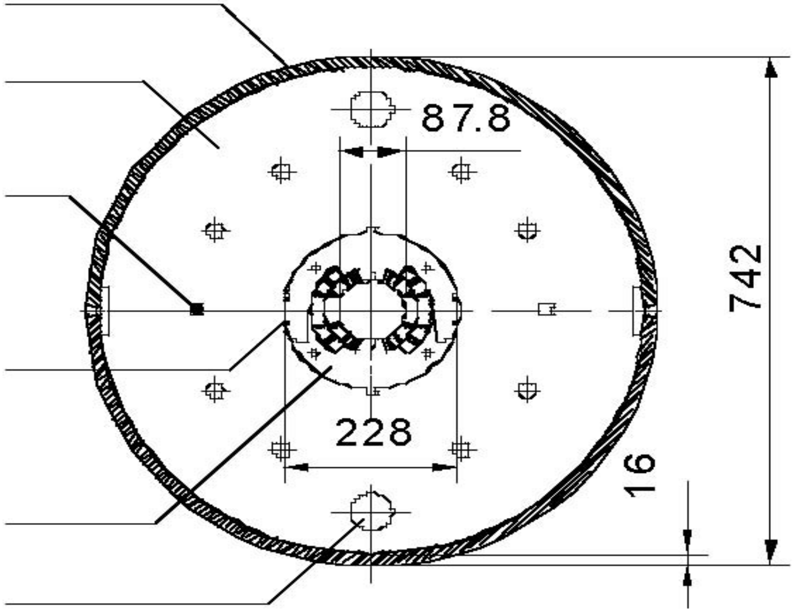
Potential improvements in acceptable power density:



LHC dipoles

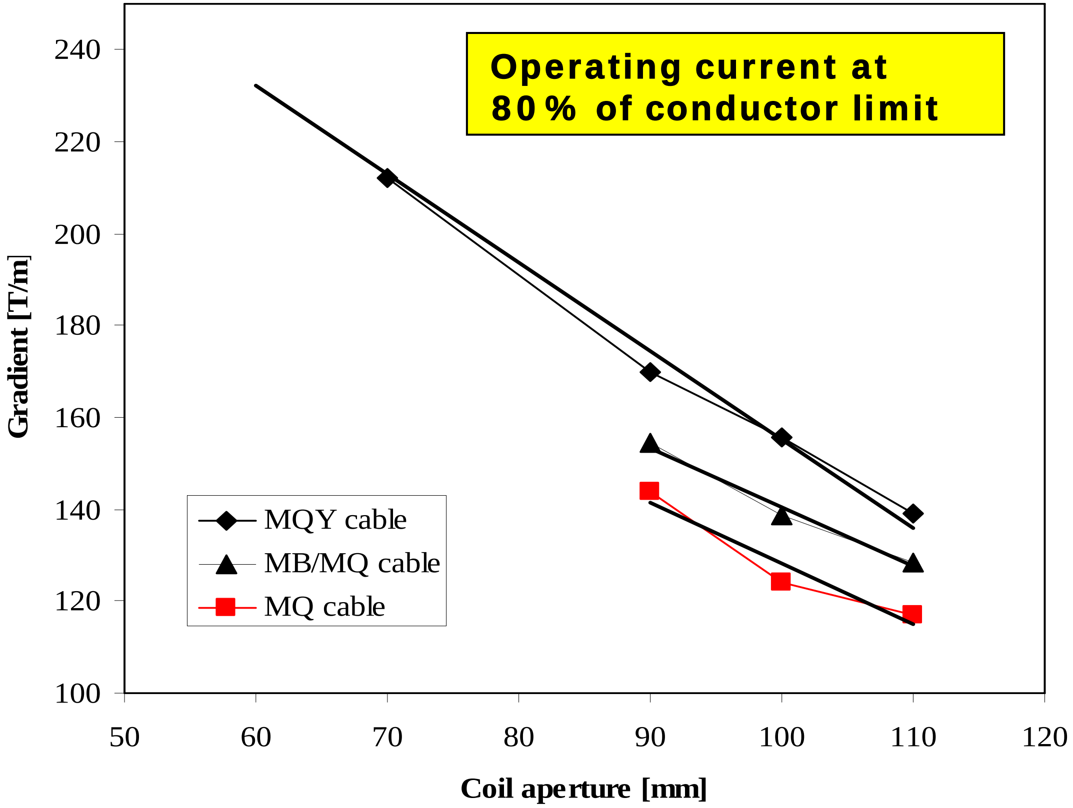
C. Meuris et al, 1999

Potential improvements in peak coil field:



FRESCA, 10 T, 88 mm
D. Leroy et al., 1999

NbTi Magnet Techology: Projected Performance Levels



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

To get a GL similar to the present triplet, quadrupole lengths need to be increased by 20-30%.

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

➔diameter of 120 mm seems feasible with a gradient below 120 T/m!

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Optimization and Study Goals for NbTi IR Design

- large aperture: -increased margins for crossing angle
  -reduced peak power density for given $\mathcal{L}$ goal
- minimize peak β-function inside triplet magnets
  -reduced beam size → increased aperture
  -smaller chromatic aberrations
- modular magnet design:
  -simple spare magnet policy
- minimize peak β-function inside IR magnets
  -minimum number of required magnet upgrades

LUMI'05

- solution presented at LUMI'05 was derived from an independent study related to the use of combined function magnets (➔ hybrid solution of dipole first and quadrupole first)

➔ the solution was not optimized for:
  - ➔ total triplet length
  - ➔ peak β-function ➔ chromatic aberrations
  - ➔ minimum number of magnet types

➔ but solution showed that $\mathcal{L} = 10^{35}$ and $\beta^* = 0.25$ m are compatible with NbTi magnet technology and the existing correction circuits

