Aperture requirements versus β*
in the LSS magnets.

- Strategy and general considerations
- First inventory for Phase I
- Do we really need to change D1 for Phase I?
- Perspectives for Phase II
- Summary and conclusions

Strategy and general considerations (1/5)

- **Starting point:**

→ **Start from the nominal LHC layout Version 6.5**, for survey, Power Converter limitations, magnet aperture (in particular b.s. orientation).

→ **Rematch IR1/IR5 for different values of β^* with a b-b sep. of 10σ** while respecting the **nominal gradients of the MS and DS magnets.**

→ Using the present set of mechanical and beam tolerances for CO, beta-beat,..(see LHC design report), **evaluate the new aperture requirements** of the LSS magnets to be compatible with an opening of the primary jaw of **n1=9** (relaxed in order to partially eliminate any impedance related problems at least up to the ultimate intensity, JPK et al., PAC2007).

→ When applicable, try to modify the **beam-screen orientation** (e.g. in Q4/Q5/D2), the **beam-pipe characteristics** (e.g. elliptical vs rectangular for D1) or **the aperture requirements for warm magnets** (D1) **before requesting any magnet changes**.

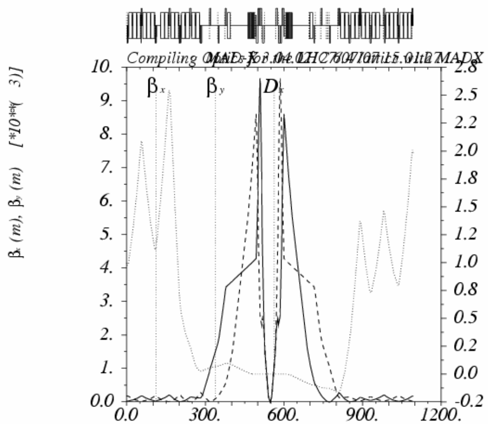
Strategy and general considerations (2/5)

- **First good news:**

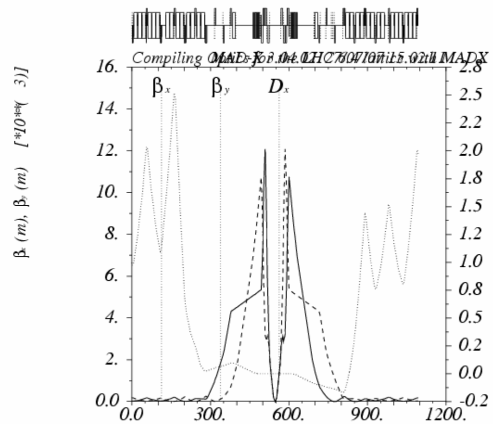
1. Forgetting aperture, IR1/5 are matchable up to the **ultimate β^* of 15 cm**

(~ Q' correct-ability limit by the arc sextupoles for two squeezed IR's with round beams)

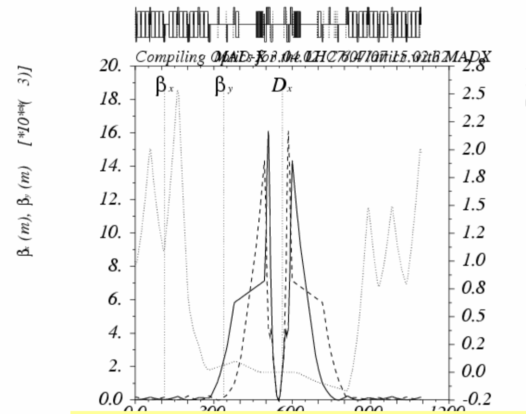
2. Below 15 cm, **gradient limitation obtained at Q7 and in some MQT/MQTL.**



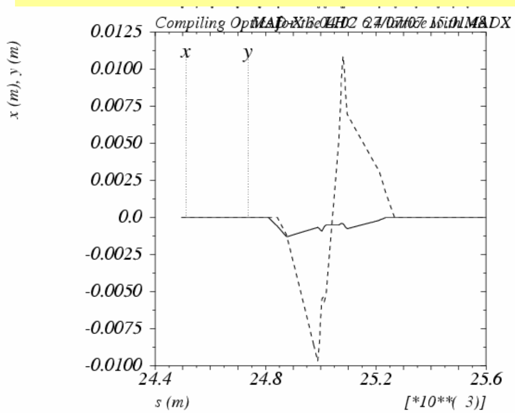
β^*=25 cm → β_{max}=9.7 km
θ_c =225 μrad → x_{max}=10.9 mm

