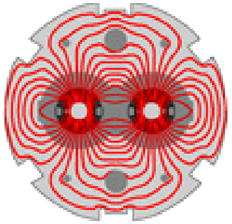
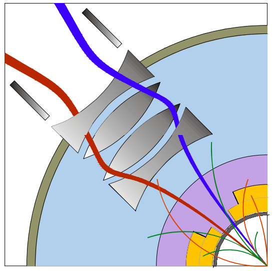


# LHC IR Upgrade Phase-I: Goals and Conceptual Design

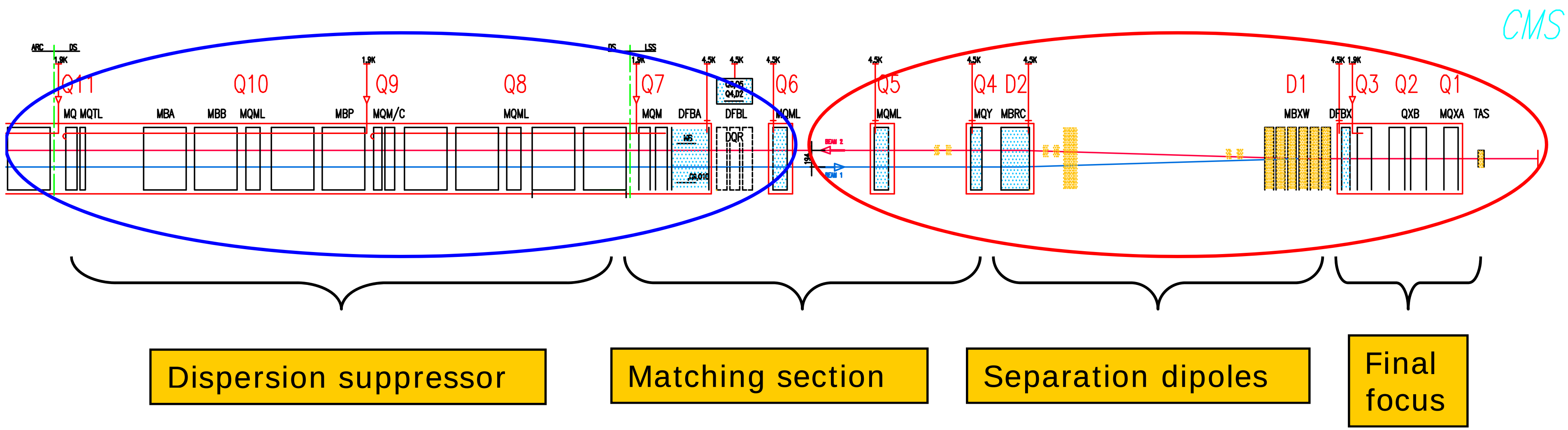


1. Upgrade goals and constraints
2. Conceptual design
3. Collaborations
4. Perspectives

Acknowledgments to all contributors to the LHC Phase-I Upgrade conceptual design

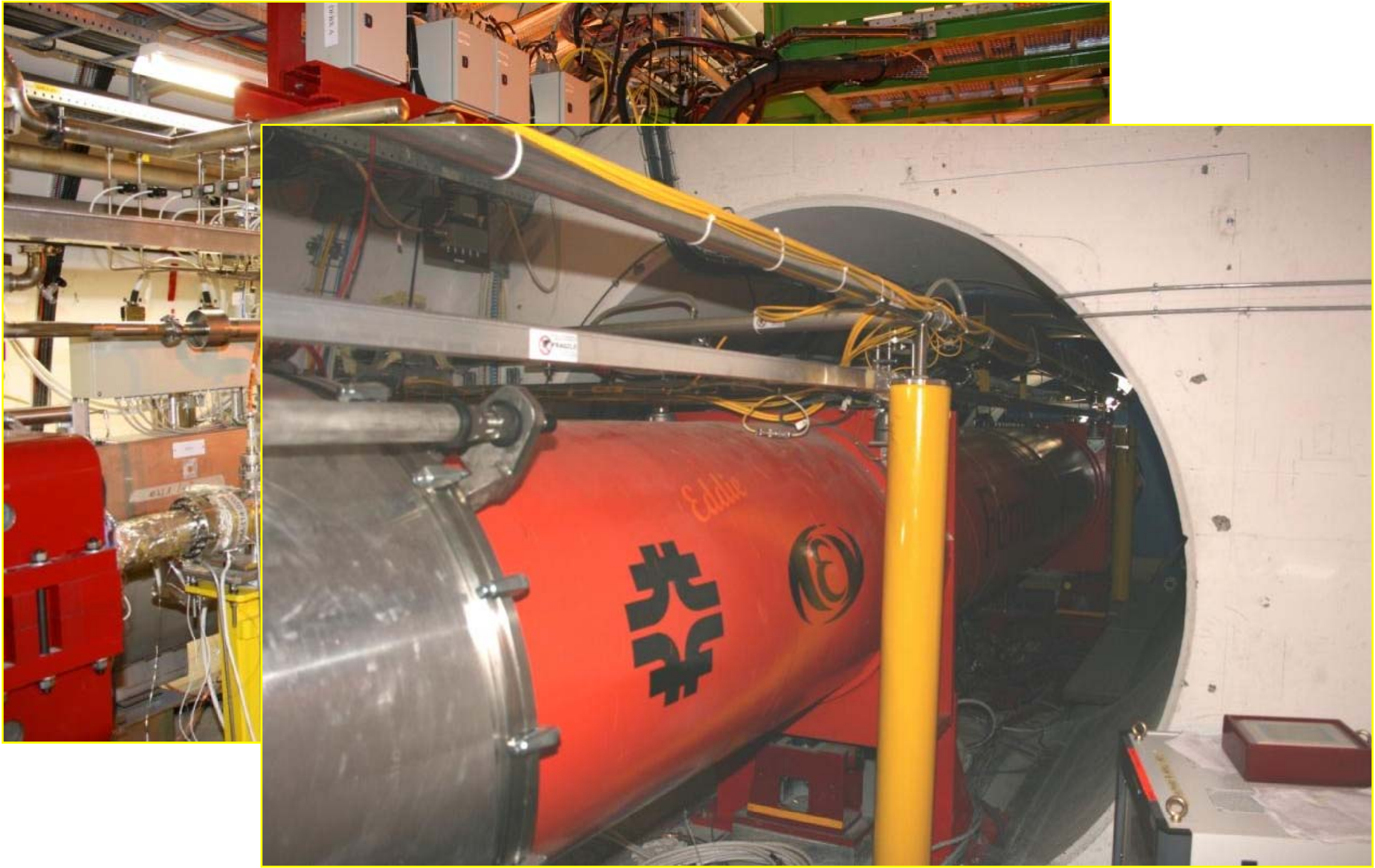
R. Ostojic, LHCC, 16 Feb 2009

# The ATLAS and CMS interaction regions

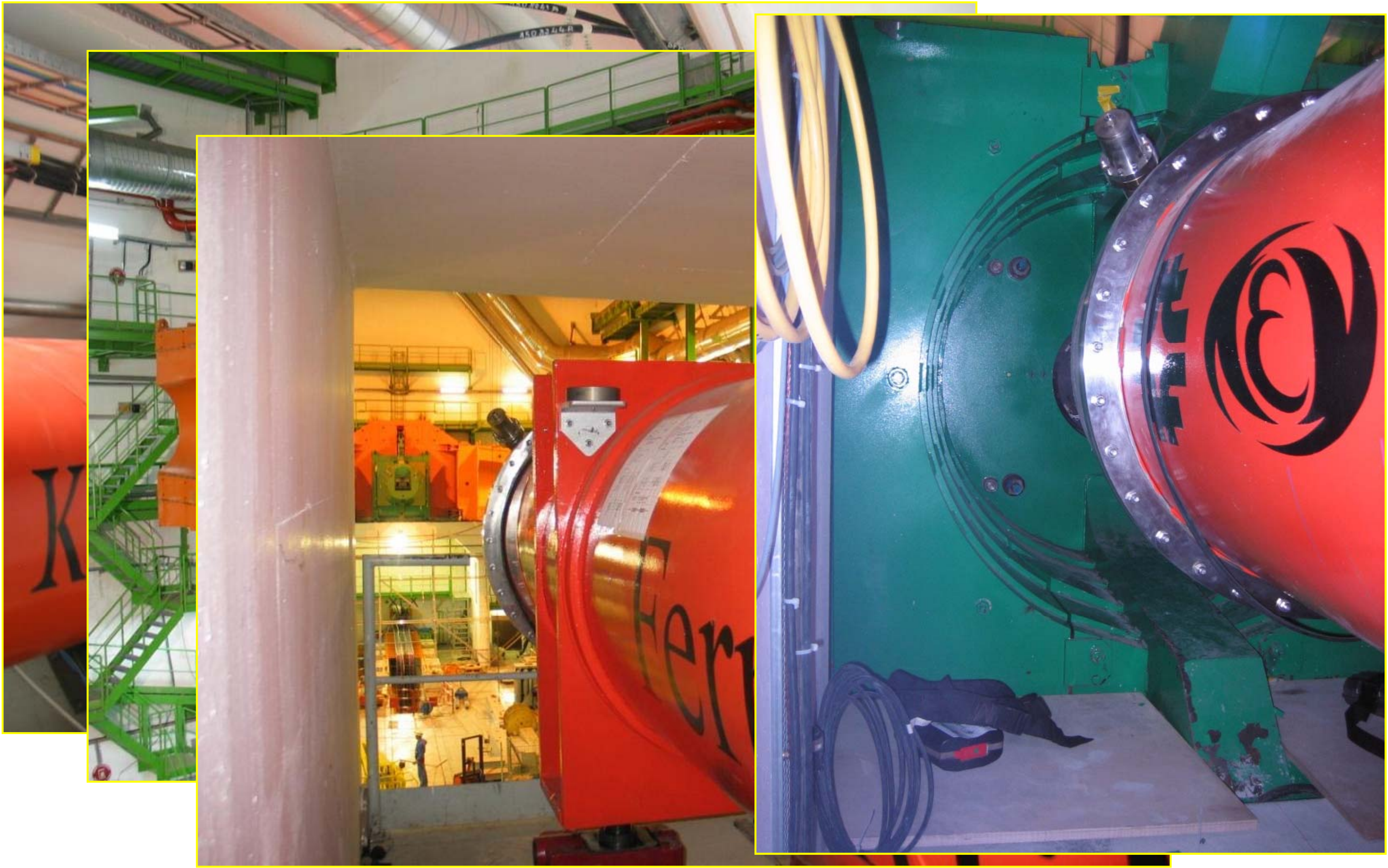



- Triplet position $L^* = 23$ m
- Triplet gradient 205 T/m
- Triplet aperture
  - Coil 70 mm
  - Beam screen 60 mm $\rightarrow \beta^* = 0.55$ m
    $\rightarrow \mathcal{L} = 10^{34}$
- Power in triplet ~ 180 W @ 1.9 K

