# Overview of the LHC injection and transfer line optics configurations and tolerances

- **Introduction. Matching needed to which level ?**
- **Required flexibility from possible optics changes and tolerances**
- **To which extend can the transfer line optics adapt to changes ?**

based on many discussions and input from

O. Brüning, B. Goddard, W. Herr, V. Kain, V. Mertens, A. Lombardi, T. Risselada, A. Verdier, J. Wenninger, R. Schmidt, et al.

# Introduction

- **Excellent matching at injection needed for the LHC**

  in LEP it was sufficient that a good fraction of the particles were captured,

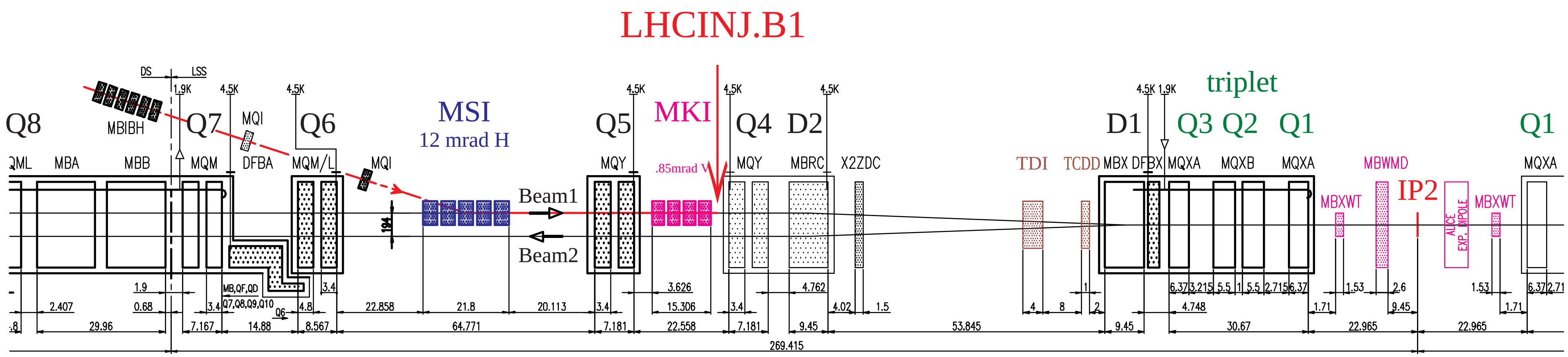
  the rest was taken care of by radiation damping

- **Any emittance blow-up at injection will directly reduce the luminosity**

  **LHC design allows for only 7% emittance increase (from 3.5 to 3.75 μm ) between extracted SPS beam and emittance in collisions in the LHC**

- **A single injection** (288 bunches of design intensity) is **well ( ~ 20 x ) above damage and 4 orders of magnitude above quench level**

- **The geometrical emittances are largest at injection and the LHC physical aperture is tight** ( ~ 7.5 σ )




**Layout: Left side of IR2 with the injection**

**Transfer Line TI 2 and LHC ring 1 are matched at LHCINJ.B1 close to Q4**

**similar for TI 8 and LHC ring 2 matched at LHCINJ.B2 close to Q4**

where about $\beta_{x,y} \approx 60$ m both in IR2 and IR8 and dispersion < 12 cm in all cases

There are theoretical expressions and there is experience at CERN on the effect of mismatch, i.e.

L. Vos, G. Arduini, K. Hanke Chamonix 1999 (mismatch 2 -> 1.1 - 1.3 SPS )

ICFA Mini-Workshop CERN Nov. 1997 on transv emit. preservation (Fermilab-Conf-97/419)

# Target levels for injection matching

to stay within the 7% emittance budget from SPS extraction to LHC collisions

try to keep individual contributions at 1 - 2 % level

- specified injection precision 1.5 $\sigma$, blowup small with damper on ( 0.5% emit. increase )

- $\beta$ - match to $\lesssim$ 10%   for < 2% in emittance

$$\frac{\Delta\epsilon}{\epsilon} = \frac{1}{2}\frac{\Delta\beta/\beta^2 + (\Delta\alpha + \alpha\,\Delta\beta/\beta)^2}{1 + \Delta\beta/\beta}$$

- dispersion match to $\lesssim$ 10 cm or 4 mrad in D' for < 2% in emittance for $\sigma_e = 5 \times 10^{-4}$

$$\frac{\Delta\epsilon}{\epsilon} = \frac{1}{2}\frac{(\Delta D)^2 + (\beta\Delta D' + \alpha\Delta D)^2}{\sigma^2}\left(\frac{\sigma_p}{p}\right)^2$$

still consider geometrical mismatch, coupling, energy error, tail repopulation, ...

more complete study and report with simulation planned (HB, BG, VK, TR et al.)