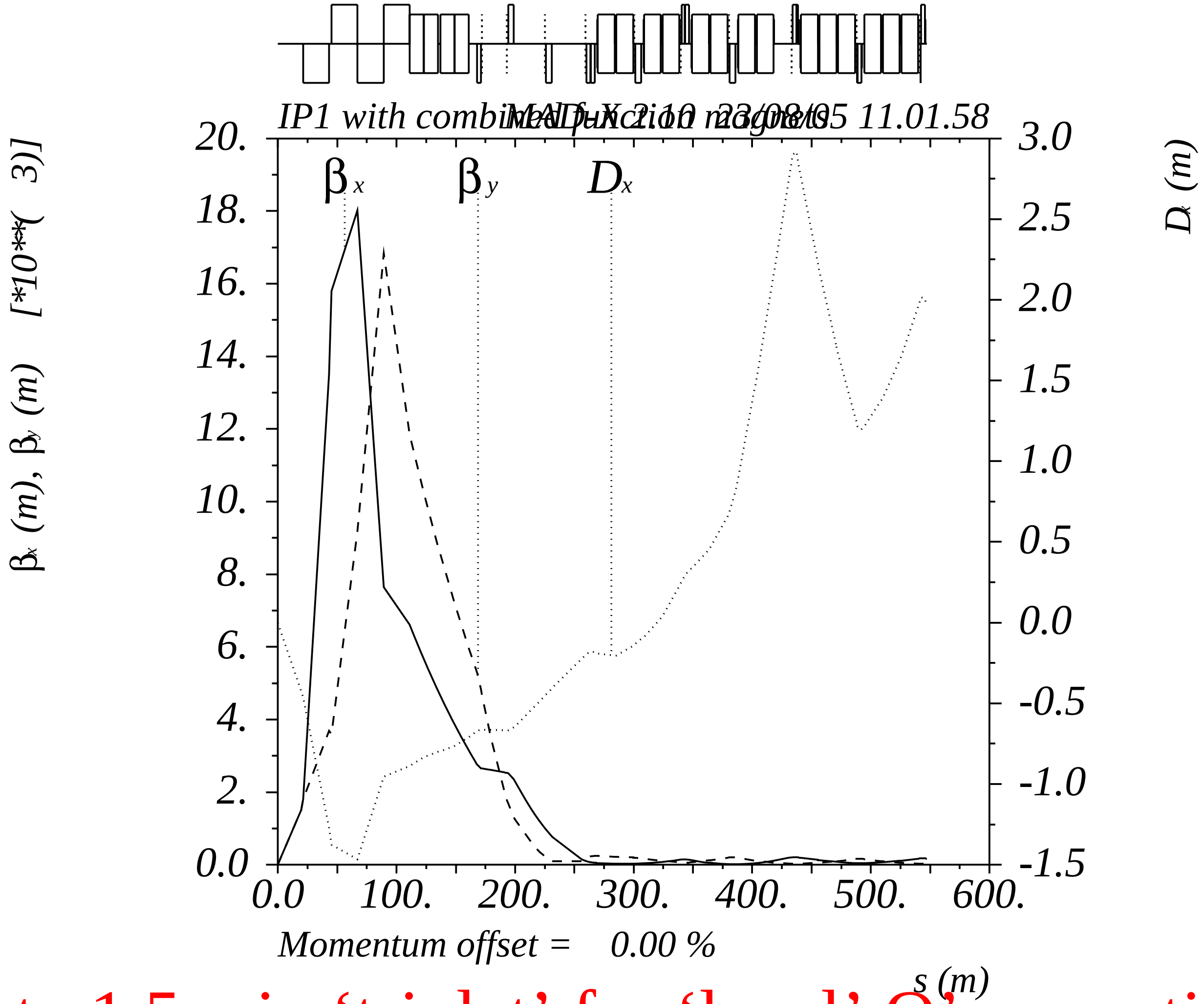
LUMI'05 IR Optics Solution

- Layout and optics derived from Combined function solution:

L* = 19.45 m

D1/D1 ➔ 3.7 T
Q1 ➔ 47T/m ➔ d = 212mm
Q2 ➔ 70T/m ➔ d = 143mm
Q3 ➔ 47T/m ➔ d = 212mm
Q3b ➔ 6T/m

➔ aperture estimate assumes a peak coil field of 5 T!



➔ dispersion matched to 1.5m in 'triplet' for 'local' Q' correction!

Low Gradient Triplet Magnets

- design criteria for LUMI'06 solutions:

-aim at β-max below 15km → 50% higher than Nb_3Sn design
→ 20% lower than LUMI'05 design
→ relaxed field quality requirements
→ reduced chromatic aberrations

(see the talk by R. de Maria)

-balanced gradients in triplet magnets → optimized magnet use

-compact triplet assembly → optimized length of SC magnets

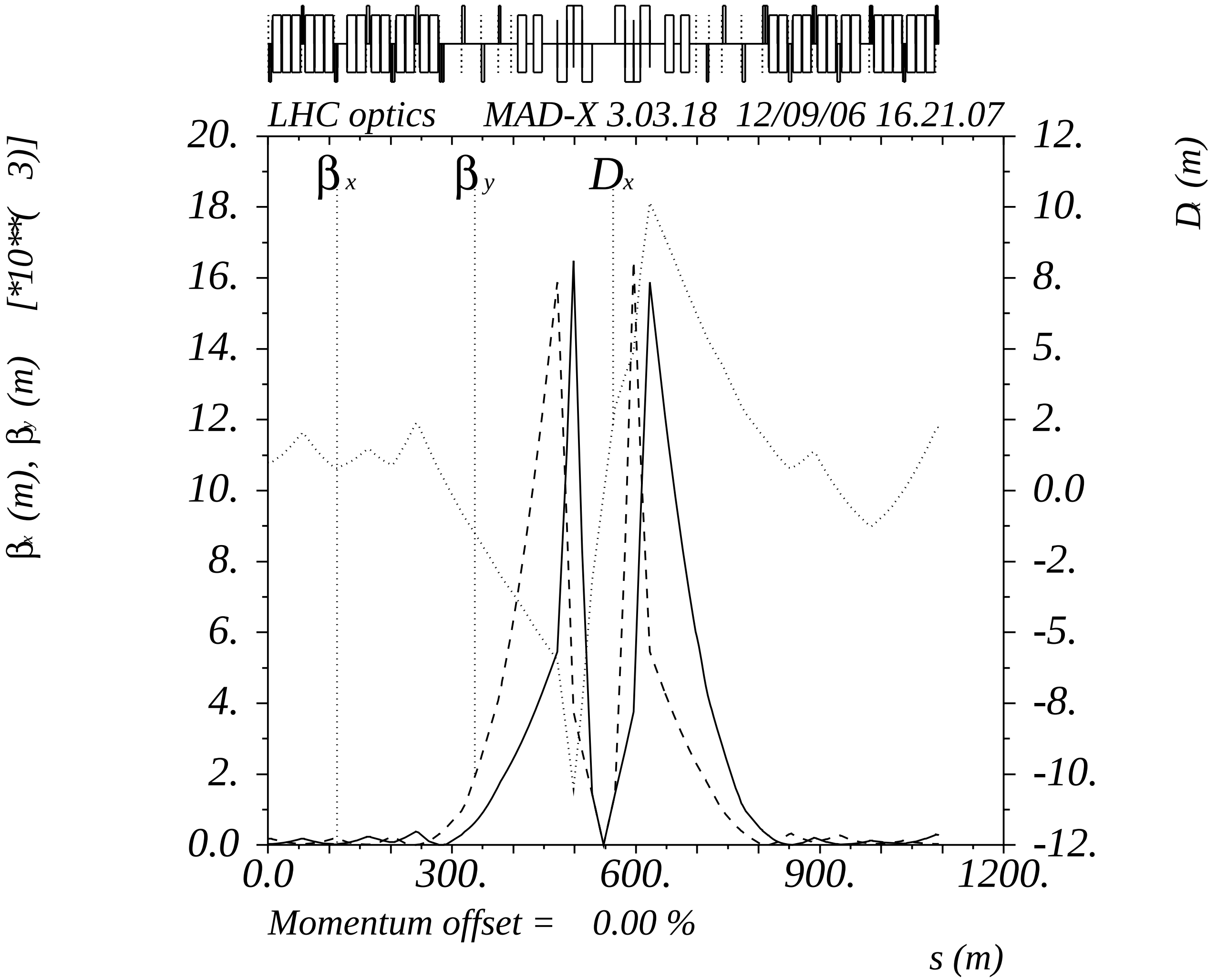
-aim at modular triplet magnets → simple spare magnet policy

Solution with Standard Triplet Layout 1

- aiming at small β-functions in Q4 and β-max below 16 km:

$L^* = 19$ m

Q1 ➔ 75T/m ➔ d = 200mm
Q2 ➔ 75T/m ➔ d = 200mm
Q3 ➔ 65T/m ➔ d = 250mm



➔ aperture estimates assumes a peak coil field of 9 T and 10% operation margin!