# The low-β triplet in IR1



# The low-β triplet in IR5



# The matching sections

# LHC IR Upgrade - Phase I

**Goal of the upgrade:**

**Enable focusing of the beams to $\beta^*=0.25$ m in IP1 and IP5, and reliable operation of the LHC at 2 to 3 $10^{34}$ $cm^{-2}s^{-1}$ on the horizon of the physics run in 2013.**

**Scope of the Project:**

1. Upgrade of ATLAS and CMS interaction regions. The interfaces between the LHC and the experiments remain unchanged.
2. The cryogenic cooling capacity and other infrastructure in IR1 and IR5 remain unchanged and will be used to the full potential.
3. Replace the present triplets with wide aperture quadrupoles based on the LHC dipole (Nb-Ti) cables cooled at 1.9 K.
4. Upgrade the D1 separation dipoles, TAS and other beam-line equipment so as to be compatible with the inner triplets.
5. Modify matching sections to improve optics flexibility and machine protection, and introduce other equipment relevant for luminosity increase to the extent of available resources.

# Project milestones

| | |
|---|---|
| **Project Start** | **Jan 2008** |
| **CD Report** | **Nov 2008** |
| TD Review | mid 2009 |
| Model magnets | end 2009 |
| Pre-series quadrupole | end 2010 |
| String test | 2012 |
| Installation | shutdown 2013 |

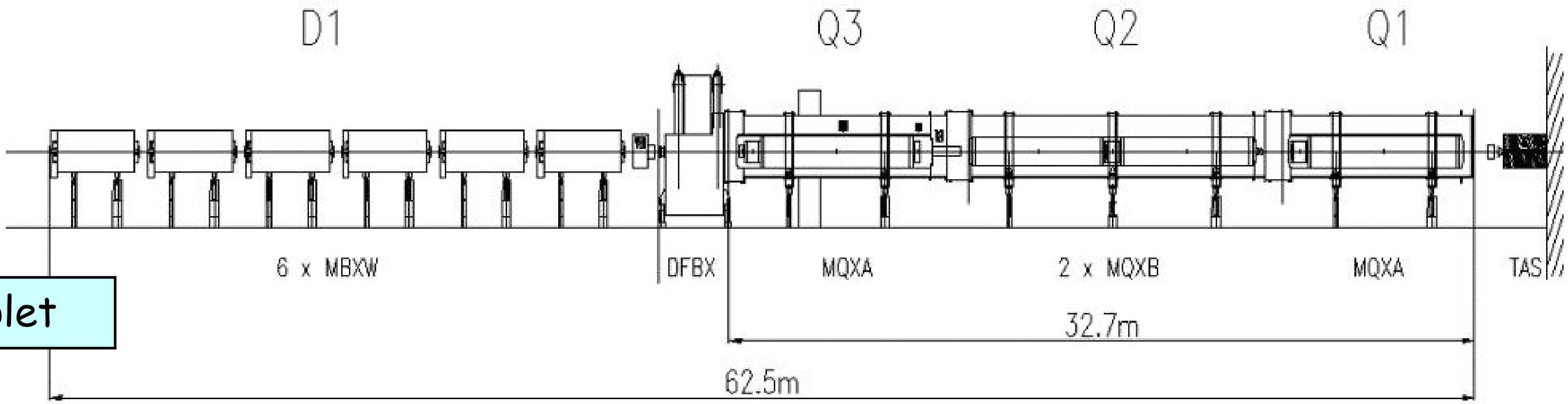
# Constraints (1)

- Interfaces with the experiments: Very tight interfaces between the triplet, TAS, shielding, vacuum and survey equipment, and beam instrumentation; no possibility of reducing L* (23m). Replacement of the TAS vacuum chamber requires removal of the TAS from the experimental caverns.
- Cryogenics: Ultimate cooling capacity is 500 W@1.9K in each triplet. The triplet in 5L may have less cooling capacity available than the others. Replacement of triplets in IR1/5 requires at present warm-up of 4 sectors.
- Quench protection of the triplets: Due to considerably higher stored energy, energy extraction must be included.
- Chromatic aberrations: Reduction of $\beta^*$ drives chromatic aberrations all around the LHC. A new optics solution for all arcs and insertions is necessary.

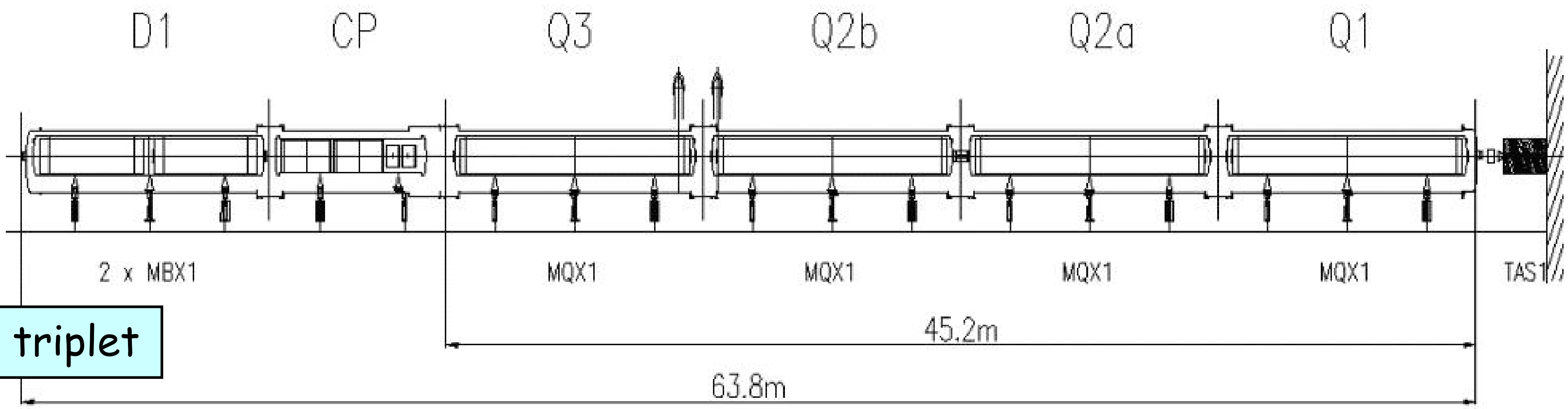
# Constraints (2)

- Accessibility and maintenance: all electronics equipment around the triplets and the DFBX should be located in low-radiation areas. Severe space constraints around IP1 and IP5 for any new equipment.
- Tunnel transport: access from the surface to IR1/5 requires that the overall dimensions of the new magnets are similar to the LHC main dipole.
- Upgrade implementation: during the extended shutdown Nov 2012-June 2013, compatible with CERN-wide planning (Linac4 commissioning, phase-I upgrade of the experiments).

# Triplet layout




LHC triplet




Phase-I triplet

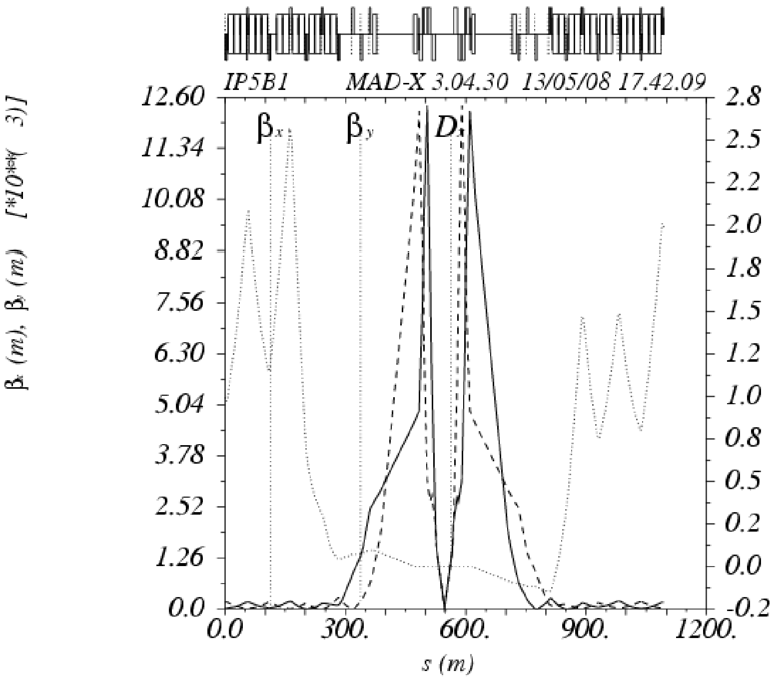
Initial proposal, iterations expected.