# Optics Flexibility required in the Transfer lines TI 2 and TI 8

## SPS side:

• change of working point, from ~ 26.6 to ~ 26.2 3% in $\beta_{x,y}$, 10 cm in Dx

possible to absorb with the existing flexibility

## LHC side:

more difficult, since TCDIs added in matching section

several items considered, details on next slides

1) Q3 move, rematch transfer lines to LHC optics versions 6.5

2) various crossing angle configurations

3) LHC working point. Integer tune changes

4) alignment optics

5) change of $\beta^*$ at injection

6) match to real optics in LHC with magnet and alignment errors

# 1) Rematch transfer lines to LHC optics V6.5

**after the change in the LHC optics in the insertions with**

**LHC Q3 moved** ( MQXA 0.3 m towards IP in IR 1,2,5,8; space for non-linear correctors )

comparison at LHCINJ.B2, sep. bumps off

| | $\beta_x$ m | $\alpha_x$ | $D_x$ m | $\beta_y$ m | $\alpha_y$ | $D_y$ m |
|---|---|---|---|---|---|---|
| V6.4 | 49.13 | -1.69 | -0.11 | 84.93 | 1.24 | 0.0000 |
| V6.5 | 53.23 | -1.73 | -0.11 | 75.20 | 1.22 | 0.0000 |

or about

+10% $\beta_x$

- 10% $\beta_y$

and Q5 common to LHC and transfer line, strength reduced by 11% kq5 = .0047292 -> .0042568 .

**After rematch** (without Δμ TCDI constraint) **: up to 24$^o$ change in phase advance**

**worst in TI 8 which has little space, not enough flexibility to rematch for 0,45,90,135$^o$**

(see also talk by Thys). Together with cost arguments, this

**triggered a redesign of TCDI positions with 3 phases 0 , 60, 120$^o$ which is a bit easier to fit and adjust than the previous 4 phases 0, 45, 90, 135$^o$**

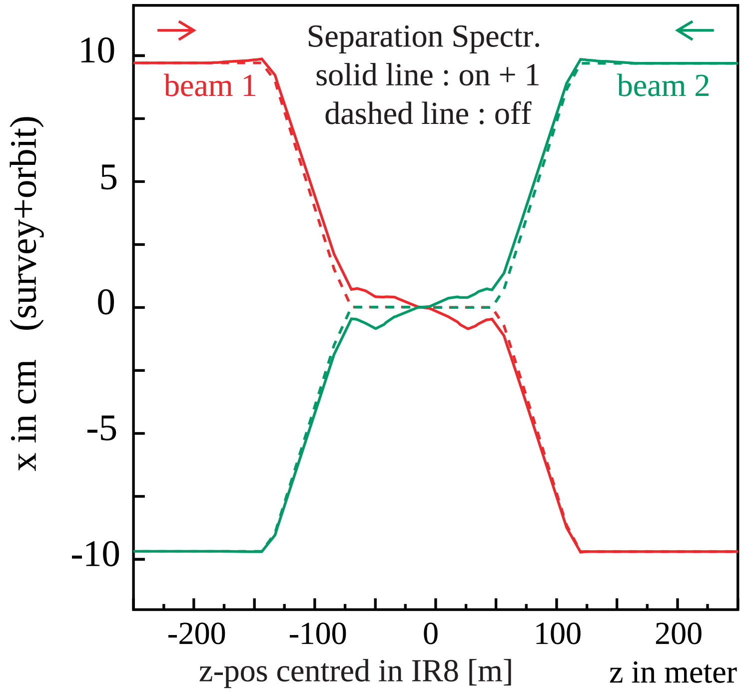
at similar level of protection

$$1/\cos\frac{60^\circ}{2} = 1.15 \qquad 1/\cos\frac{45^\circ}{2} = 1.08$$

**LHC layout frozen. Major changes (like Q3 move) not expected in future.**

# 2) Crossing Angles, Spectrometers and Separation

IR8, with/without 170 μrad
horizontal crossing angle
no -170 μrad




**many possible cases, effect on injection small**

- **Spectrometers** (IR2 ALICE, IR8 LHC-B):

  optics relevant for injection at Q4 not affected

  ( Local bumps, closed within Q1 )