➔ dispersion can not easily be matched!

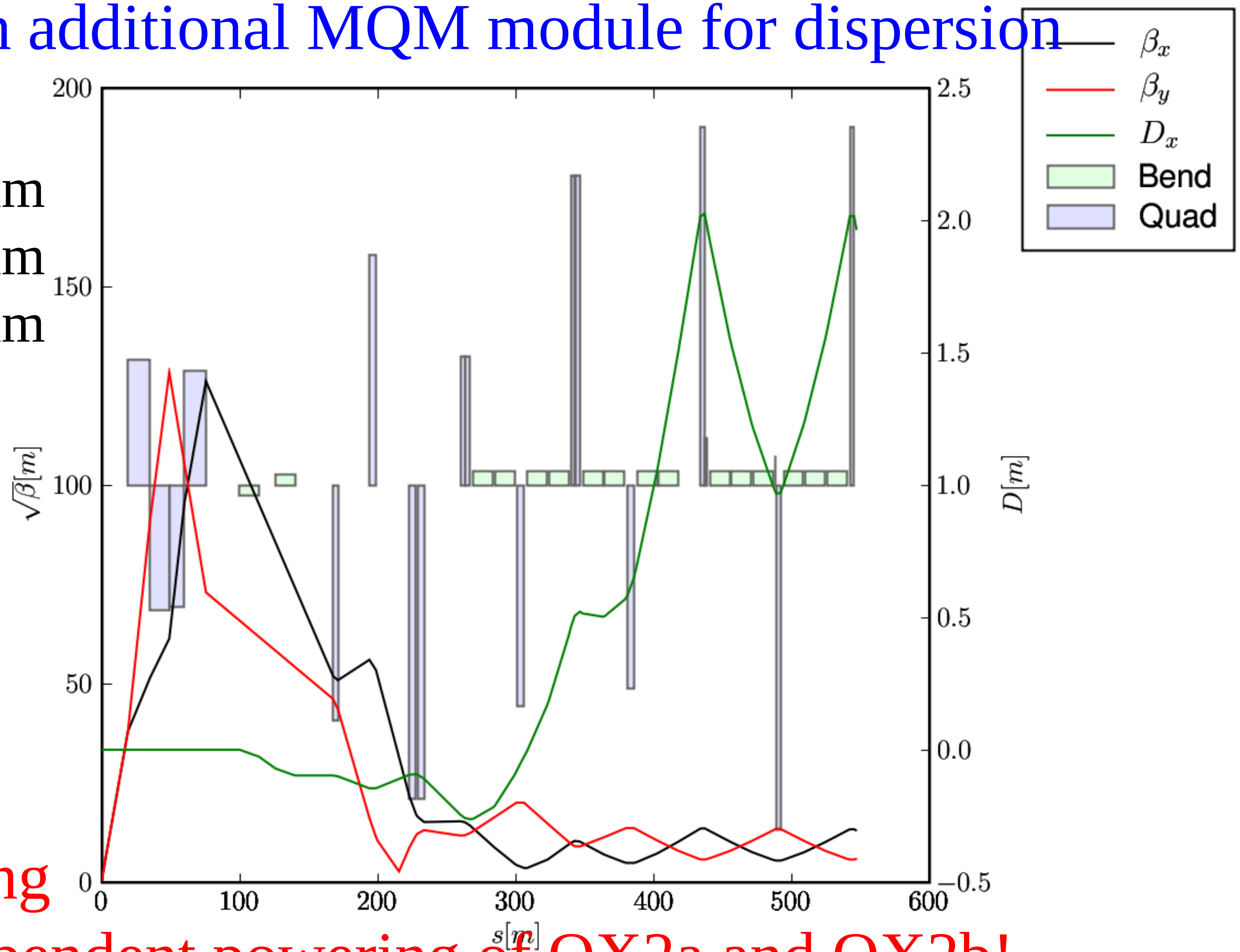
Solution with Standard Triplet Layout 2

- Upgrade Q6 with additional MQM module for dispersion matching:

Q1 ➔ 75T/m ➔ d = 200mm
Q2 ➔ 75T/m ➔ d = 200mm
Q3 ➔ 70T/m ➔ d = 250mm

➔ aperture estimates assume a peak coil field of 9 T and 10% operation margin (σ = 2.85mm –> 33σ < 94mm)!