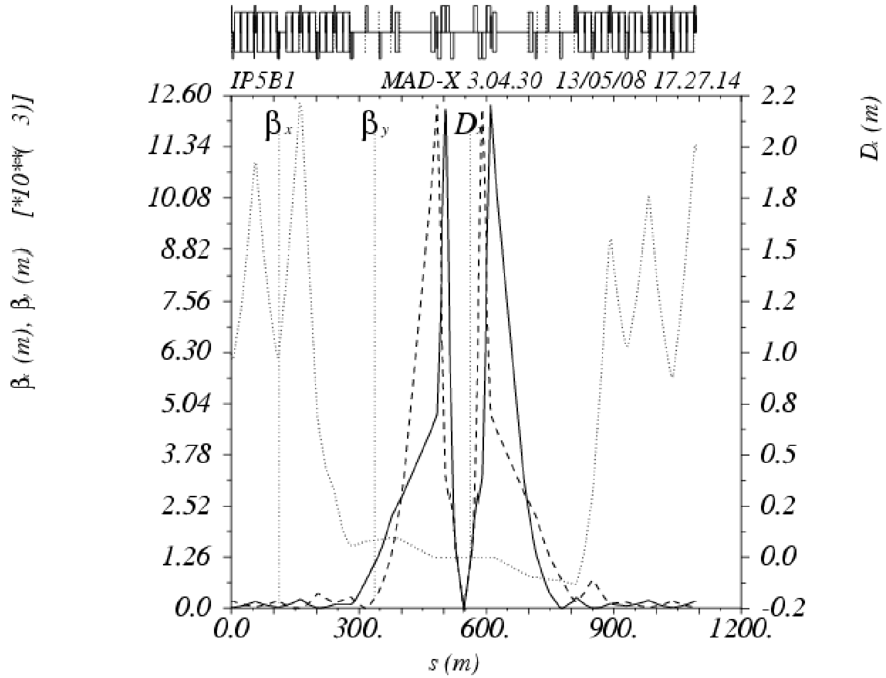
# Optics issues

- *Insertions.* The strength and aperture of the magnets are the limiting factors for reducing $\beta^*$. The largest aperture (longest triplet) is defined by the strength limitation of DS magnets and aperture of Q5.
- *Arcs*. Correction of chromatic aberrations in IR3, IR7 and in the inner triplets in IR1 and IR5 requires re-phasing of all the arcs and insertions for $\beta^* < 0.5$ m.
- *Triplets*. Parasitic dispersion in the triplets due to large crossing angle has to be controlled. Beam crossing schemes in IP1 and IP5 need to be conform.

*A complete solution for the new LHC collision optics has been developed. Considerable work is required to fully validate the flexibility and robustness of the new optics.*

# IR optics with 120 mm/125 T/m (1)




**Case IIa:**

→Triplet matched with **P=450 m, and displaced TAN, D2, Q4 and Q5.**

→ No problem of strength and matching to the arcs.

→ Injection optics easy to find.

→ Sufficient aperture expected in the LSS.

**Case IIb:**

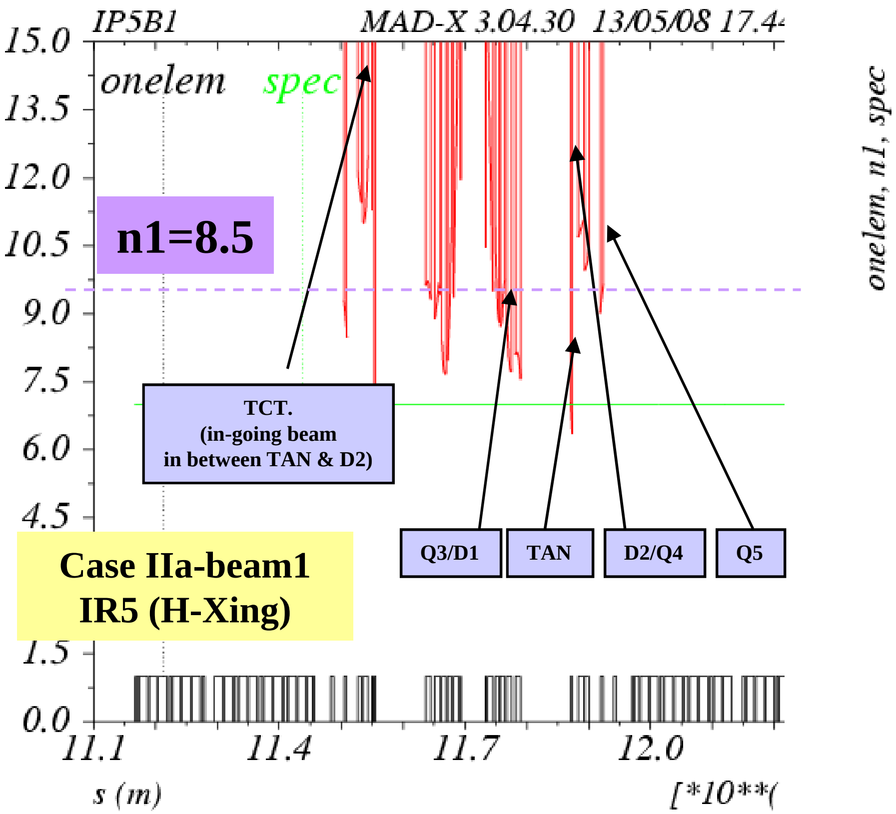
→Triplet matched with **nominal LSS** and **P further reduced to P=345 m.**

→ Matching problems: Q7 ~ 200 T/m, Q4/Q5 ~ 0.

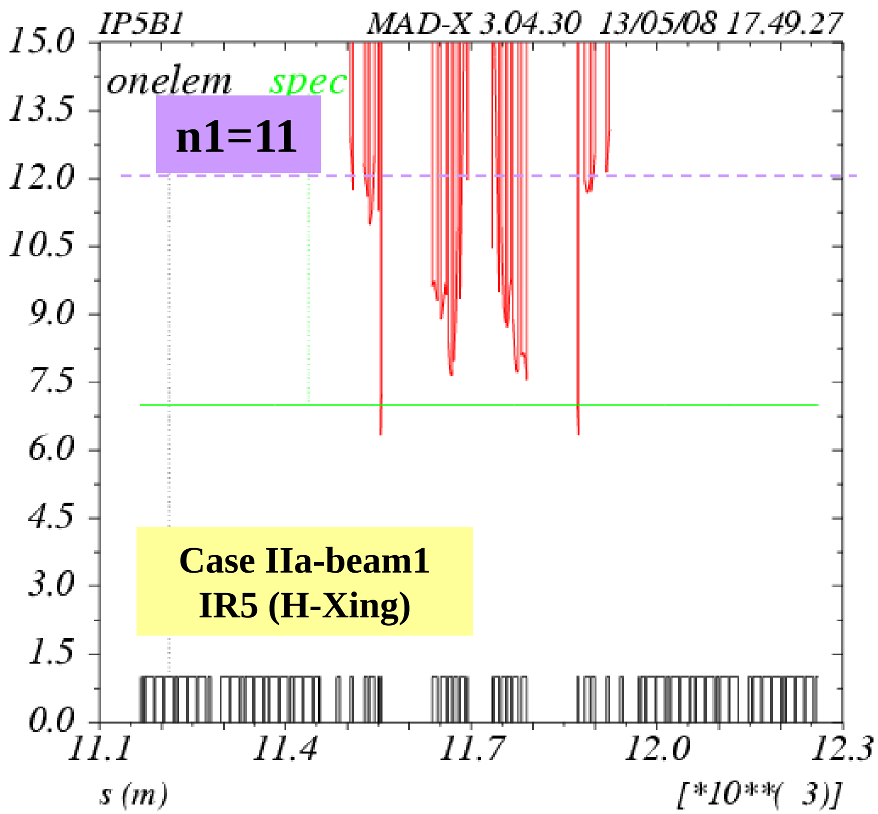
→ The natural IR phase cannot be reached limiting the injection β* (for a squeeze at constant IR phase).

→ Sufficient aperture expected in the LSS.

# IR optics with 120 mm/125 T/m (2)




**W/o beam screen rotation**




**After b.s. rotation in Q5.L, D2.R, Q4.R & Q5.R**

# Chromatic aberrations

## Linear chromaticity

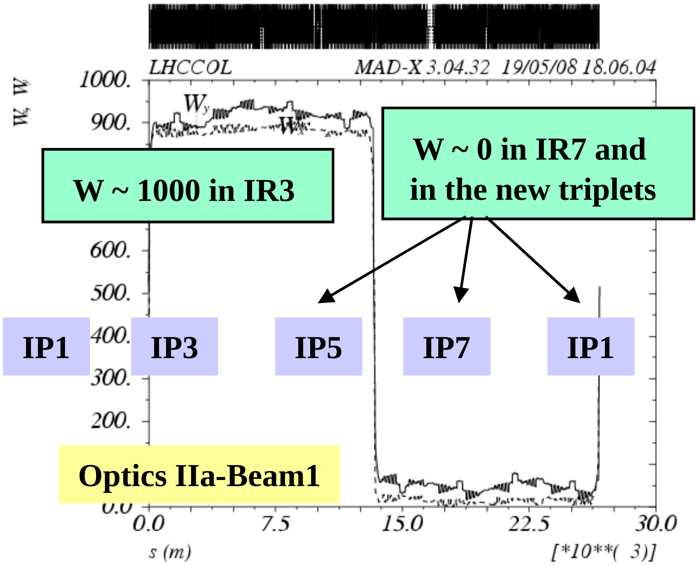
- Nominal LHC: $I_{IP} \sim 350$
- Upgrade: $I_{IP} \sim 800 \div 850$
- $Q'_{IP} \sim -65$, i.e. $\sim \Delta Q'_{nat}$ induced by the 8 LHC sectors.