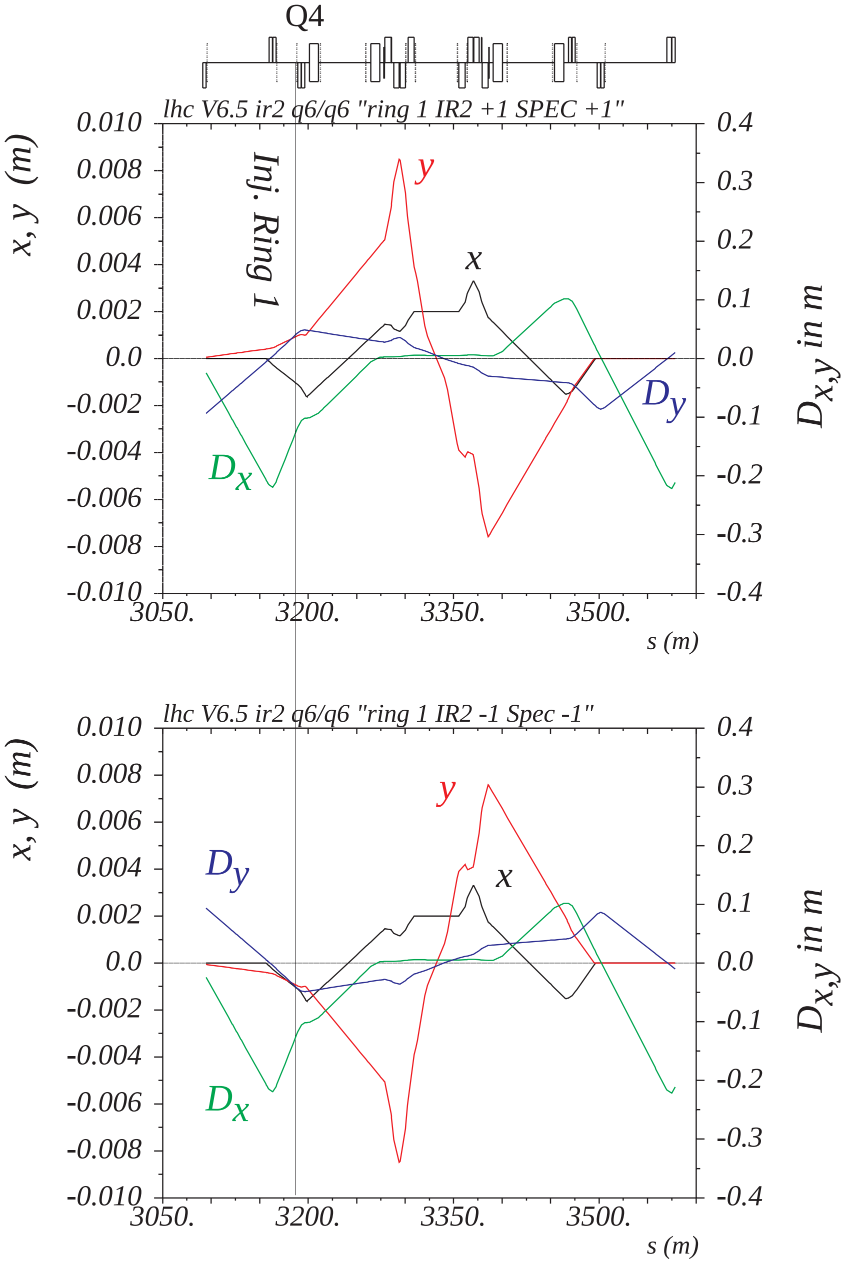
- **Crossing angle, Separation**

  **checking the various cases, including effects from residual dispersion of other IRs. Bumps closed within Q6-Q6, already small at Q4. No effect on** β.

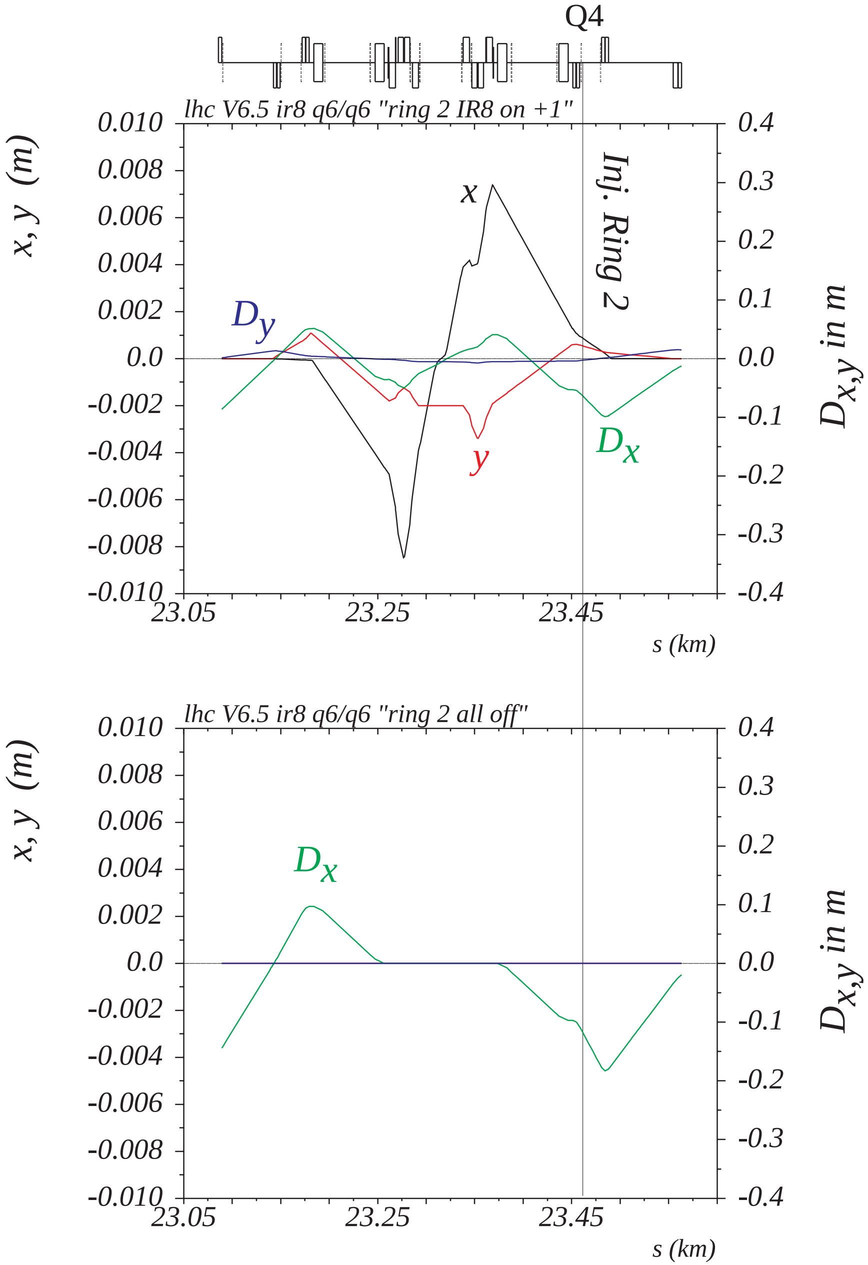
**Dispersion :**

| | max. range | | main change from crossing angle |
|---|---|---|---|
| **IR 2:** | **Dx = -11 to - 15 cm** | **Dy = +/- 5 cm** | **± 170 μrad vertical** |
| **IR 8:** | **Dx = -6 to - 11 cm** | **Dy = 0 - 0.4 cm** | **+ 170 μrad horiz. and all off** |