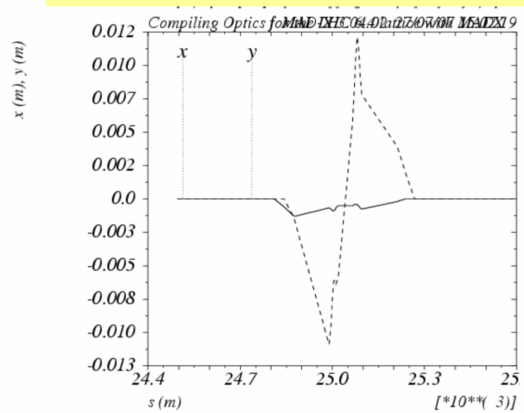


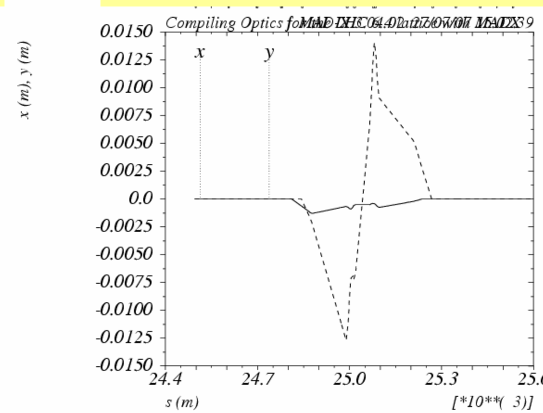
β^*=20 cm → β_{max}=12.1 km
θ_c =251 μrad → x_{max}=12.1 mm



β^*=15 cm → β_{max}=16.1 km
θ_c =290 μrad → x_{max}=14.1 mm







Strategy and general considerations (3/5)

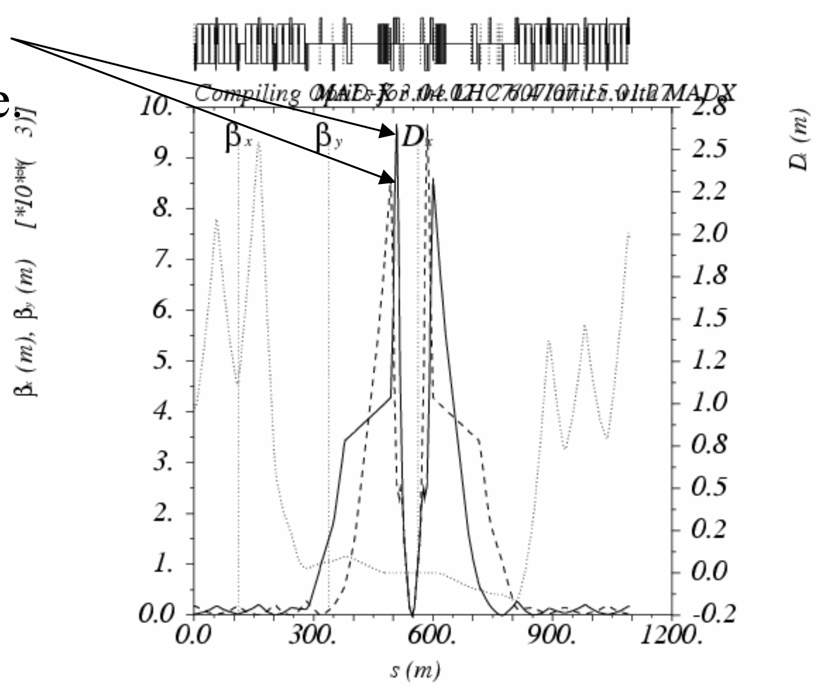
- **Second “good” news:**

→ The V6.5 triplet layout (quad. inter-distance) is no longer optimized due to the need of repositioning the BPM@Q2 (in between 2 parasitic Xings) and the (a3,a4,b4) corrector package on the non-IP side of Q3 (LPN349).