## Q'' and $\Delta\beta(\delta)/\beta(0)$ (linear off-momentum $\beta$-beating)

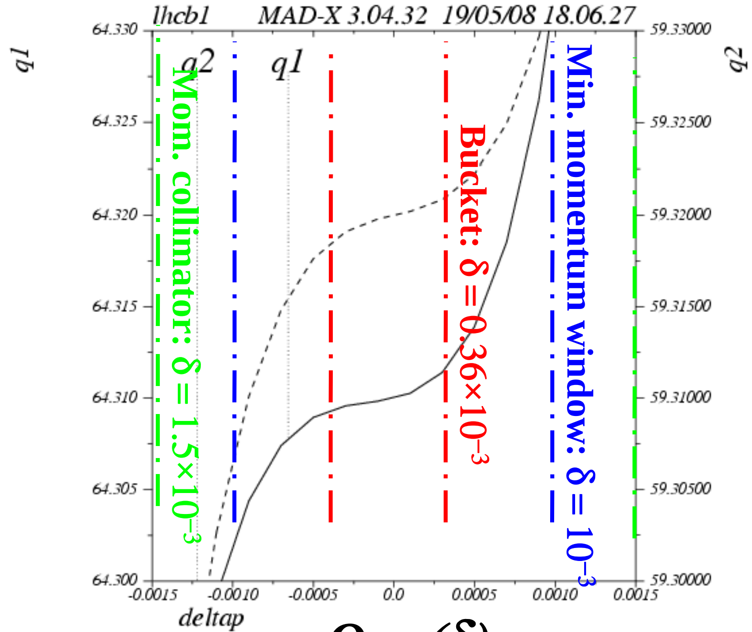
- $\Delta\beta(\delta)/\beta(0)$ can reach ~100% for $\delta=10^{-3}$. This has considerable consequences, in particular as it compromises the collimation system. The acceptable value is ~10%, as in the nominal LHC.
- By phasing IR1 and IR5, $\Delta\beta(\delta)/\beta(0)$ can be cancelled in half of the ring but is then maximized in the other half for the nominal LHC tunes (0.31/.32).
- Using the sextupole families, the contribution of the triplet to $\Delta\beta(\delta)/\beta(0)$ and Q'' can be compensated. However, depending on the sextupoles settings significant Q''' and non-linear off-momentum beta-beating can be generated.

# Chromatic corrections – strategies (1)

IR phasing (π/2 between IR1 and IR5 and correction of the IR2/3/7/8 b1-b2 phase splits).




$W_{x,y}$ (s)

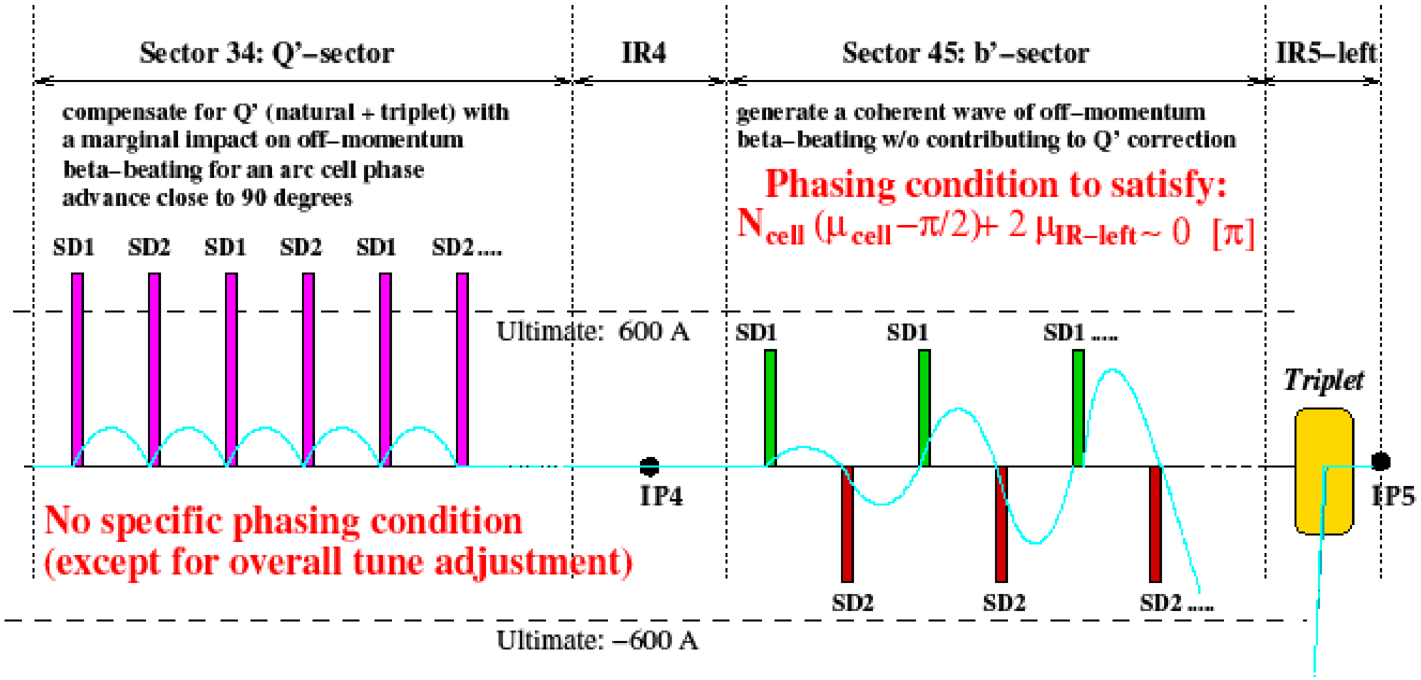



$Q_{x,y}$ (δ)

- $\Delta\beta(\delta)/\beta(0)$ minimized in IR7 but maximized in IR3 (strong reduction of collimation efficiency).
- Q' corrected to 2 units: 40%- 68% of Imax (600A) needed in SF-SD.
- No Q'', but huge Q''' (the phase advance from IP1 to IP5 is no longer π/2 for non-zero δ) which is the indication of large non-linear off-momentum β-beat.

# Chromatic corrections – strategies (2)

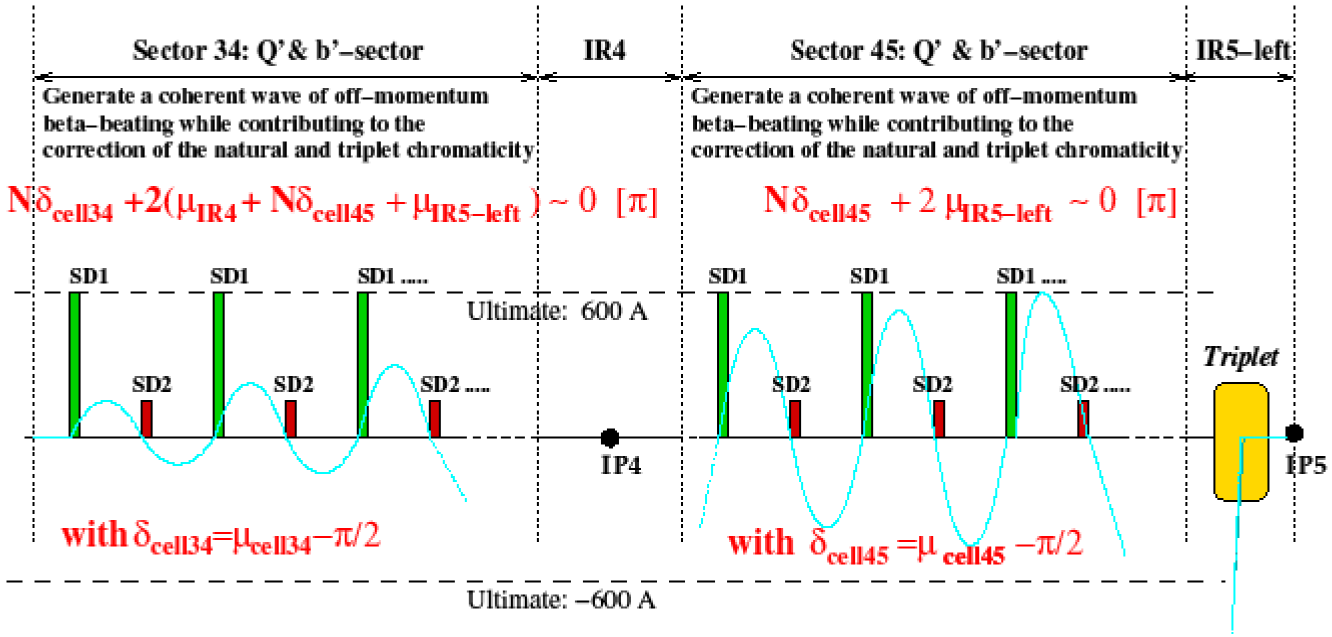
Use of sextupole families in the flip-flop mode in sectors adjacent to IP1 and IP5, and in the normal mode in other sectors.




- Combination of schemes tried but unsuccessful due to strength limit of SD family and zero crossing during squeeze.
- The generation of the $\beta'(\delta)$-wave and the correction of the MQX contribution to Q' needs to be done in the same sectors to get rid of Q''', $\beta''(\delta)$, and to avoid zero-xing of RSF/D during squeeze.

# Chromatic corrections – strategies (3)

Two β'-sectors per triplet with specific conditions for the arc cell and IR phase advances.