**IR2**
vertical crossing, horizontal separation




**IR8**
horizontal crossing, vertical separation



## 3) LHC working point. Integer tune changes

there is a certain tradition from LEP to change optics in Chamonix workshops

for coup., b.b., low ε, etc, we had $60^o/60^o$ (70/78, 71/77, 71/76) , $90^o/90^o$, $90^o/60^o$, $102^o/90^o$ ,..

Could this happen again for the LHC ? What about re-matching at injection ?

currently **LHC V6.5 $Q_x = 64.28$ $Q_y = 59.31$ with integer tune difference of 5**

**one possible alternative : "resonance-free" lattices (A. Verdier)**

**with other drawbacks like beam-beam, pro / con not the subject here, just see match for**

**$Q_x = 59.28$, $Q_y = 51.31$ or**

**$Q_x = 67.28$, $Q_y = 59.31$ both with $\Delta Q = 8$**

**The tune change is done in the arcs**

**The matching to the interaction region can be done with Q6 to Q13**

**such that the $\Delta\mu_y = 90^o$ constraint between the kicker and TDI**

**and the optics at injection remain unchanged (A. Verdier)**

no fundamental objection from injection matching to break with our tradition

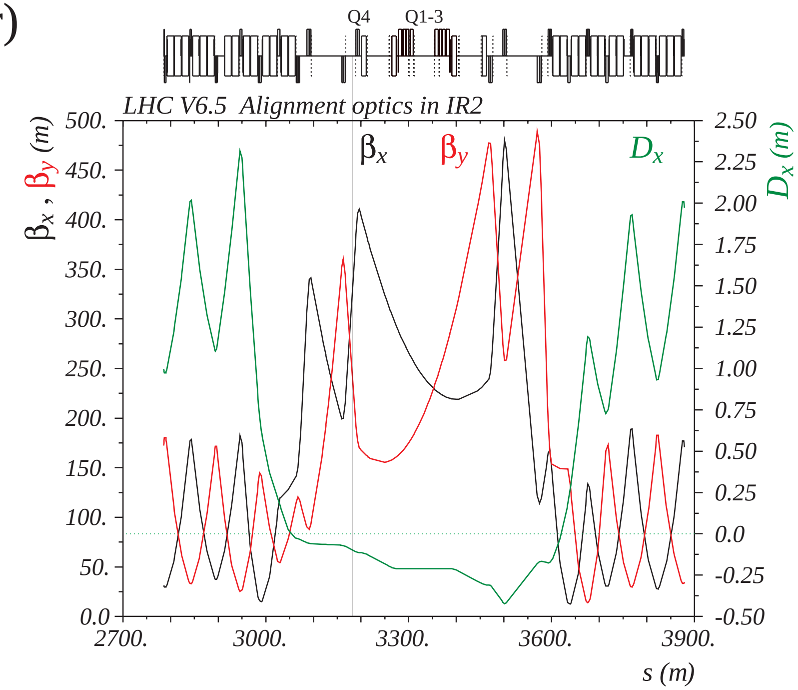
# 4) Special alignment optics

**This has been studied for IR 1, 5     (small β*)**

**by A. Verdier et al.   and is included in the  LHC Design Report, Chapter 4.6.1**

**Now also considered for IR2**   (no request for IR8 so far)

**The triplet Q1-Q3 is turned off**




**Optics at injection changes a lot,**

**about factor 5 increase of β at injection**

**the 90º phase between kicker and TDI is lost**

($\Delta\mu_y \approx 20^o$)

**MD - optics, low intensity pencil beam,**

**inj. not matched or rather**

**one IR at a time, inject in 8 to align 2 and vice versa**

## 5) Change of $\beta^*$ at injection

**Currently $\beta^* = 10$ m in IR2, 8**

**What would happen if $\beta^*$ would increase up to 18 m as in IR1, 5**

**(for example to optimize aperture and background at injection ?)**

**Studied by Alessandra Lombardi for IR8 with MKI / TDI constraint**

**starting from $\beta^* = 10$ m , going to $\beta^* = 13$, 15 and 18 m** (both in x,y)

**optics at LHCINJ.B2 (injection close to Q4) was found to increase about**

**in the same proportion, by factor 1.3, 1.5, 1.8**

**or up 80% increase in $\beta^*$ with major consequences for injection matching**

## 6) Match to real LHC optics with magnet and alignment errors

**Try first to globally correct the largest errors in the LHC itself,**
**to a level of about 20 % in β and 10 % res. dispersion (about 12 cm at inj. )**
**This is also relevant for aperture but not necessarily for luminosity**
**as errors will change with ramp & squeeze**

**To minimize blowup at injection, make a special effort to obtain a good match between the transfer lines and the real LHC optics at the injection points**

# Flexibility of the transfer lines to adapt to optics changes

**To be able to adapt to crossing schemes and the real LHC optics, requires a flexibility in betas of about ± 20 % and 10 cm in dispersion**