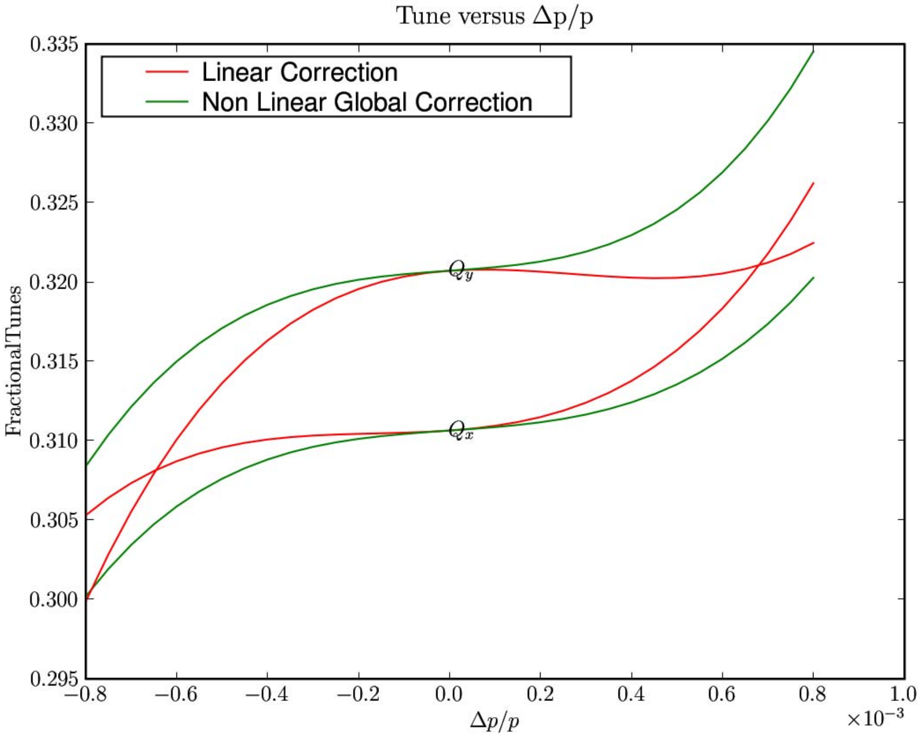
β-max in D2 > 6 km

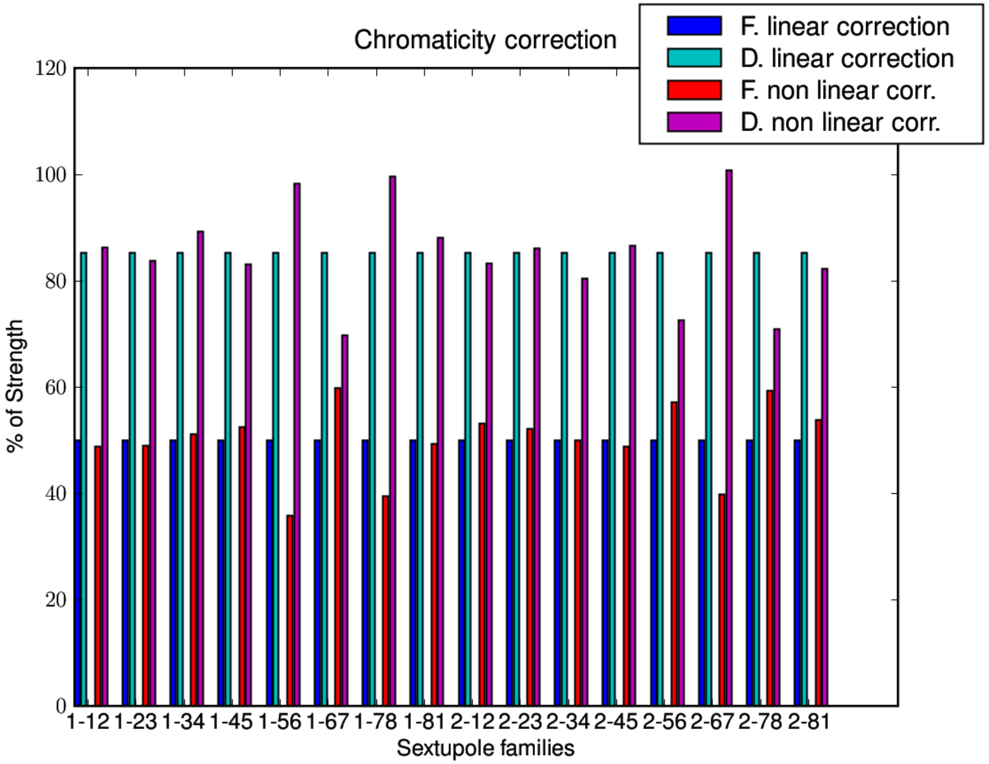


➔ dispersion matching still requires independent powering of QX2a and QX2b!

Chromaticity Correction (2 IRs)

- Q’ and Q’’ can be corrected using the existing LHC circuits:





- off-momentum β-beat remains below 10% in the final focus for $dp/p_0 < 8\ 10^{-4}$ and no β-beat correction

Chromaticity Correction (2 IRs)

- β-beat and Q’’ are proportional to $I_z = \int_{IR} k_1(s)\cdot\beta_z(s)ds$

(S. Fartoukh, LPR 308, 1999)

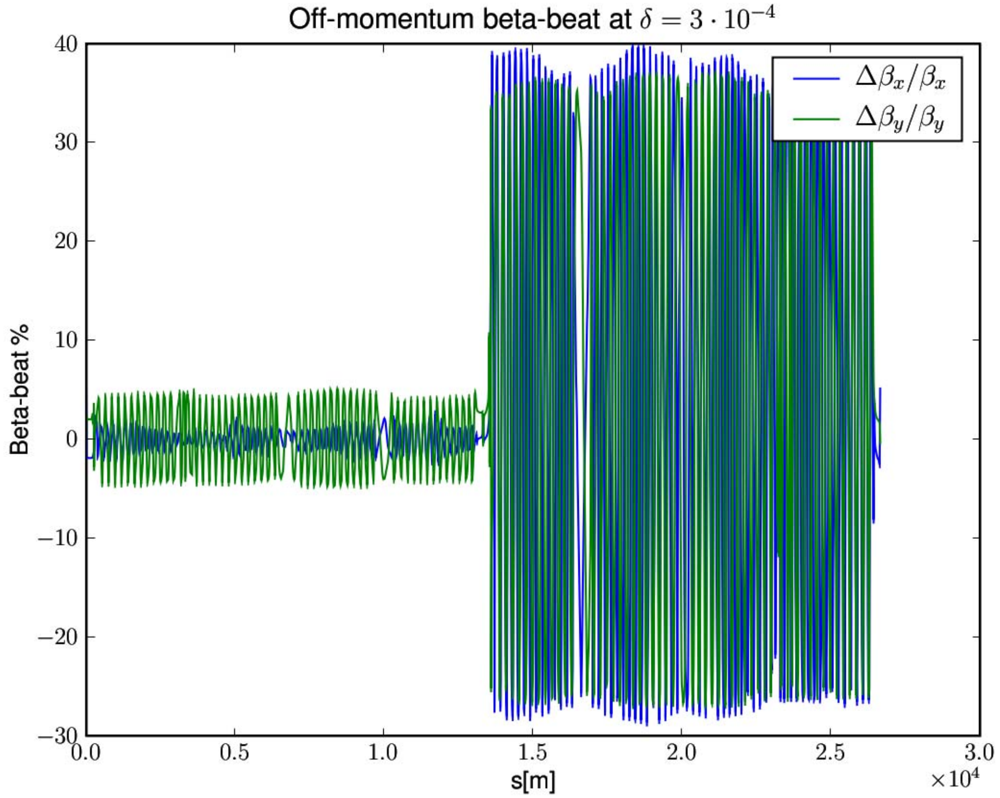
$$\frac{\partial\beta_z}{\beta_{z,0}} \propto I_z \cdot \cos(2\Delta\mu_z^{12} - 2\pi Q_z) \qquad Q_z'' \propto I_z^2 \cdot \cos(2\Delta\mu_z^{1,2} - 2\pi Q_z)$$

	nominal NbTi β*=0.5m	Nb_3Sn β*=0.25m	NbTi triplet β*=0.25m	NbTi modular β*=0.25m
$I_z = I_z^L + I_z^R$	350	700	???	900

→ chromatic aberrations are comparable for all upgrade proposals!