☺ SD families just strong enough (600 A required).
☺ No zero-crossing during the squeeze.
☺ Non-interleaved scheme (strong SD or SF spaced by ~π), small high order effects expected

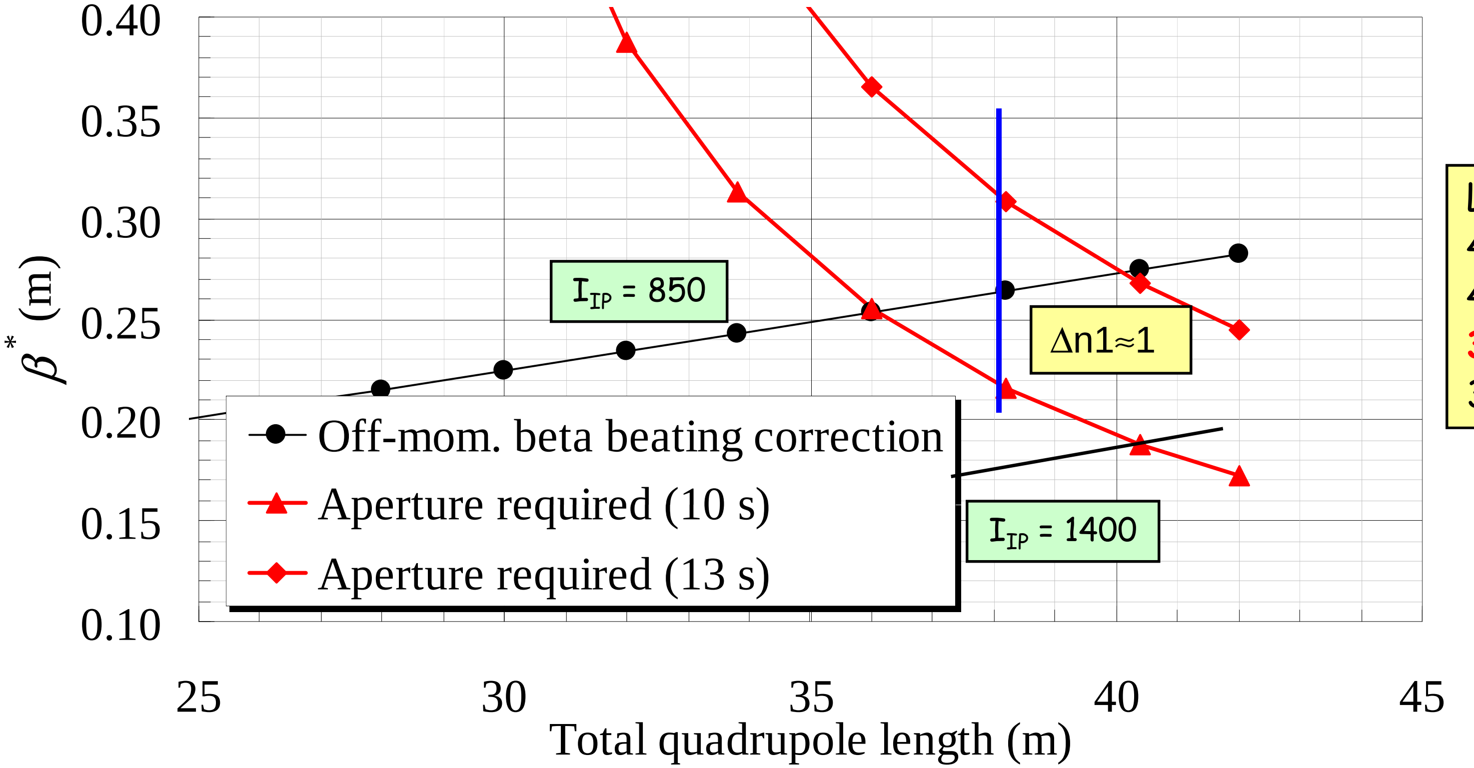
# Chromatic corrections – strategies (4)

Two β'-sectors per triplet with specific conditions for the arc cell and IR phase advances – consequences.

- Injection optics has to be changed, with a tune split of 3.
- Arc tune-shift quadrupoles are used (DS now extends up to Q22) with some impact on the aperture @ 450 GeV.
- Adjustment of phase across L/R side of IP required.
- Residual Q'' expected, correctable by the arc MO's if needed.
- The SD efficiency and then the minimum achievable $\beta^*$ depend (smoothly) on the working point.

| IR phase $\Delta\mu_x$ / $\Delta\mu_\psi$ [2π] and overall tune | V6.500 | | New optics | |
|---|---|---|---|---|
| | Beam1 | Beam2 | Beam1 | Beam2 |
| IR2 | 2.974 / 2.798 | 2.991 / 2.844 | 3.020 / 2.875 | 3.020 / 2.875 |
| IR3 | 2.248 / 1.943 | 2.249 / 2.007 | 2.220 / 1.990 | 2.220 / 1.990 |
| IR4 | 2.143 / 1.870 | 2.143 / 1.870 | 2.050 / 1.875 | 2.050 / 1.875 |
| IR6 | 2.015 / 1.780 | 2.015 / 1.780 | 2.270 / 1.625 | 2.270 / 1.625 |
| IR7 | 2.377 / 1.968 | 2.483 / 2.050 | 2.456 / 1.963 | 2.456 / 1.963 |
| IR8 | 3.183 / 2.974 | 3.059 / 2.782 | 3.050 / 2.875 | 3.050 / 2.875 |
| IR1&IR5 | 2.633 / 2.649 | 2.633 / 2.649 | 2.658 / 2.644 | 2.658 / 2.644 |
| IR1 & IR5 left | Never specified | | 1.044 / 1.754 | 1.614 / 0.890 |
| IR1 & IR5 right | Never specified | | 1.614 / 0.890 | 1.044 / 1.754 |
| Qx/Qy | 64.31/59.32 | | 63.31/60.32 | |

# Quadrupole aperture and β*




Length vs. aperture:
42 m - 140 mm
40 m - 130 mm
**38 m - 120 mm**
36 m - 110 mm

Quadrupole with a 120 mm aperture, 120 T/m chosen for the Phase-I Upgrade

# Matching sections

- The Phase-I Upgrade assumes that the operating parameters (temperature, strength, aperture) and the position of the matching section magnets (D2-Q6) remain unchanged.
- Reduction of β* inevitably reduces the aperture margin in Q4, D2 and Q5 and nearby equipment.
  - TAN vacuum chamber will have to be replaced.
  - Protection against the beam halo (tertiary collimators) will need to be extended to matching section magnets.
  - Protection of the arc magnets against diffractively scattered particles needs to be confirmed.
  - Integration of forward-physics experiments to be confirmed.
  - Background will need special attention.

Interventions on the warm equipment can be done in normal shutdown periods.

# Magnet cooling

## Triplets and correctors

- Pressurised static superfluid He bath at 1.3 bar, cooled by two-phase flow of saturated superfluid helium.
- Heat exchanger dimensioned for the ultimate power of 500 W/1.9 K and vapour velocity of 7 m/s.
- Due to the length of the QRL, the temperature from the refrigerator (1.776 K) will increase to 1.97 K in the coils at 500 W.
- Baseline: single internal heat exchanger with ID 95 mm.

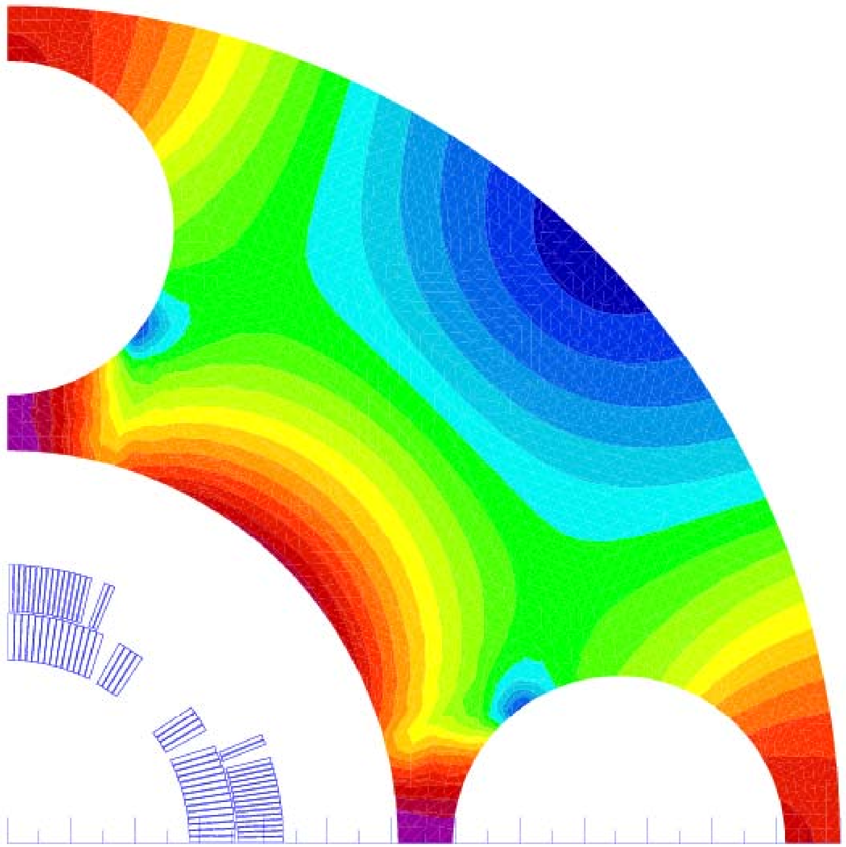
## Beam screen

- Cooling with supercritical helium, 5-20 K.
- Four standard cooling tubes (ID 3.7 mm) for a heat load of 4 W/m.

## D1 cooling

- Two-phase saturated helium (pool boiling), 4.5 K ± 0.2 K, similar to the other stand-alone magnets in the LHC.