→ **Asymmetry of the peak beta-functions** inducing an increase by ~10% of the β's, i.e. a loss of aperture of $\Delta n1 \sim 0.05 \times n1$

→ **A margin of 10% in β_{max}** (and possibly slightly more in the LSS) has to be kept in mind for an optimized triplet:

- fine tuning of l^* vs triplet layout to accommodate the BPMs.
- equal and possibly minimal inter-distance between Q1/Q2 and Q2/Q3.



→ Input urgently needed to define the min. quad interconnect length

Strategy and general considerations (4/5)

- **Disclaimer:**

→ Given different working points $(n1, \beta^*)_{target}$, the present approach will produce **optimistic aperture specifications** for the LSS and MQX magnets because assuming **no limitation of peak field in the triplet, G_{MQX} ~203 T/m** (quite constant with β^*).

→ Then for a **"real" triplet of max. gradient G_{max}** and a given aperture [mm] in the LSS magnets compatible $(n1, \beta^*)_{target}$ w/o MQX field limitations, a **simple scaling law** can be applied to guess **the actual LSS acceptance $n1_{actual}$ for a target β^*_{target}** or **the minimum allowed β^*_{actual} for a given target $n1_{target}$** in the LSS:

$$\frac{n1_{actual}}{n1_{target}} = \underbrace{\sqrt{1.1}}_{\text{gain of 10\% in beta for an optimized triplet layout}} \times \underbrace{\sqrt{\frac{G_{\max}[\mathrm{T/m}]}{203}}}_{\substack{\text{increase of the beta function for a longer triplet at constant } l^* \\ (G_{\max}\times L_{MQX}\sim Cst \text{ and } \hat{\beta}\times L_{MQX}\sim Cst)}} \times \underbrace{\sqrt{\frac{\beta^*_{actual}}{\beta^*_{target}}}}_{\text{increase of the beta function for a smaller } \beta^* \text{ at constant } l^*} \qquad (1)$$

→ Example given in the next slides.

→ Of course, as soon as the triplet related parameters will have been frozen, a rematching of the optics will have to be performed to cleanly validate these results.

Strategy and general considerations (5/5)

- **Few words on the nominal aperture of LSS1/5**

1) Beam-screen orientation:

→Possible bottle-neck expected in D2-Q4:

VV orientation as in the arcs, which is not optimized both for the inj. and col. optics, but still OK (n1 >> 7) for the nominal LHC ($\beta^* = 55$ cm).

Only one aperture is concerned in D2/Q4.

→ Possible bottle-neck expected at Q5:

The orientation is optimized for the injection optics in contradiction with the demand of the collision optics at smaller β^*.

The two apertures of Q5 are concerned.

2) Clearance between b.s. and coils

Rather similar for MQM/MQY/MQX (~11-12 mm in diameter), but substantially larger in D2 (17.4 mm).

→ This clearance will be assumed constant regardless of the b.s. absolute dimension, but for D2 (within 2 mm, see next slides)

3) Shape of the beam-screen

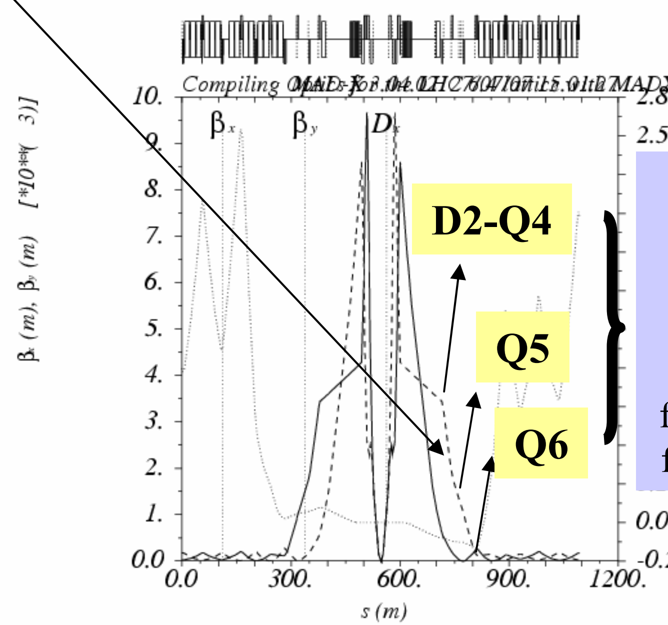
Diam. – Height ~ 10 mm for all magnet types

→ will be assumed constant regardless of the b.s. absolute dimension.