Chromaticity Correction (2 IRs)

- off-momentum β-beat in the arcs varies between 5% and 40%



$dp/p_0 = 3\ 10^{-4}$ (bucket size)

β-beat can be balanced by changing phase advance between IR1 and IR5 -> 22%

β-beat could be reduced by using lattice sextupole circuits

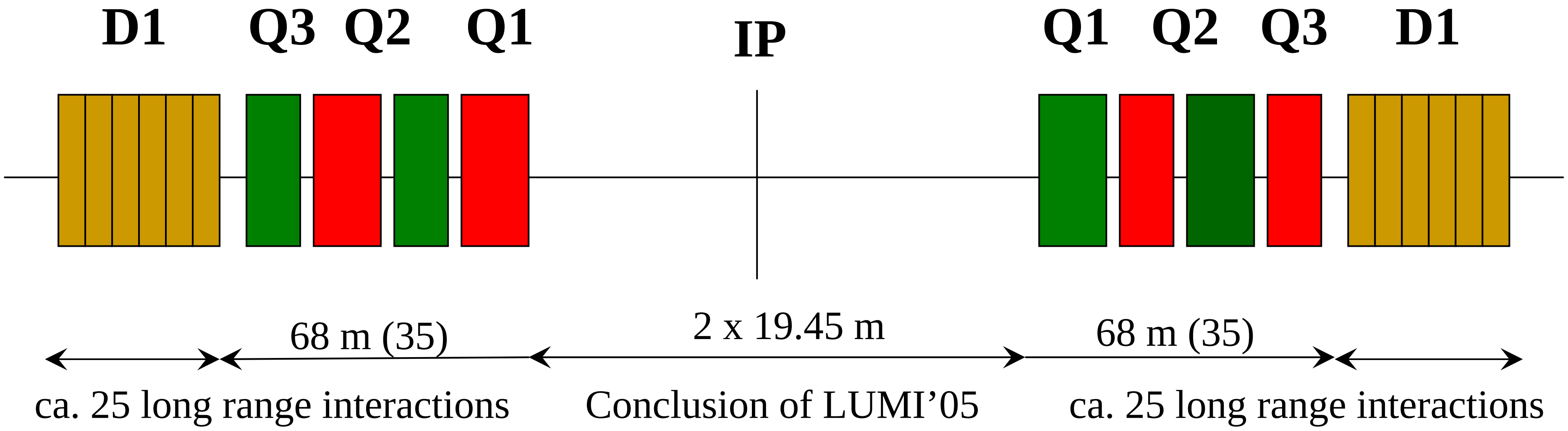
➔ reduced Q’’ correction

➔ use of sextupole spool circuits for Q’ correction

Solution with New ‘Triplet’ Layout

- 4 functional magnet elements:

  ➔ provide 2 parameters for β-max control and 2 for controlling β-functions in Matching Section



D1 **Q3** **Q2** **Q1** **IP** **Q1** **Q2** **Q3** **D1**

68 m (35) 2 x 19.45 m 68 m (35)

ca. 25 long range interactions Conclusion of LUMI’05 ca. 25 long range interactions

➔ controlling β-function in MS facilitates dispersion matching

➔ longer triplet section increases number of long range collisions

Solution with Modular 'Triplet' Layout

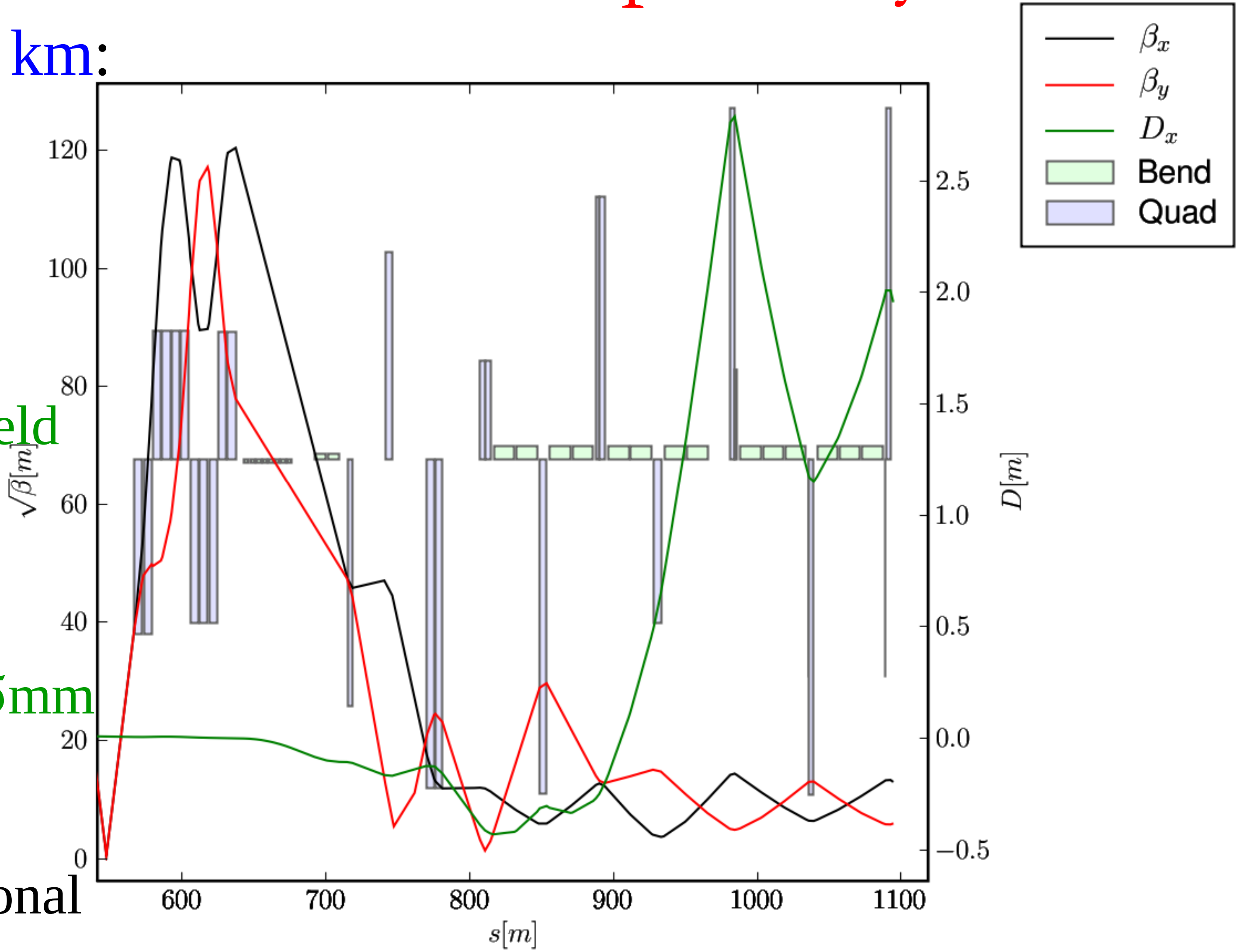
- choose modular triplet design:

-choice of standard magnet module → 5.5 m long quadrupole (Q2)
→ QX1 = 2 modules, QX2 = 4 modules;
→ QX3 = 3 modules; QX4 = 2 modules

-implement standard inter module space
→ 1m for inter-connect and corrector elements
→ total 'Triplet' length = 70.5 m

Solution with Modular 'Triplet' Layout

- β-max below 15 km:



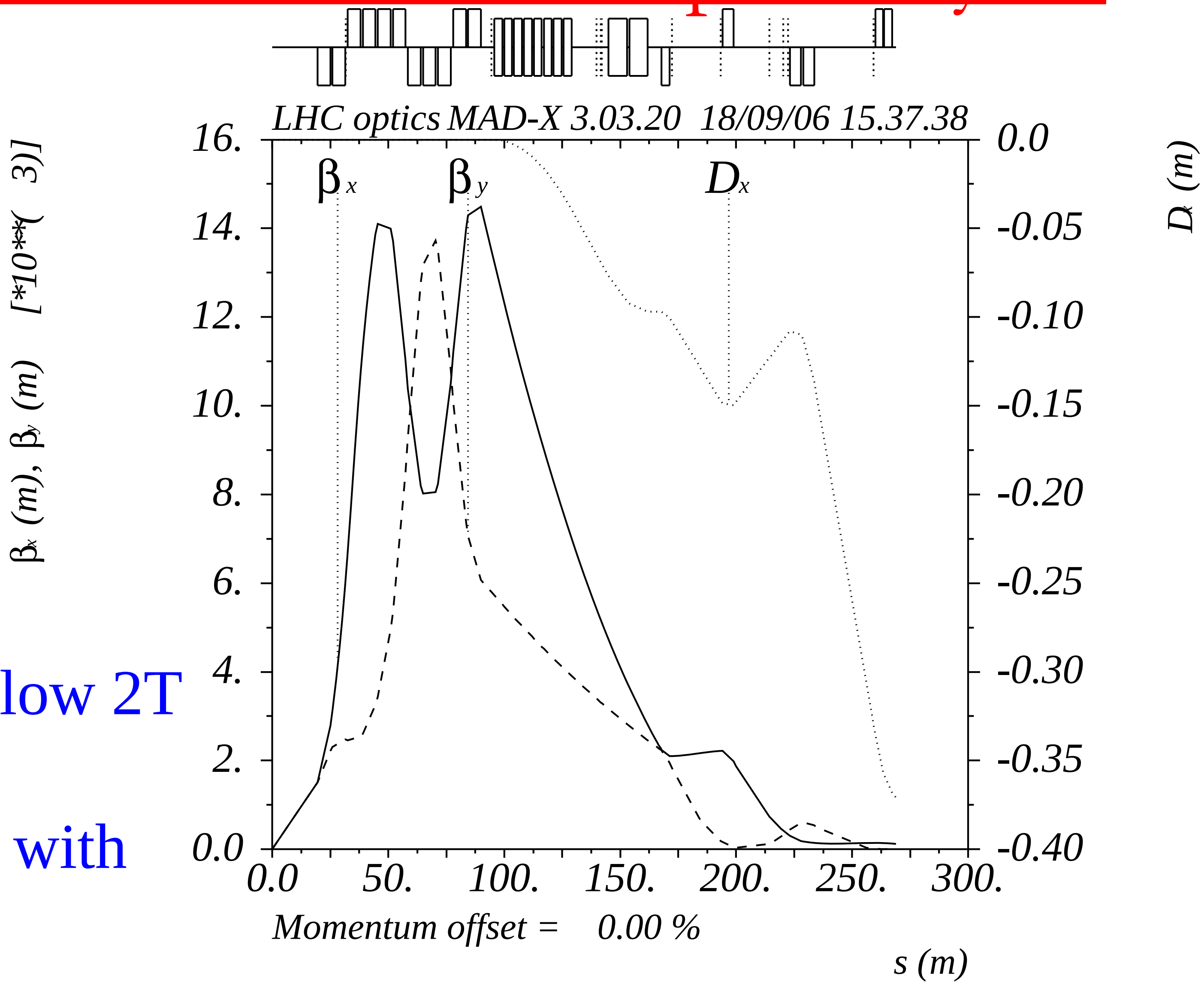
QX1 ➔ 100T/m
QX2 ➔ 80 T/m
QX3 ➔ 100T/m
QX4 ➔ 80 T/m

➔ assuming a peak coil field of 9 T the magnets can provide an aperture of 180 mm diameter with 10% operation margin (σ = 2.75mm
–> 33σ < 100mm
–> 80% margin!!!)

Q6 upgrade with an additional MQM module

Solution with Modular ‘Triplet’ Layout

🟩 MS-right:



β-max in D2
< 6 km

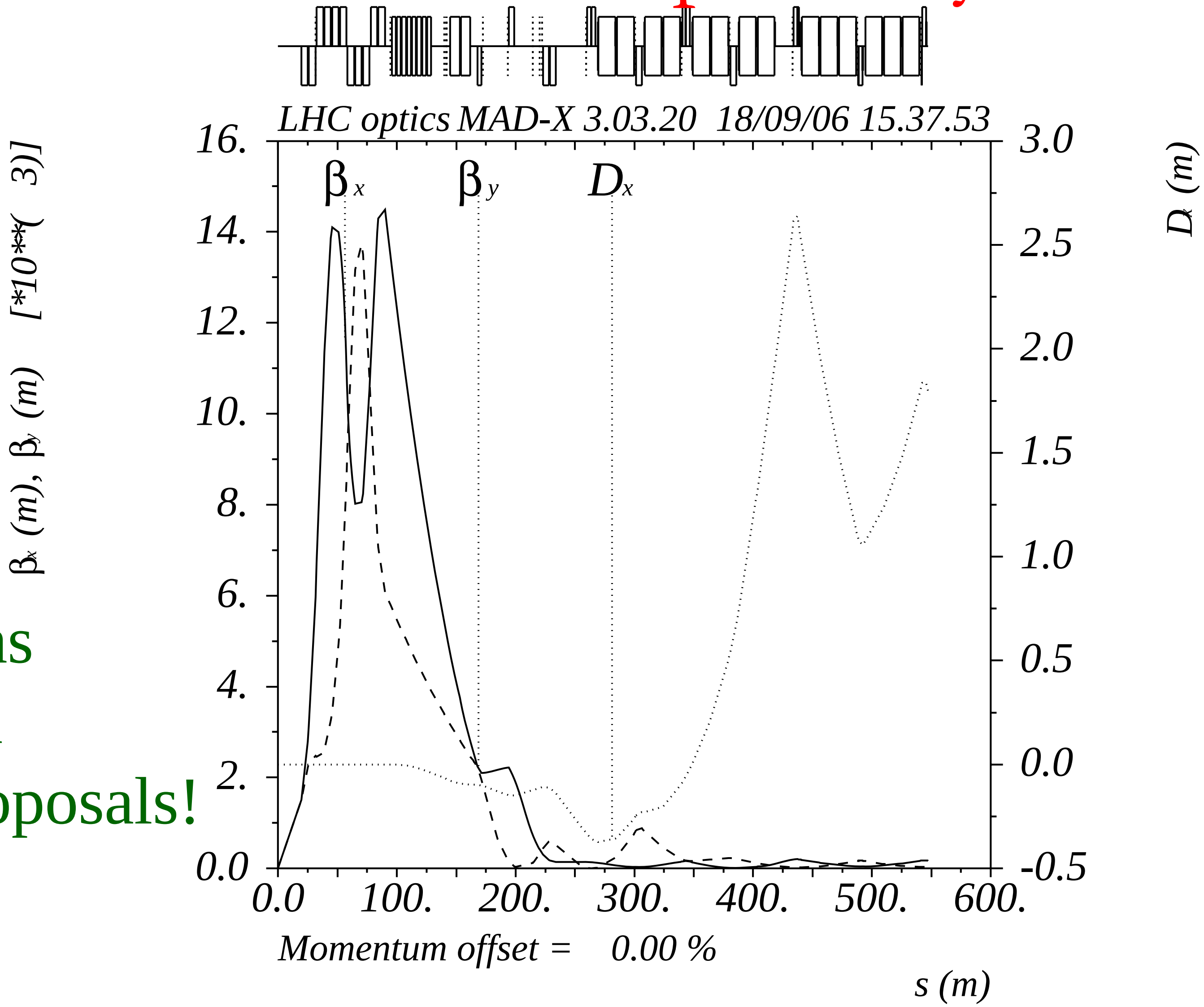
β-max in
Q4, Q5 < 3 km

compatible with
warm D1: field below 2T

relaxed D2 design with
B = 3.5 T

Solution with Modular 'Triplet' Layout

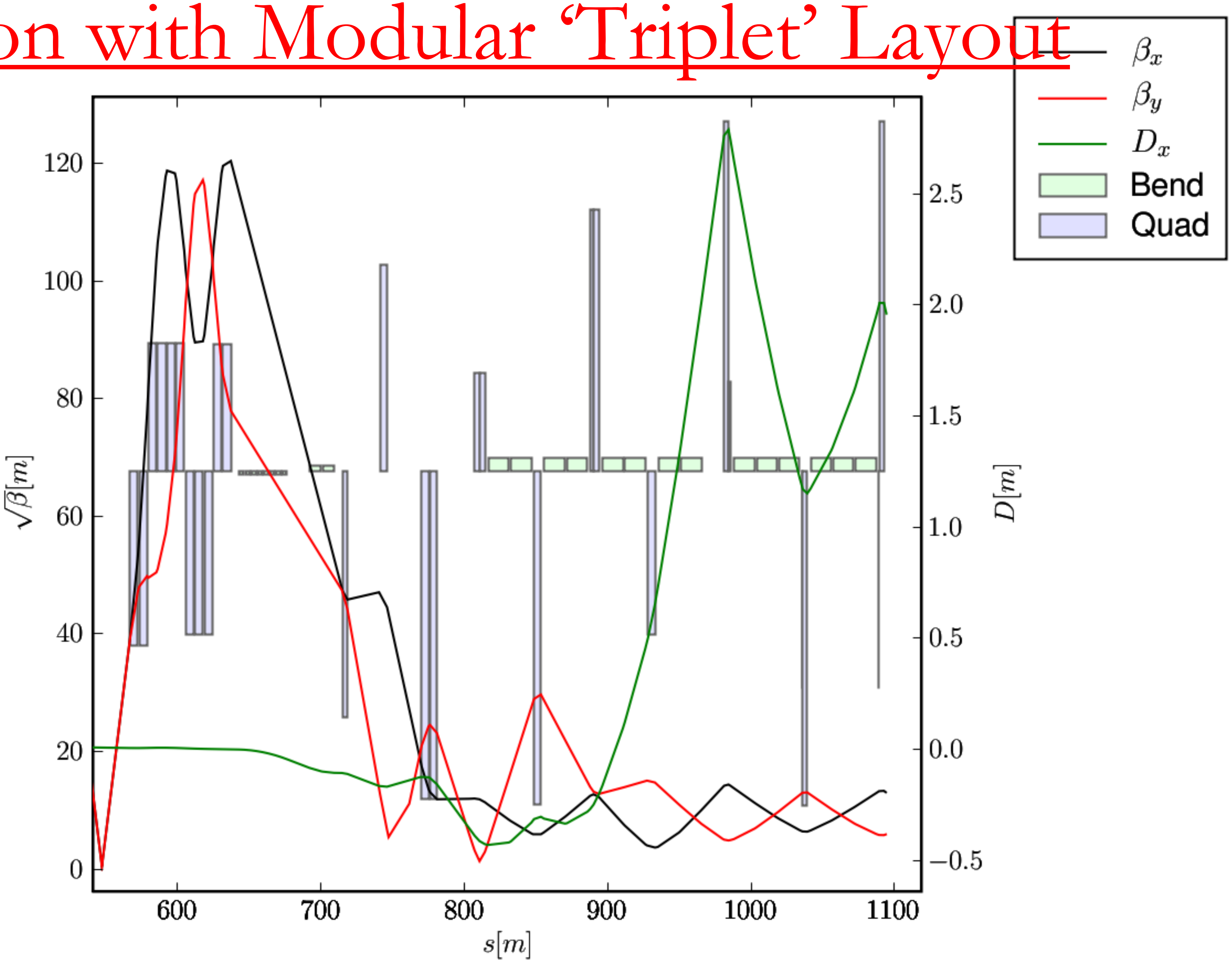
🟩 IR-right:



chromatic aberrations
are comparible to all
other IR upgrade proposals!