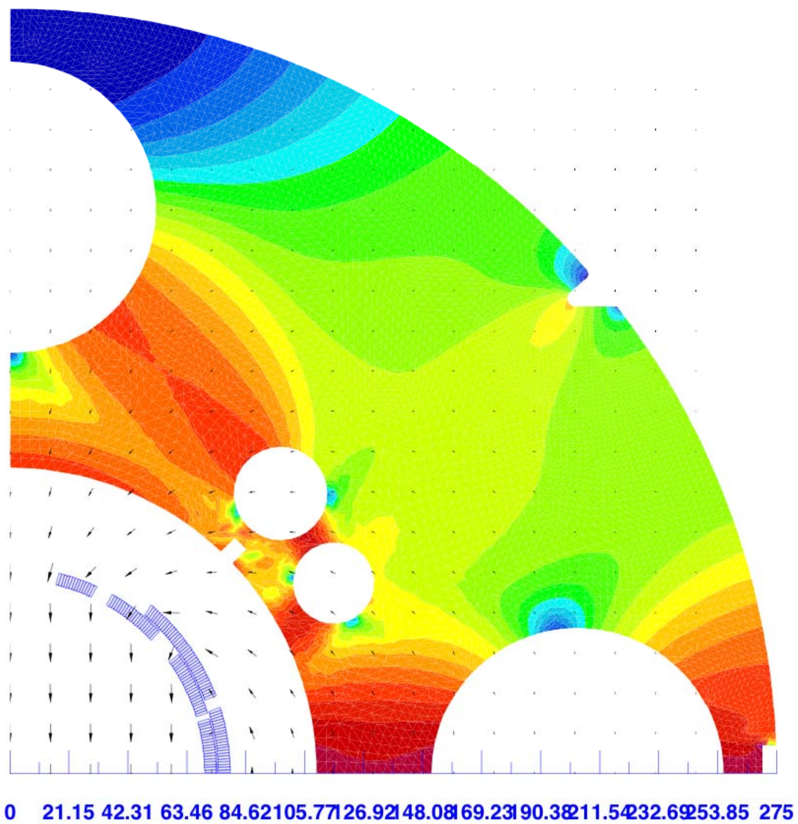
# Low-β quadrupole



- Coil aperture 120 mm
- Gradient 120 T/m
- Operating temp 1.9 K
- Current 13 kA
- Inductance 5 mH/m
- Yoke ID 260 mm
- Yoke OD 550 mm

- LHC cables 01 and 02
- Enhanced cable polyimide insulation
- Self-supporting collars
- Single piece yoke
- Welded-shell cold mass

# Correctors




MCBX

- Coil aperture 140 mm
- Field strength 6 Tm
- Operating temp 1.9 K
- Current 2.5 kA
- Inductance 55 mH/m
- Yoke ID 260 mm
- Yoke OD 550 mm

- New cable design
- Cable polyimide insulation
- Self-supporting collars
- Single piece yoke
- Welded-shell cold mass

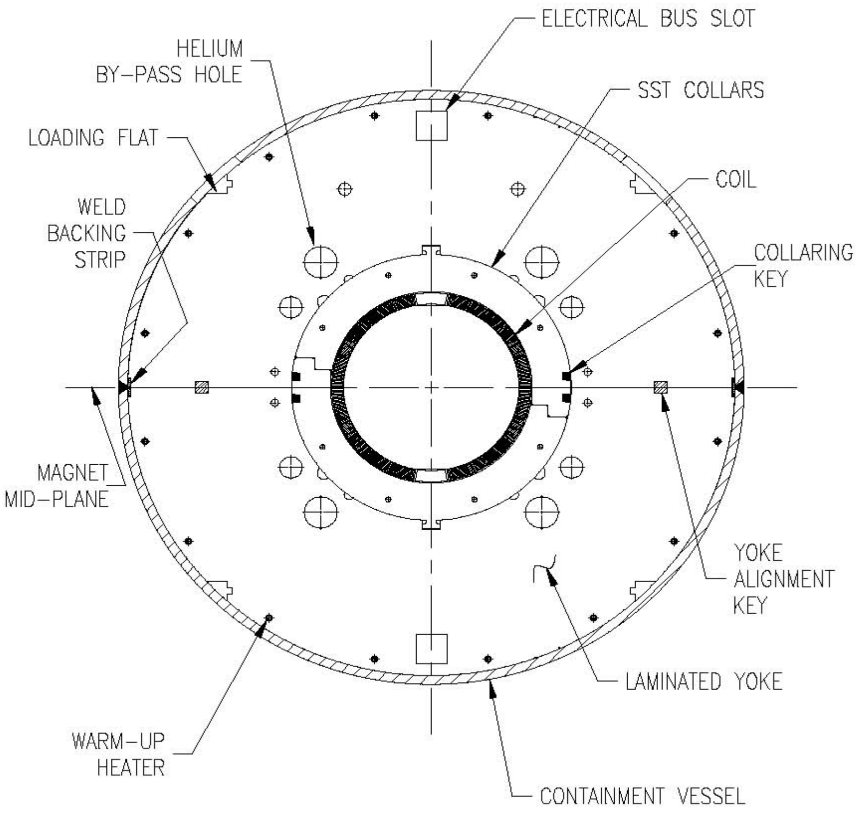
# D1 separation dipole

Several possibilities for D1: NC, SC and superferric magnets.
A large aperture 4 T SC dipole is the most cost effective.

RHIC DX magnet

| | |
|---|---|
| • Coil aperture | 180 mm |
| • Cold bore | 163/174 mm |
| • Warm bore | 140 mm |
| • Magnetic length | 3.7 m |
| • Operating temp | 4.5 K |
| • Field | 4.4 T |
| • Current | 6.8 kA |
| • Stored energy | 1100kJ |
| • Inductance | 49 mH |

D1 = two DX in one cryostat



# Powering and circuit protection

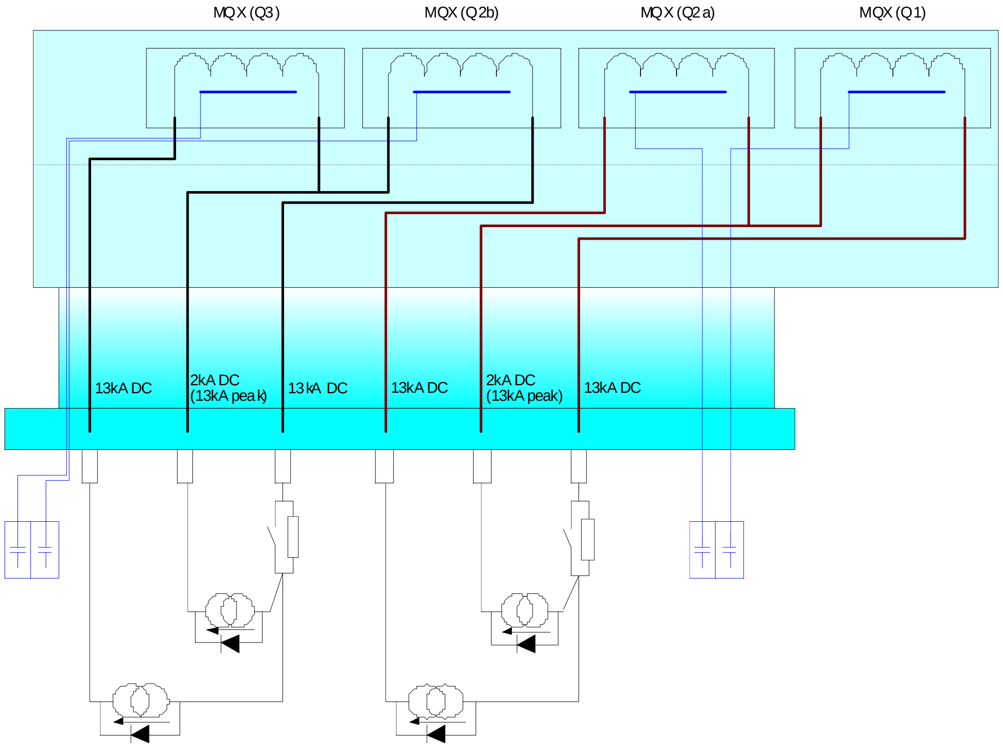
Options considered:

- Individual powering
- Nested powering
- Split powering
- Powering from surface

Split powering chosen as a compromise between volume and complexity.

Protection of the magnets ensured by both the energy extraction system and by the quench heaters.

Busbars and link integrally protected, leads protected separately. Appropriate signal routing to minimize noise.

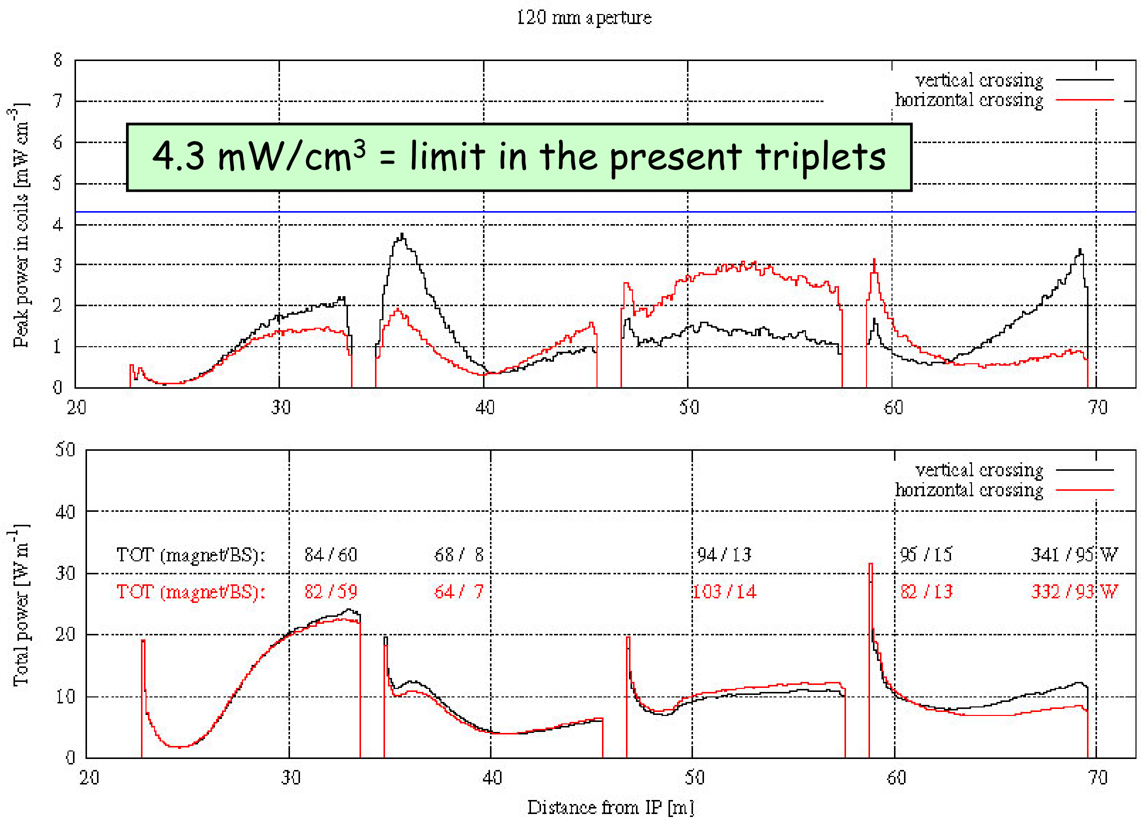



String test to check interfaces and compatibility of all systems.