Mag.	Inner coil diameter[1)] [mm]	Cold bore diameter OD/ID [mm]	Aperture separation [mm]	Aperture type	Inner dimension of the beam-screen[2,3)] [mm]	Beam-screen orientation
MQX	70	66.5/62.9	×	*Rectellipse*	Diameter :57.8 Gap height:48.0	H in IR1 V in IR5
D1	63	×	×	*Ellipse*	Big axis :128 Small axis: 53	V
D2	80	73.0/69.0	188	*Rectellipse*	Diameter :62.6 Gap height:52.8	VV for D2.L1/5 VV for D2.R1/5
Q4	70	66.5/62.9	194	*Rectellipse*	Diameter :57.8 Gap height:48.0	VV for Q4.L1/5 VV for Q4.R1/5
Q5	56	53.0/50.0	194	*Rectellipse*	Diameter :45.0 Gap height:35.3	HV for Q5.L1/5 VH for Q5.R1/5

[1)]: gap height for the warm D1. [2)]: beam pipe for D1. [3)]: including alignment and thickness toleran

Key parameters defining the nominal X-section and the aperture of the MQX. D1,D2,Q4 and Q5 in IR1 & IR5 (LHC V6.5)



$\beta_y > \beta_x$ even if Q5 is x-focusing (conversely for the left side and for the other beam)

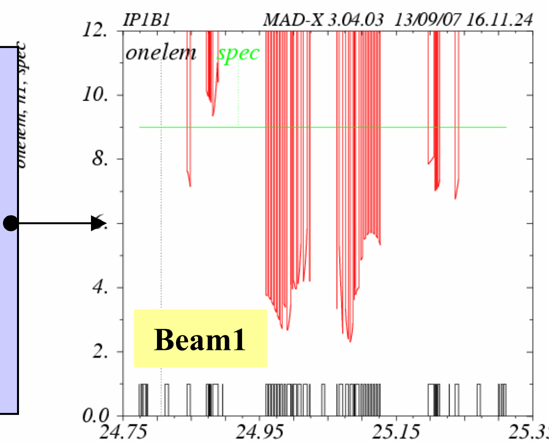
Modifications needed for Phase I (1/3)

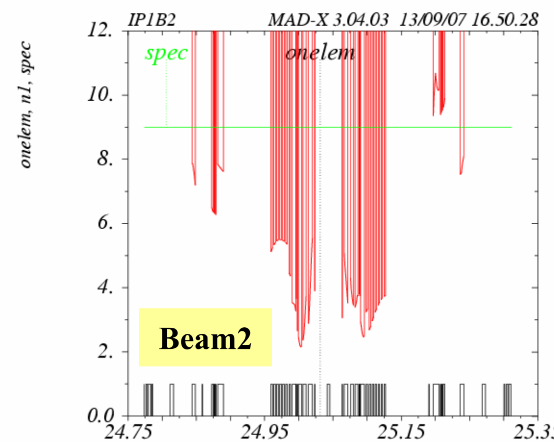
- **Proposed target parameters:**

  $\beta^* = 25$ cm and n1=9 for all magnets (see next slide for a warm D1)

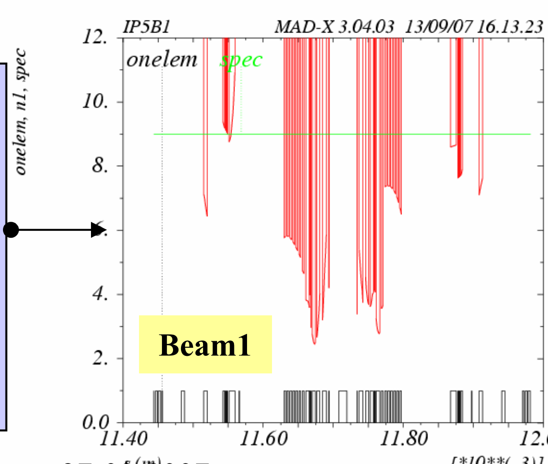
- **What happens w/o changing any magnets?**