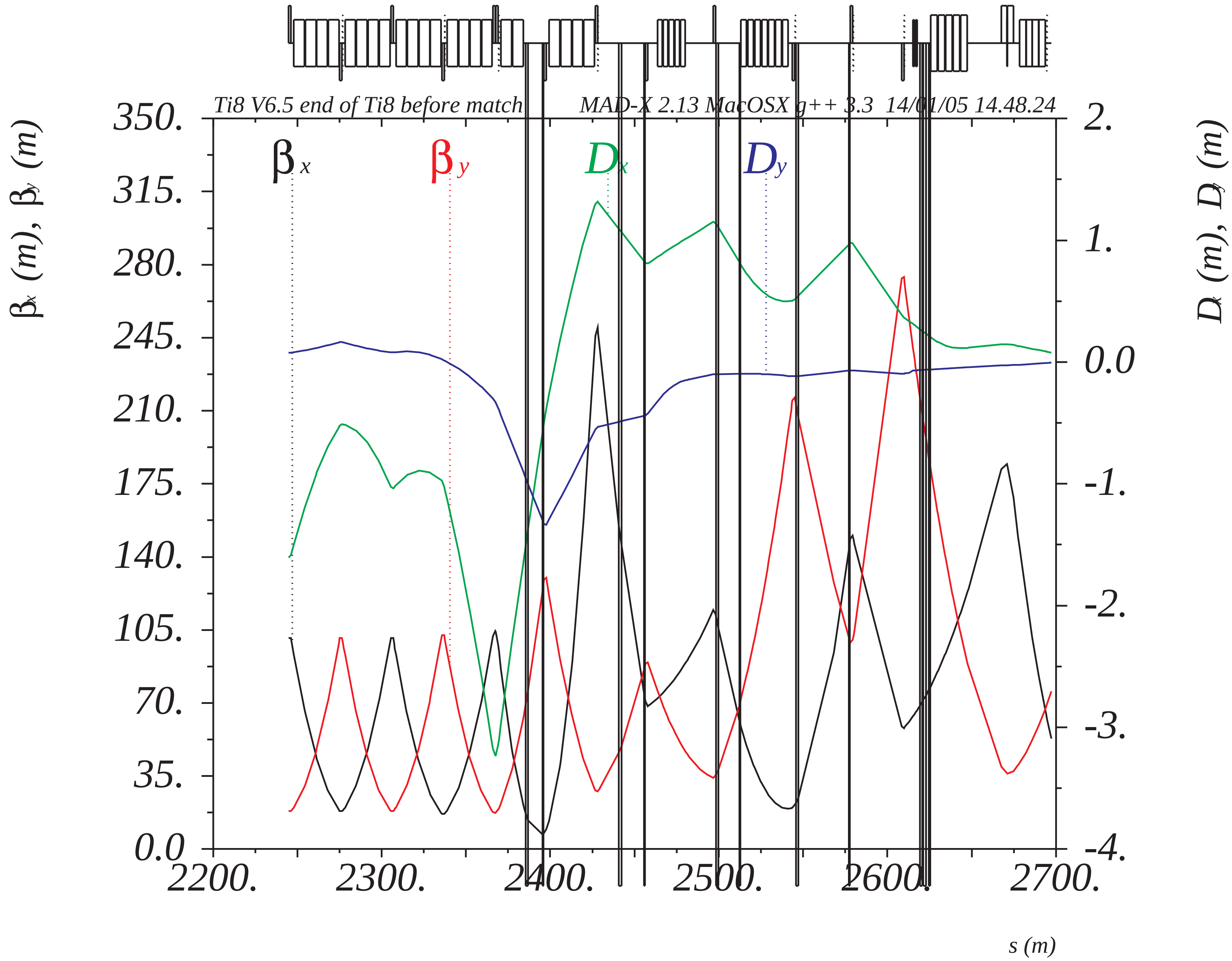
- **the simultaneous rematch to β, β' (α); D, D' in x/y on both SPS / LHC side with constraints on 4 TCDIs phases (3 Δμ in x/y) can already fail at half of the required level, as seen in the rematch to V6.5 after Q3 move**

- **a more flexible optics was found for the fewer 0/60/120º TCDIs which fit better in the very confined space available in TI 8**