# Energy deposition in the coils

Protection against particle debris is the single most serious issue of the upgrade.

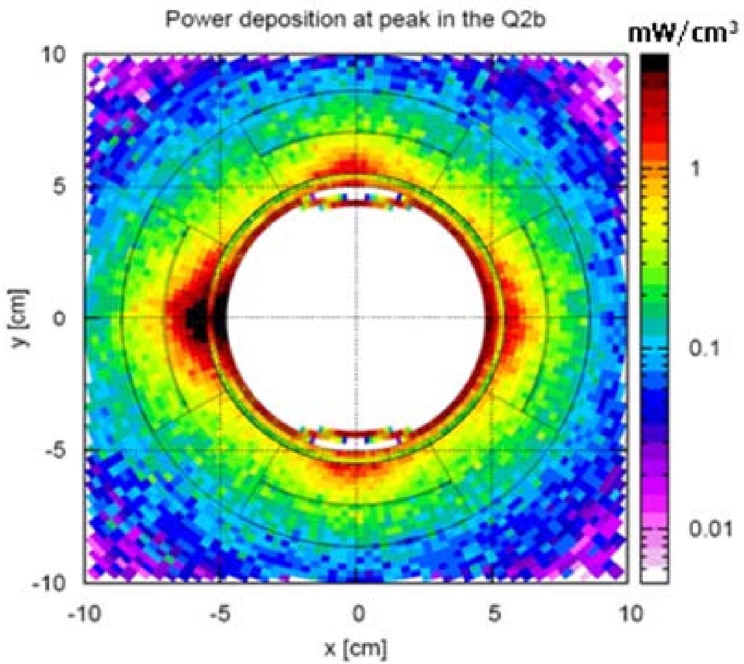
- Heating of the coils.
- Magnet protection (TAS, TAN) and lifetime.
- Protection of electronic equipment.
- Maintenance and interventions …

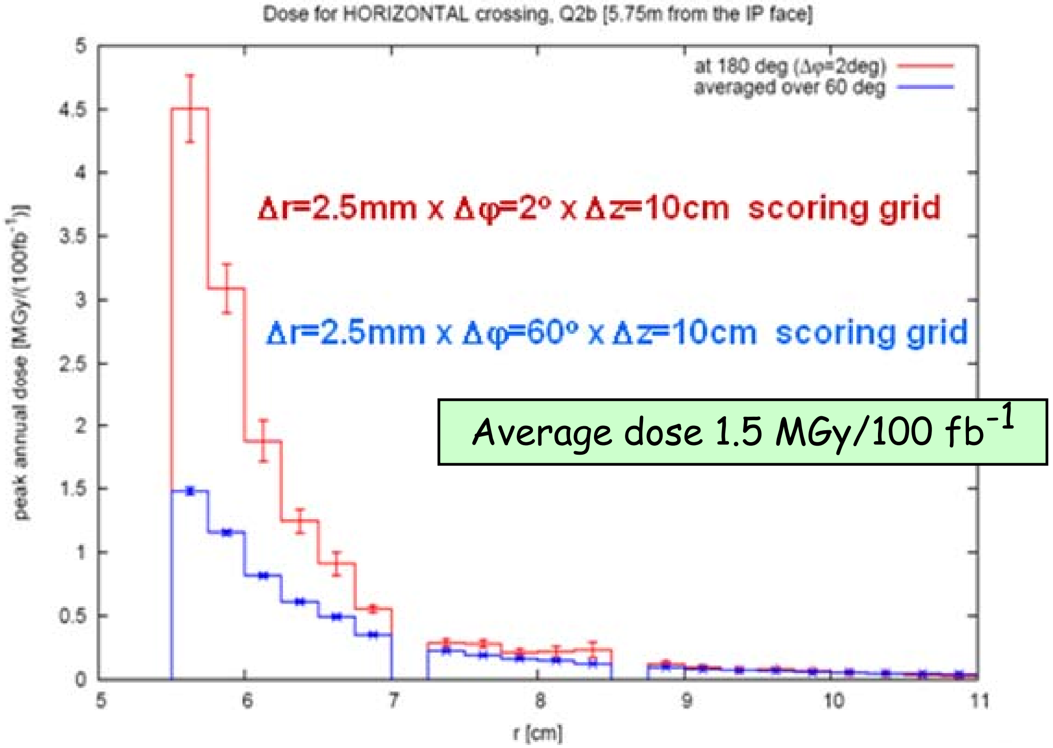



**Protection efficiency significantly increased**

$\mathcal{L} = 2.5\ 10^{34}$

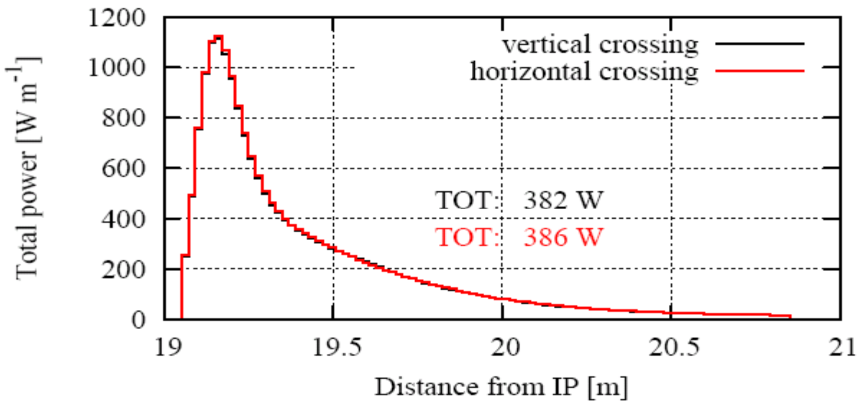
# Expected magnet lifetime

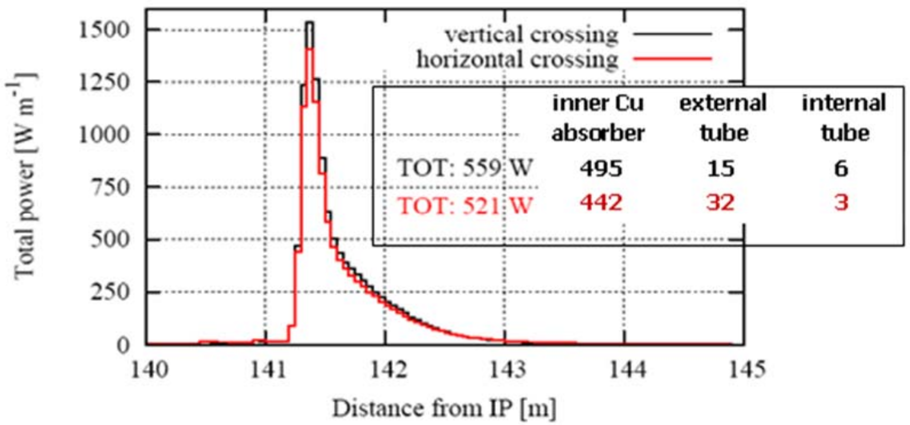


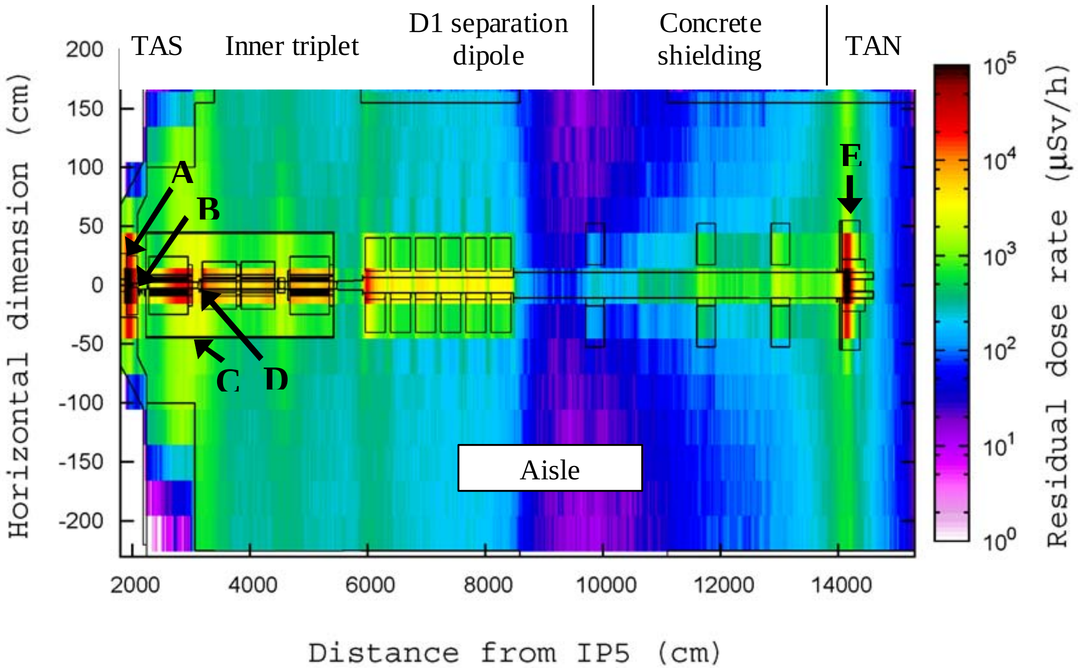




All magnets built for a lifetime > 500 $fb^{-1}$, compatible with the lifetime of ATLAS and CMS before the phase-II upgrade.