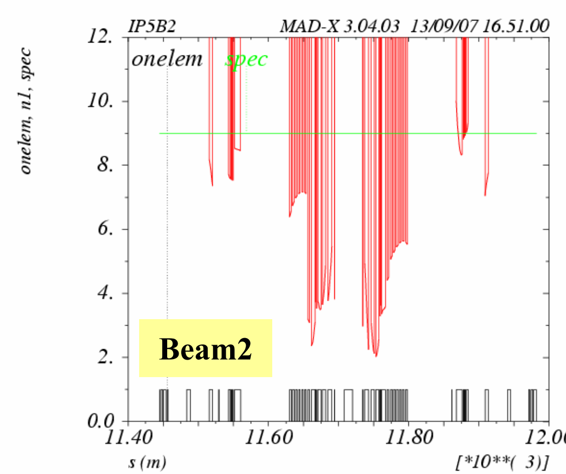
> ## ➢ IR1 (V-Xing)
> 1) MQX: n1 ~2.5
> 2) D1 : n1=2.5→4 (first module more critical)
> 3) D2 : n1~7.5 (for beam1/2 on the R/L side)
> 4) Q4 : n1~6.5 (for beam1/2 on the R/L side)
> 5) Q5 : n1=6.5→7.5 (both beams, both sides)
> 6) No problem at Q6 and beyond





> ## ➢ IR5 (H-Xing)
> 1) MQX: n1 ~2.5
> 2) D1 : n1=5→6 (first module more critical)
> 3) D2 : n1~8.5 (for beam1/2 on the R/L side)
> 4) Q4 : n1~7.5 (for beam1/2 on the R/L side)
> 5) Q5 : n1=6.5→7.5 (both beams, both sides)
> 6) No problem at Q6 and beyond





Modifications needed for Phase I (2/3)

- **Proposed modifications:**

→ **Change the triplet**: aperture increased from 70 mm to 113 mm.

→ **Change the D1**: new gap height increased from 63 mm of 101/89 mm in IR1/5.

→ **Reorient the beam-screens in D2/Q4/Q5**: VV→ VH for Q4.L & D2.L, VV→HV for Q4.R & D2.R, HV→VH for Q5.L, and VH→HV for Q5.R (one aperture concerned in Q4/D2 and both apertures in Q5).