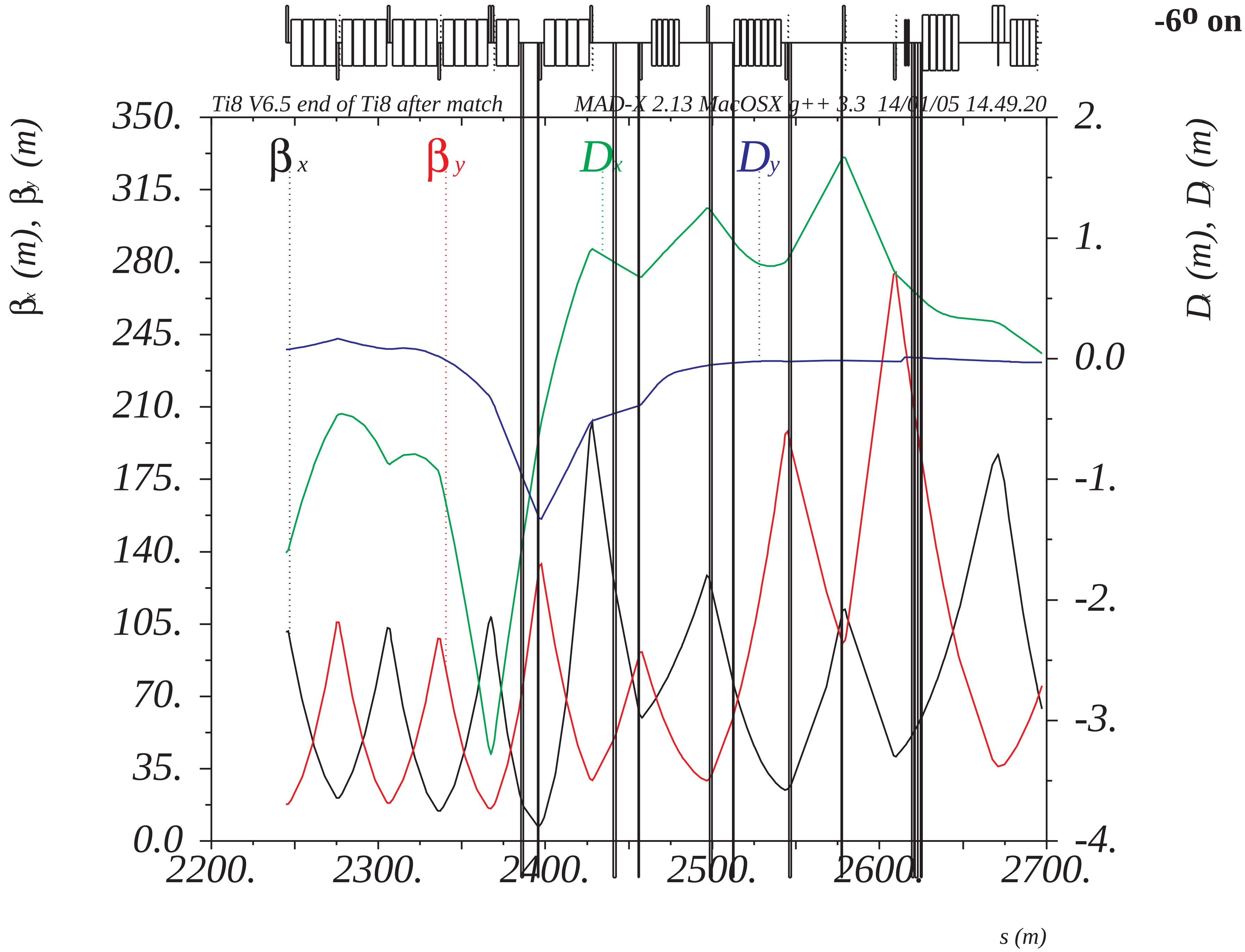
  TI 2 has more space and should be easier - 0/60/120º TCDI positions being finalized, flexibility checks on TI 2 just started

- **several particular cases to adapt to changes on the LHC side have been considered --->**

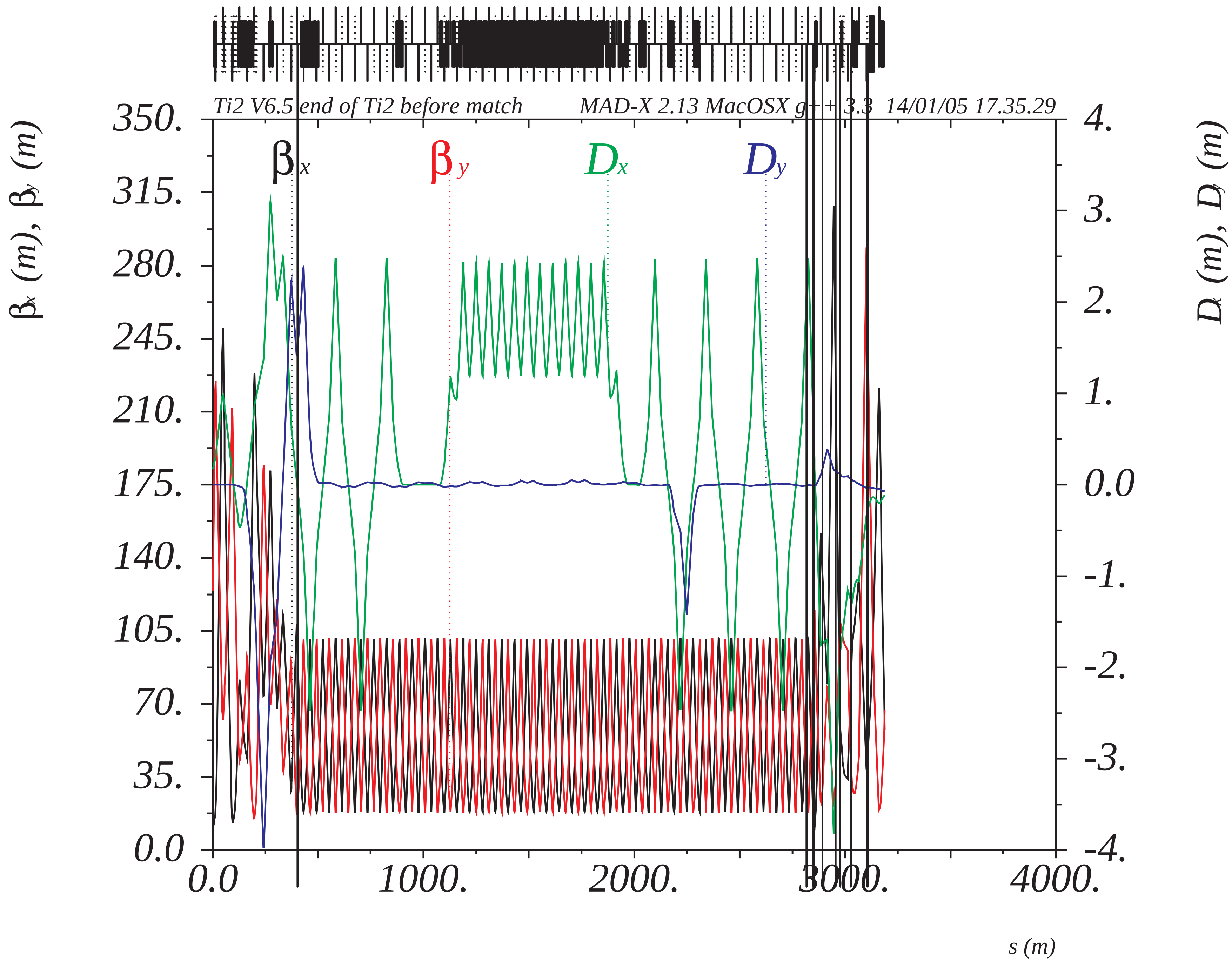
**current TI 8 optics and TCDI positions**