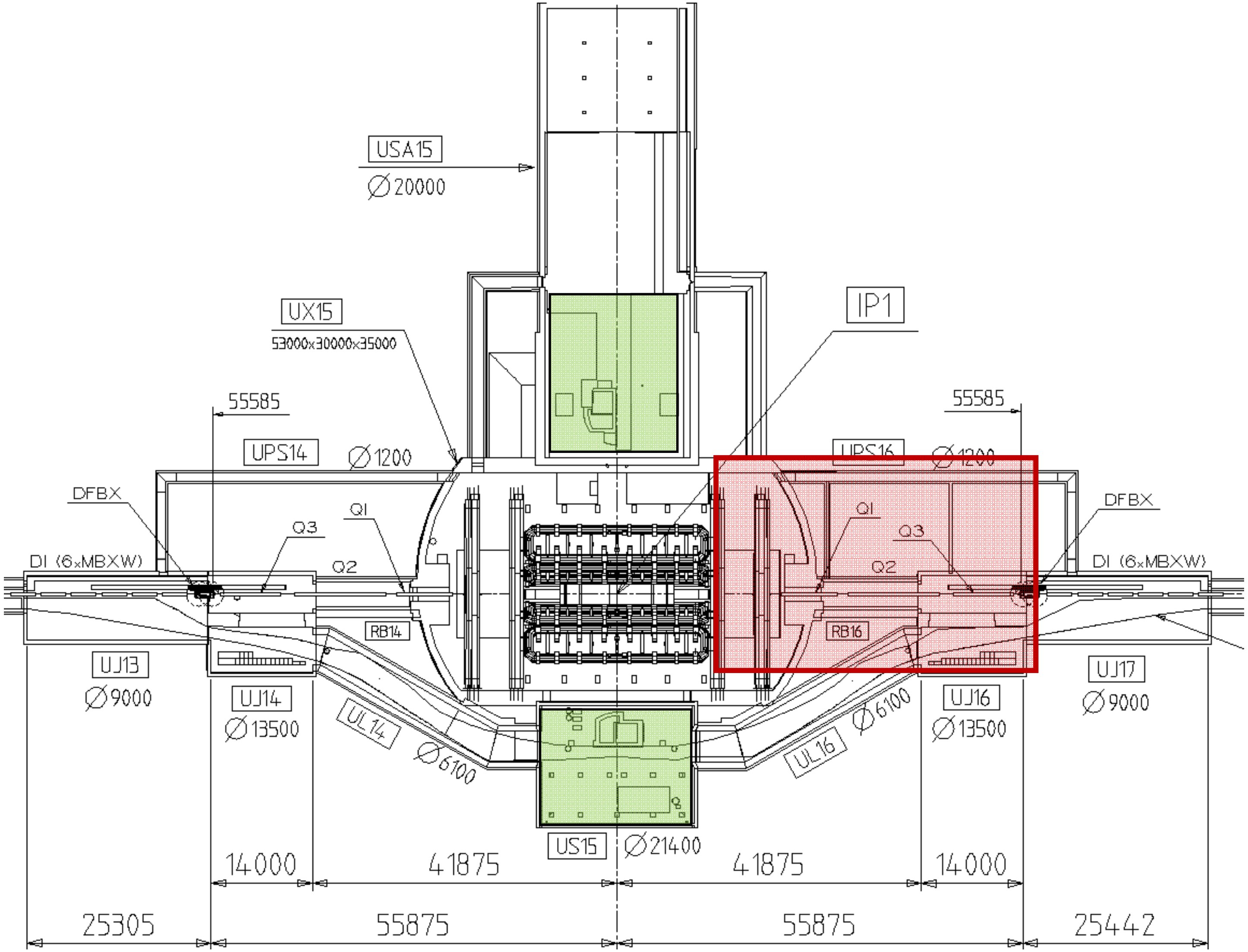
# TAS and TAN absorbers



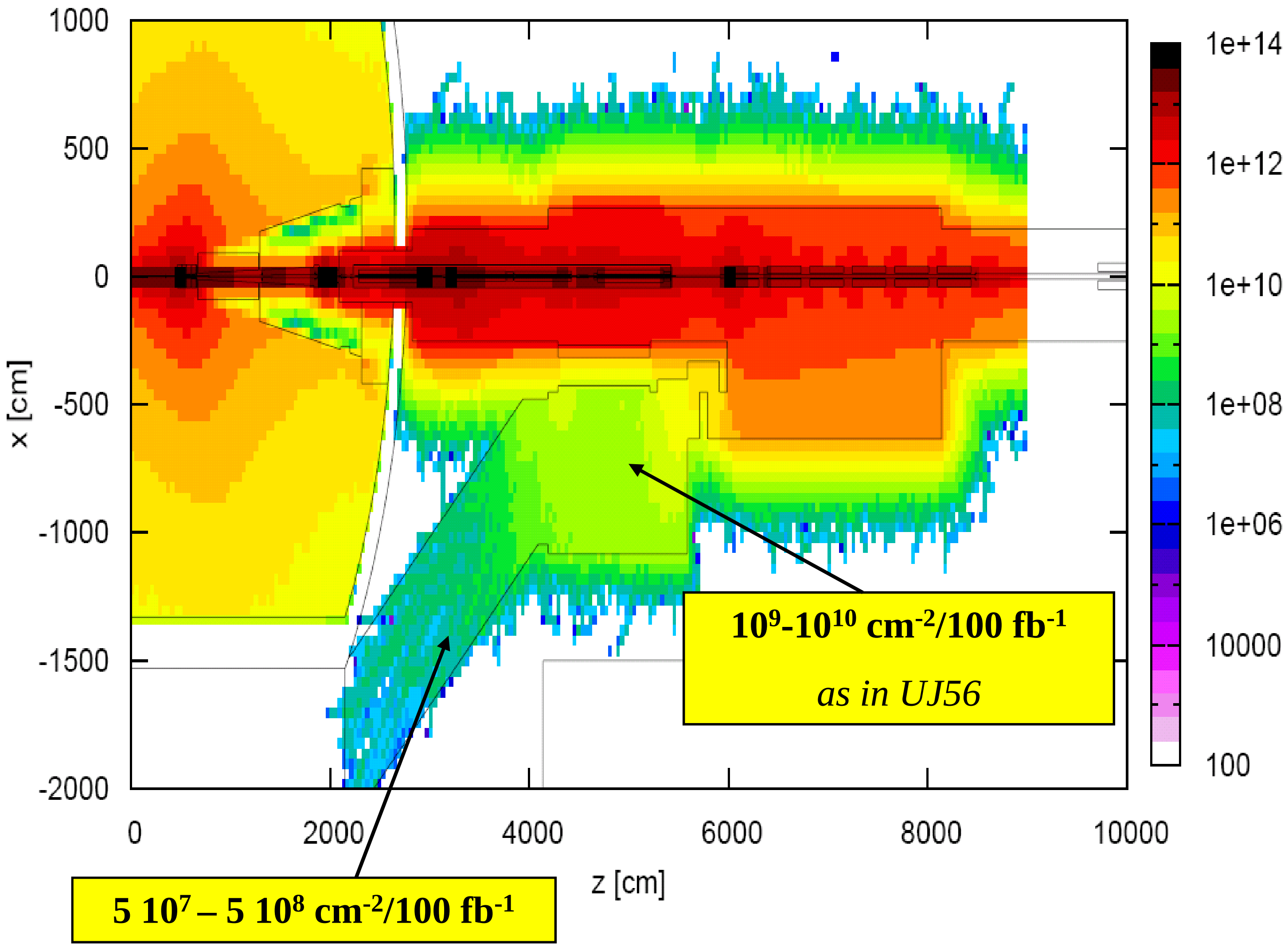



# Equipment areas



# Equipment areas (> 20 MeV hadron fluence)



# Collaborations

**EU-FP 7**
**SLHC-PP**
(CEA, CIEMAT, CNRS, STFC)

- Design and construction of the model quadrupole
- Design of the correctors
- Design of the cryostats

**CERN**

- Quadrupole production
- Cryostating and testing
- Power converters
- Protection
- String test
- Integration

**LHC IR Upgrade**
**Phase I**

**Special French contribution**
(CEA, CNRS)

- Quadrupole components
- Cryostat components
- Production of the correctors

**US-APUL**
(BNL, Fermilab)

- D1 separation dipole
- Cold powering

# Perspectives

- Since several years the LHC physics and accelerator communities have been discussing the directions for maximizing the physics reach of the LHC by upgrading the experiments, the LHC machine and the CERN proton injector complex, in a phased approach.
- The first phase of the LHC interaction region upgrade relies on the mature Nb-Ti magnet technology with the target of increasing the LHC luminosity to 2 to 3 $10^{34}$ $cm^{-2}s^{-1}$, *while maximising the use of the existing infrastructure*.
- A solid, reviewed and coherent conceptual design, in line with the general constraints, is at hand. The technical design, including the model work and limited R&D activities, are advancing to a tight schedule.
- Collaborations with European and US laboratories, which bring in their expertise and resources, have been formalised and are in effect.
- Bringing the LHC to nominal performance in the shortest term remains the top priority of the CERN management and LHC physics community.
  - ➢ *The available resources at CERN for the construction of the magnets and other equipment for the Phase-I Upgrade are subject to this priority.*