1) n1~9.5→ 10 in Q5

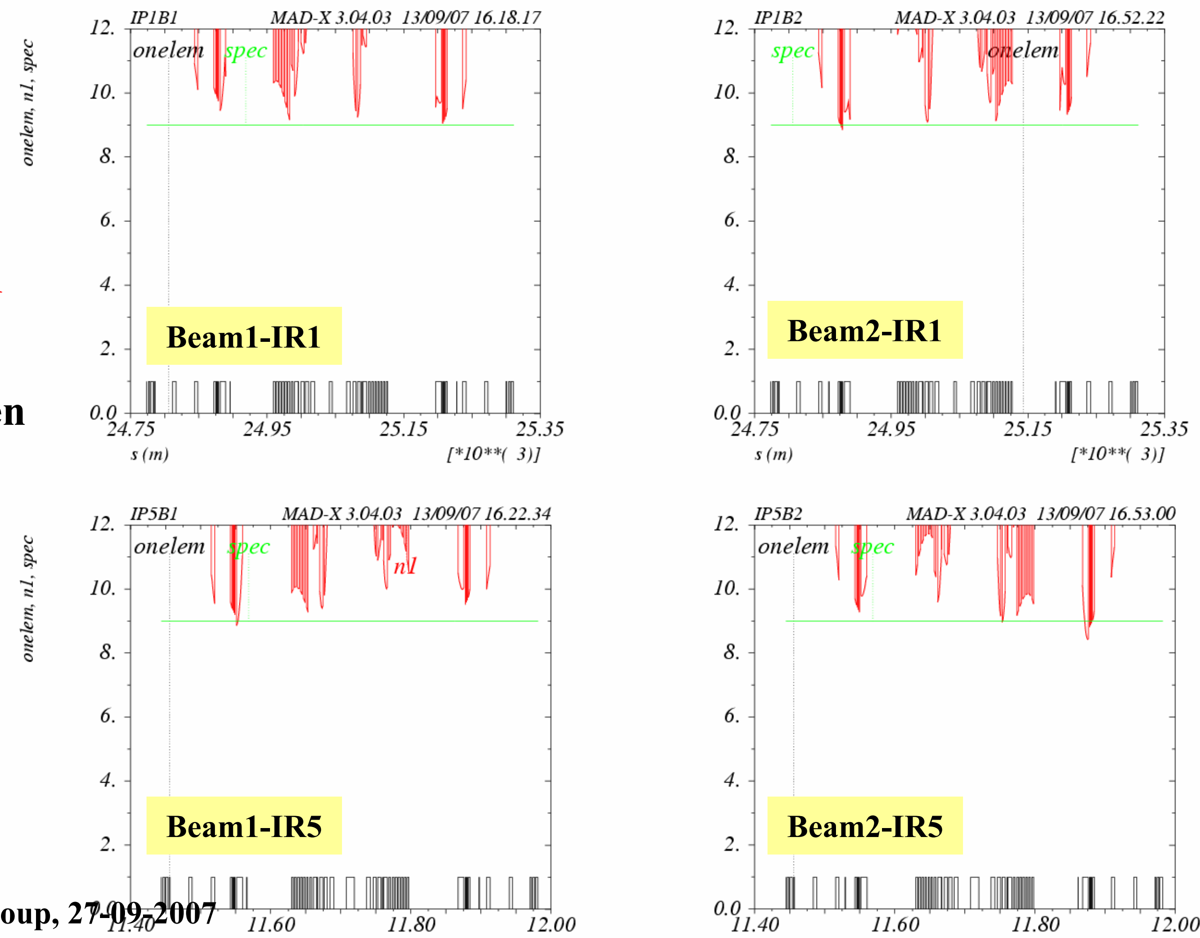
2) n1~9→ 9.5 in Q4

3) ~1mm aperture (in radius) still needed in D2 (l5.b1 and r5.b2)

→ **Re-fiducialisation with beam-screen** (to absorb the 1mm b.s. alignment tolerance),

→ or **H installation shift of ±1mm** (inter-connectability with Q4??),

→ or **Change of the cooling system** to reduce the 7 mm clearance between coils and cold bore (compared to 3-3.5 mm for other magnets).



Modifications needed for Phase I (3/3)