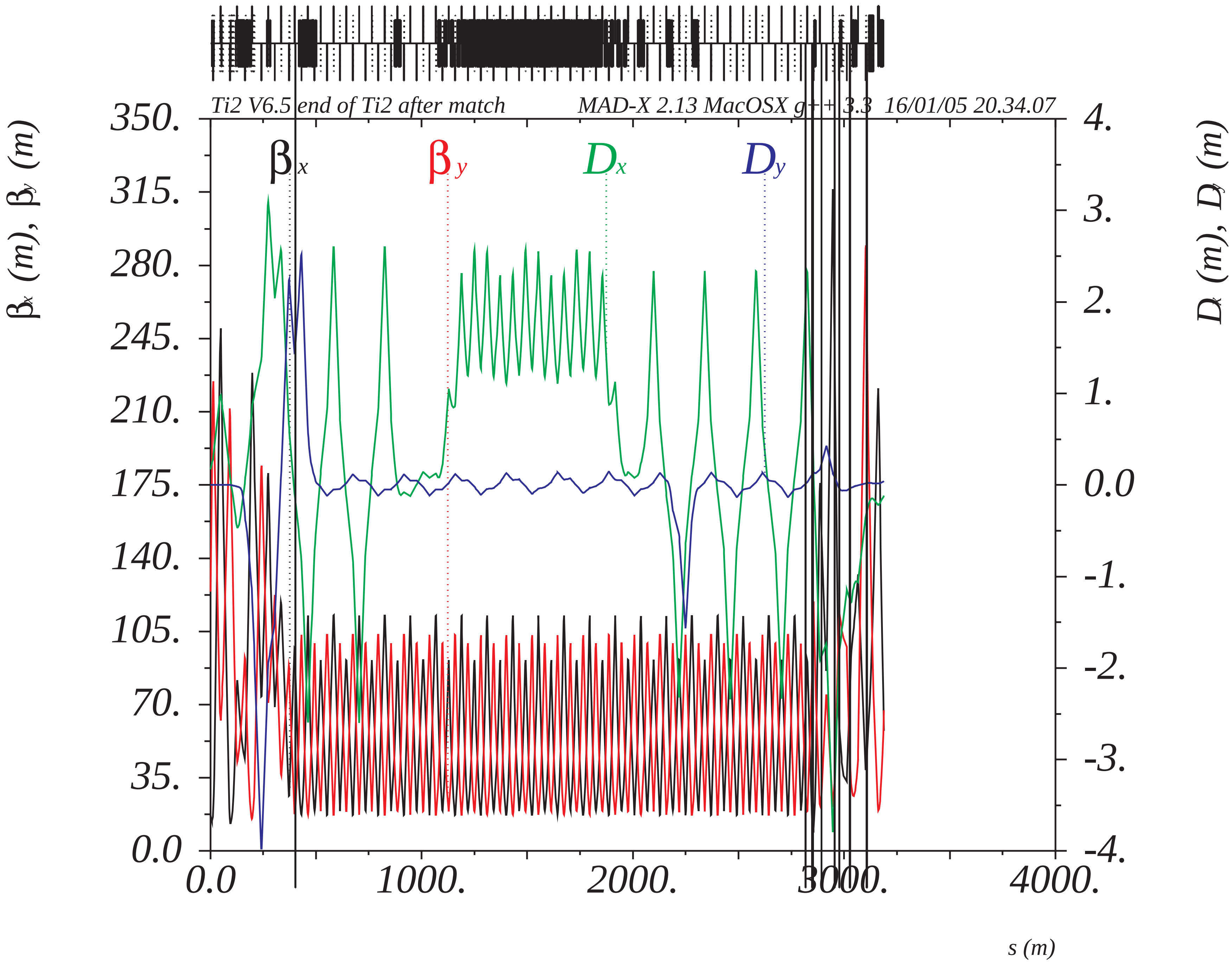
**rematch to 20% increased $\beta_x$ in the LHC at reduced TCDI protection** **+15° on TCDIH060** **-6° on TCDIH300**