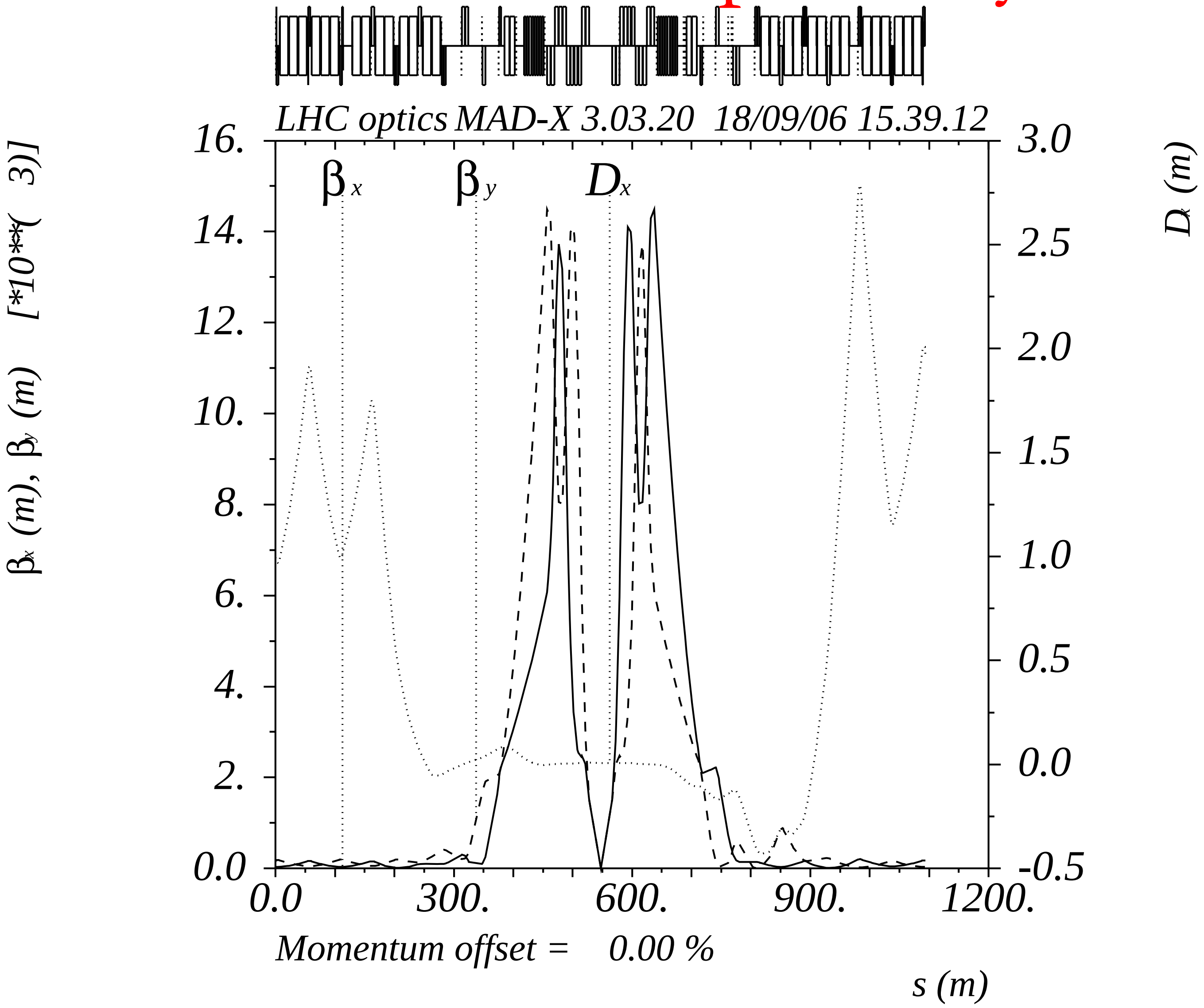
Solution with Modular ‘Triplet’ Layout

- IR-right:



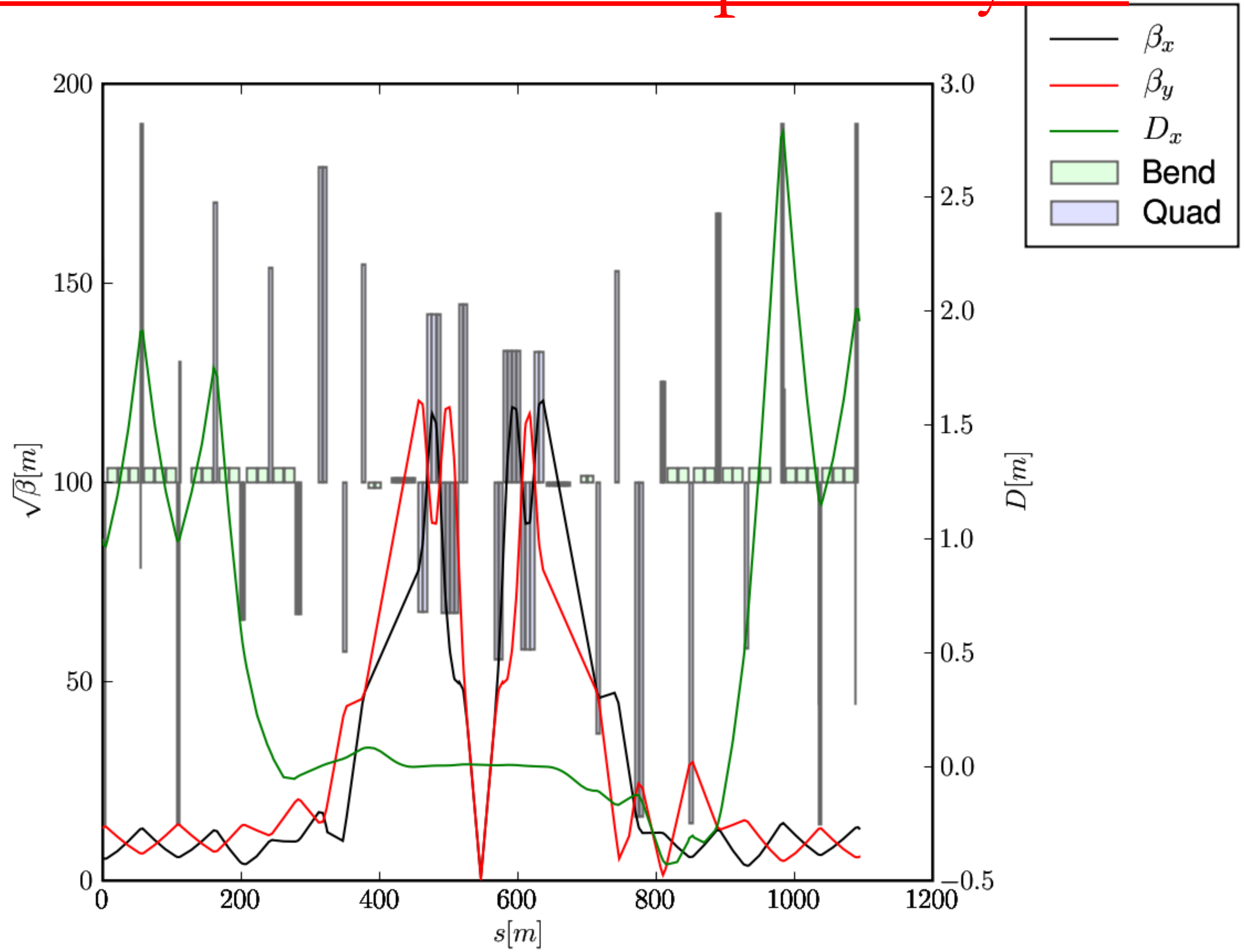
Solution with Modular 'Triplet' Layout

- Full IR:



Solution with Modular ‘Triplet’ Layout

- Full IR:



Summary

- generated 2 low gradient solutions with $L^* = 19$m using:

  -long specialized quadrupole designs
  -standard 5.5m long magnet modules with 1m interconnects

  ➔ both approaches provide large aperture margins (ca 80%)
  ➔ all solutions allow Q' and Q'' correction using the existing LHC corrector circuits (S. Fartoukh LPR 308)

- $L^* = 23$m can be achieved by reducing QX1 length and increasing its gradient (no aperture limitations)
  We still need a TAS design for $\mathcal{L}$ upgrade that fixes L^*!!!

Summary

- cost comparison:

-Nb_3Sn is approximately 5-10 more expensive compared to NbTi
-proposed NbTi solutions are approximately twice as long as
Nb_3Sn solution ➔ NbTi solutions should be price competitive

- modular IR design: ➔ simple spare magnet policy

- NbTi solutions provide synergy with an LHC magnet rescue facility