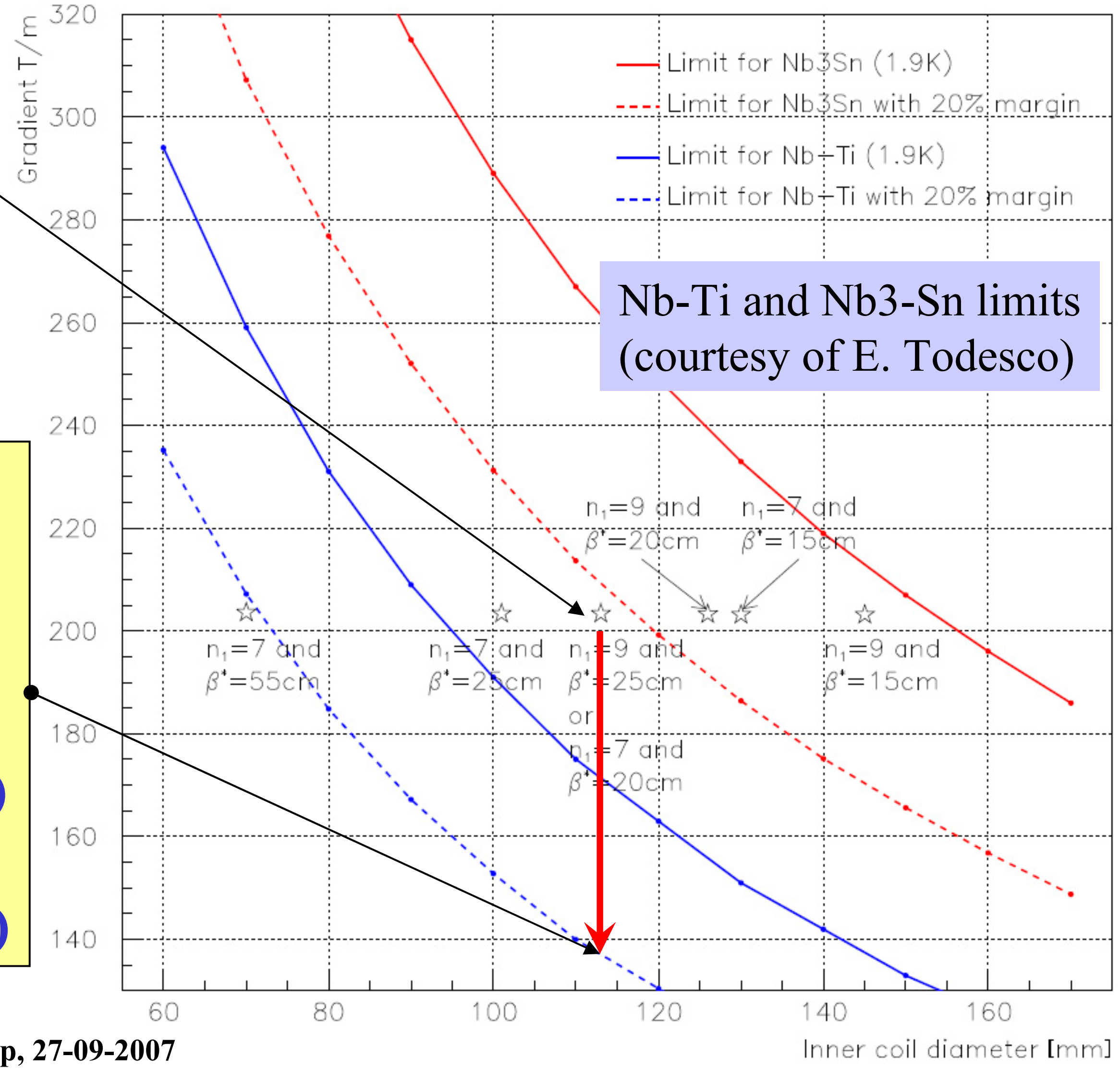
- **Downgrading the performance for a Nb-Ti triplet:**

MQX working point obtained:
G = 203 T/m, Ap. = 113 mm
→ OK for Nb3Sn

Gradient to be reduced to
G ~ 140 T/m for Nb-Ti

→ Longer triplet needed (~45% increase)
→ Present aperture requirements compatible with (see Eq. (1))

(n1=8 in the LSS, β* = 25cm)
or
(n1=9 in the LSS, β* = 33cm)



Do we really need to change D1 for Phase I ?

- **Vertical aperture limitation in D1**

→ **W/o change,** n1 ~ 2.5 in IR1 (V-crossing) and n1 ~ 5 in IR5 (H-crossing)

→ **Forgetting the V-crossing in IR1** (HH scheme, also beneficial for D_y), the D1 acceptance is increased up to n1= 6.1 (for the worst module).

→ Assuming a **rectangular instead of elliptical** chamber (h = a = 128 mm, v = b = 53 mm, possibly causing strong heat load in D1 during bake out), the D1 acceptance is in the range n1= 6.5/8.1 for the first/last module.

→ while, for the prim./second. jaws set to 9/10.5σ, a target of n1~8 (i.e. vertical aperture of 1.2 × 8 = 9.6σ) might just be acceptable in the warm D1: collimation inefficiency increased from 10^{-4} to 10^{-3} (courtesy of C. Bracco) → 100W beam deposition for 1h life-time and 3×10^{14} protons, that is comparable to the debris from the IP for $L = 2\times 10^{34}\mathrm{cm}^{2}\mathrm{s}^{-1}$.

→ D1 has to be changed (except perhaps the last module), preferably taken already into account the demands for phase 2.