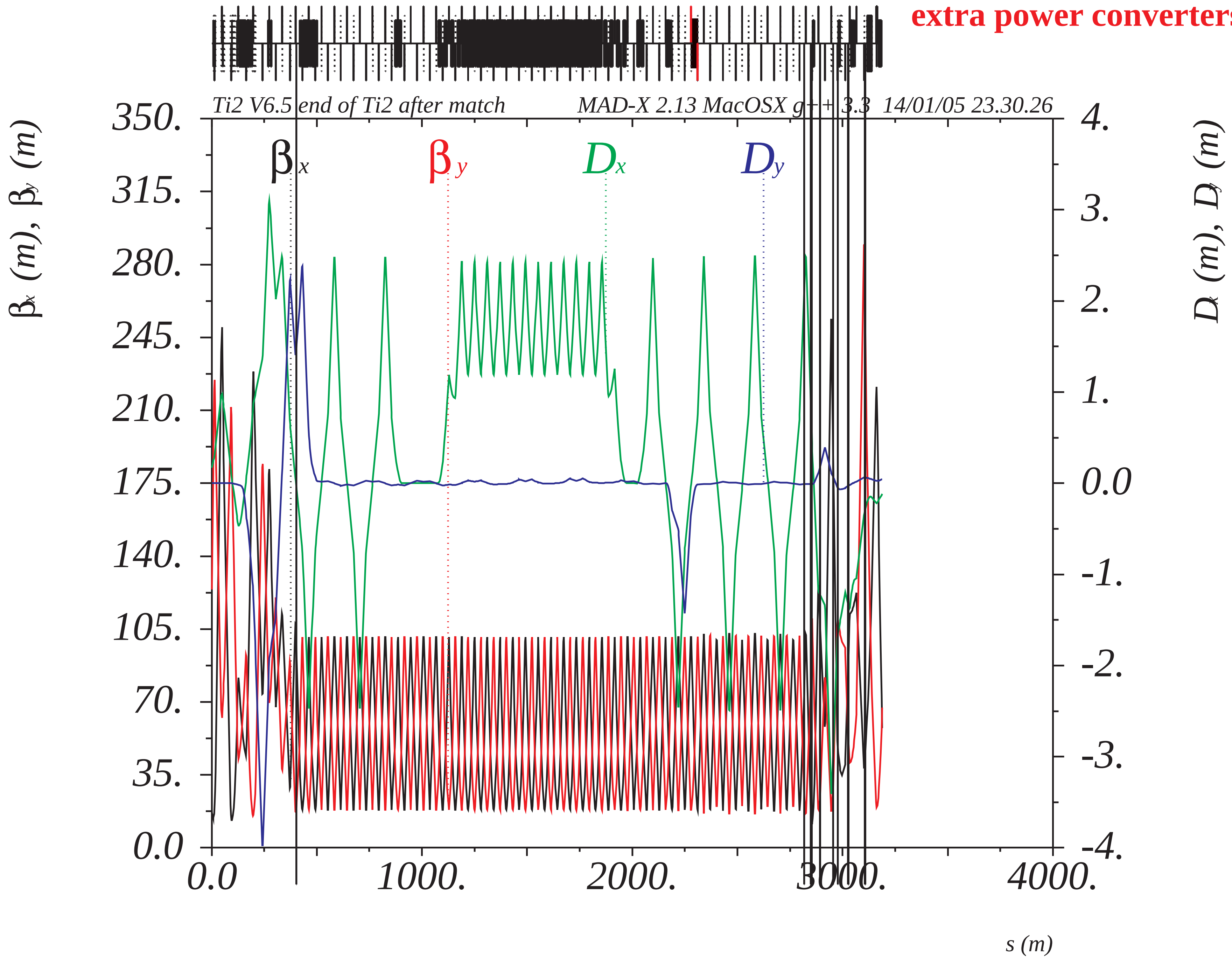
**current TI 2 optics** (to be finalized)



**TI2 optics after rematch with Dy + 12 cm**



**TI 2 optics after rematch with Dy + 12 cm with existing Quads, but individually powered with extra power converters** (280 kCHF)



# Remark on Dispersion matching

**Can also be done using orbit correctors**

**with the advantage that the βs do not change** (to first order, no offset in quads)

**this could be a nice solution to adapt to the various crossing angles**

**(good experience from LEP including dispersion free steering, CERN SL 2000-078)**

**Injection matching requires the same dispersion in the LHC and transfer lines**

**to $<$ 10 cm at the injection point, could be optimized from both sides**

**LHC : use distributed small kicks, such that the aperture is not significantly reduced**

**Transfer lines : see to which extend feasible with foreseen correctors**

**- we also need clean steering into the LHC and enough aperture in the line**

**---> to be studied**

# Conclusion

- **Excellent matching at injection is important for the LHC**
- **A flexibility of about 20% in βs and 10 cm in dispersion is required to be able to adapt to crossing angles and match to the real LHC with tolerances**
- **This is feasible with the transfer lines with some loss of collimation efficiency**

  The TCDIs are placed in the LHC matching sections which couples β and Δμ

  **A 20% change in β can cause 15º in phase advance between TCDIs or roughly 10% loss in protected aperture** (to be verified by simulations)
- **Much larger changes** (like β* 10 -> 18 m) **cannot be matched without hardware changes. Do not use the alignment optics (Q1-Q3 off) in the IR used for injection**
- **Some gain in flexibility ( in dispersion) can be achieved with extra power convertors, but probably also using orbit correctors**

  **- to be studied further** "golden orbit at injection"