Perspectives for Phase II (1/1)

- **Proposed target parameters:**

$\beta^* = 15$ cm and n1=9 for all magnets.

1) … assuming no field limitation in the triplet → 205 T/m for an inner coil diameter of 145 mm:

i) **b.s. rotation** in Q4/Q5/D2
ii) **Q5** must become "**MQYL" type**
iii) **90 mm** aperture requested for **Q4**
→ X-talk between aperture??
iv) **95-100 mm** aperture requested for **D2**
→ Warm D2, e.g. MBW type, might be the only possible option.
v) **120-130 mm** gap requested for **D1**
→ Cold D1 might be the only possible option.
vi) **145 mm** aperture in **the triplet MQX**

Mag.	Inner coil diameter[1)] [mm]	Cold bore diameter OD/ID [mm]	Aperture separation [mm]	Aperture type	Inner dimension of the beam-screen[2,3)] [mm]	Beam-screen orientation
MQX	145	141.5/137.9	×	*Rectellipse*	Diameter :132.8 Gap height:123.0	H in IR1 V in IR5
D1 in IR1 (V-cros.)	132	×	×	*Ellipse*	Big axis :140 Small axis:122	V
D1 in IR5 (H-cros.)	119	×	×	*Ellipse*	Big axis :140 Small axis:109	V
D2 in IR1 (V-cros.)	97	92.0/88.0	188	*Rectellipse*	Diameter :81.6 Gap height:71.8	VH for D2.L1 HV for D2.R1
D2 in IR5 (H-cros.)	94	89.0/85.0	194	*Rectellipse*	Diameter :78.6 Gap height:68.8	VH for D2.L5 HV for D2.R5
D2 (universal)	100	95.0/91.0	188	*Rectellipse*	Diameter :84.6 Gap height:74.8	VH for D2.L1/5 HV for D2.R1/5
Q4	91	87.5/83.9	194	*Rectellipse*	Diameter :78.8 Gap height:69.0	VH for Q4.L1/5 HV for Q4.R1/5
Q5 (becomes MQY type)	70	66.5/62.9	194	*Rectellipse*	Diameter :57.8 Gap height:48.0	VH for Q5.L1/5 HV for Q5.R1/5

[1)]: gap height for a warm D1. [2)]: beam pipe for D1. [3)]: including alignment and thickness tolerances.

2) … Rescaling the target parameters for a "real" Nb3Sn triplet

→ **Gradient limited to 170 T/m** for an inner coil diameter of **145 mm** (see slide 9).
→ Very close to the triplet parameters of LPR1000 (166 T/m and 150 mm for $\beta^* = 14$ cm).
→ Actual performance reduced to **($\beta^* = 15$ cm, n1~8.5)** or **($\beta^* = 16$ cm, n1=9).**

Summary and conclusions

- To minimize the modifications in the LSS, an **IR upgrade phase I** compatible with **n1 ~ 8→9** in the MQX and LSS magnets and **β* ~ 25 → 35 cm**, requires

1. an **as short as possible triplet**, e.g. **(G~140 T/m, D~115 mm)** at the limit of Nb-Ti.
2. a **change of D1: 90 or 100 mm gap height** for H or V Xing.
3. a **reorientation the beam-screens** in one of the two apertures of each **Q4-D2** and in both apertures of the 4 Q5 magnets of **IR1&IR5**.

- To prepare an **LHC upgrade phase II**, compatible with **n1 ~ 9** and **β* ~ 15 cm**,

1. an **as short as possible** Nb3Sn triplet, e.g. **(G~170 T/m, D~145 mm**), is recommended.
2. **wide aperture** (90 mm), moderate gradient (~120 T/m) **two-in-one quadrupoles** shall be studied to replace the **MQY type Q4.**
3. The option of a **cold D1** has to be studied (~140-150 mm aperture).
4. The cold option of a **two-in-one D2** will have to be revised (~100 mm aperture!!) and possibly replaced by a **warm option** (e.g. MBW type design).

- In all cases, **no modification of the LSS at Q6 and beyond** is a priori required but optics rematching and aperture checks a posteriori will be needed to safely validate this statement when the triplet layout and parameters will have been frozen.