Optics issues for Phase 1 and Phase 2 upgrades

Massimo Giovannozzi, CERN

- Outline:
  - Option for Phase 1 and 2 upgrades.
  - Development and issues of Phase 1 upgrade studies.
  - Issues of Phase 2 upgrade studies.
  - Conclusions and outlook.

Acknowledgements: AB and AT colleagues contributing to the upgrade studies

LHC IR Upgrade options - I

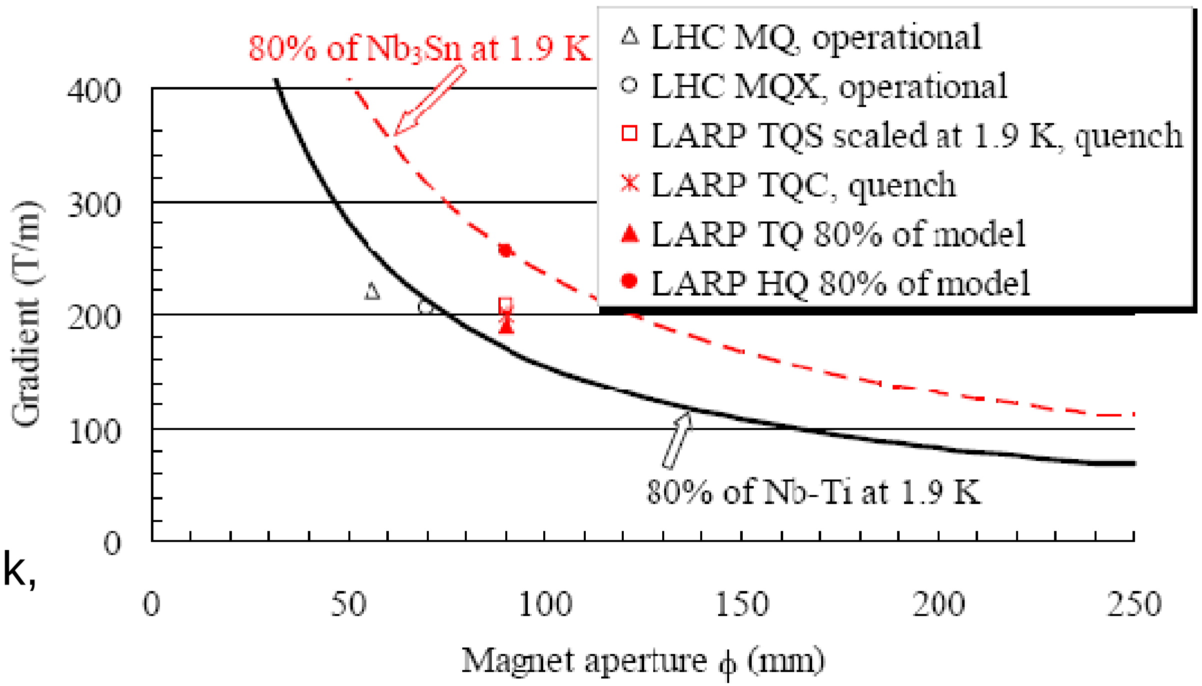
- Phase 1: consolidation of 'ultimate' performance with $L > 10^{34} cm^{-2} s^{-1}$
  - Large aperture NbTi triplet magnets using existing spare dipole cables.
  - The goal is also of introducing additional margins for the LHC operation.
  - No modifications of the experiment interface and cryogenic infrastructure.
  - Opening the option for operation with $\beta^* = 0.25$ m and the LHC 'ultimate' beam.

LHC IR Upgrade options - II

- Phase 2: ambitious upgrade of luminosity with L ~ $10^{35}cm^{-2}s^{-1}$
  - Aims at operation beyond ultimate luminosity (the goal is integrated L).
  - Implies operation in extremely radiation hard environment (35 MGy/year).
  - Less than 1 year lifetime for magnets with nominal triplet layout!
  - New magnet technology and /or special protection / absorber elements.

The path to Phase 1 layout - I

- Technological challenge of large aperture quadrupoles (see presentation of E. Todesco): where are the limits of gradient vs. aperture?

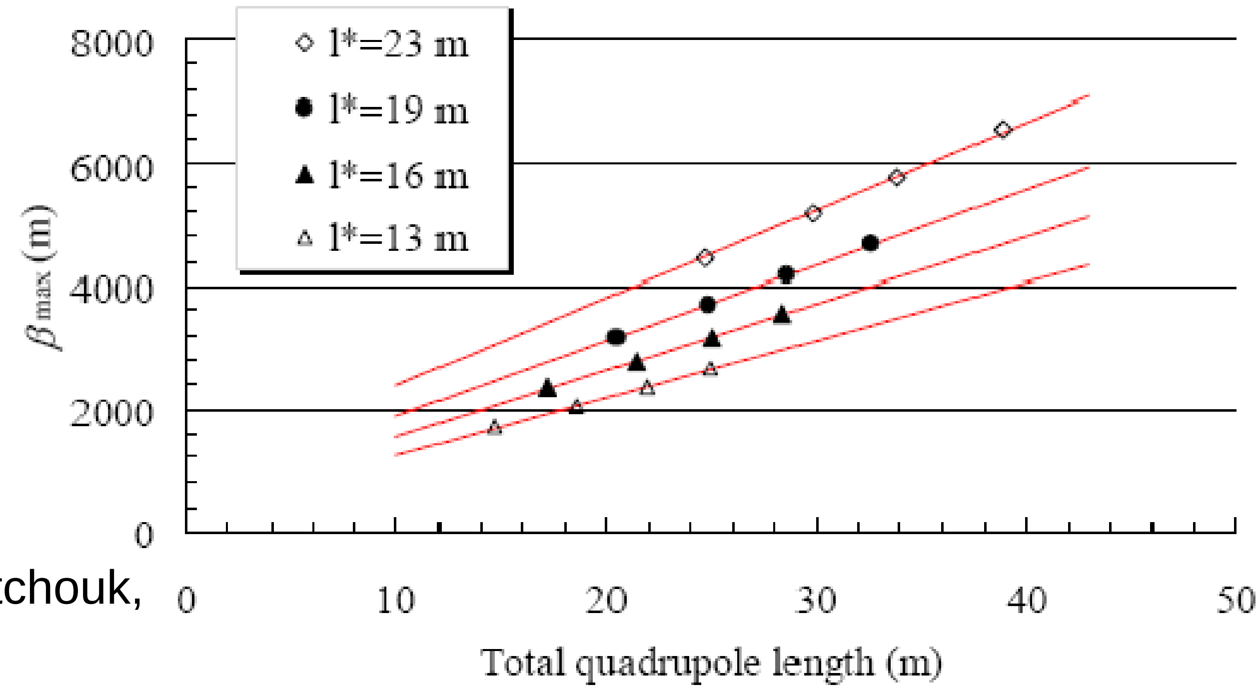


From E. Todesco, J.-P. Koutchouk, LUMI' 06 Proceedings

The path to Phase 1 layout - II

- Huge parameter space: semi-analytical approaches and fitting to determine

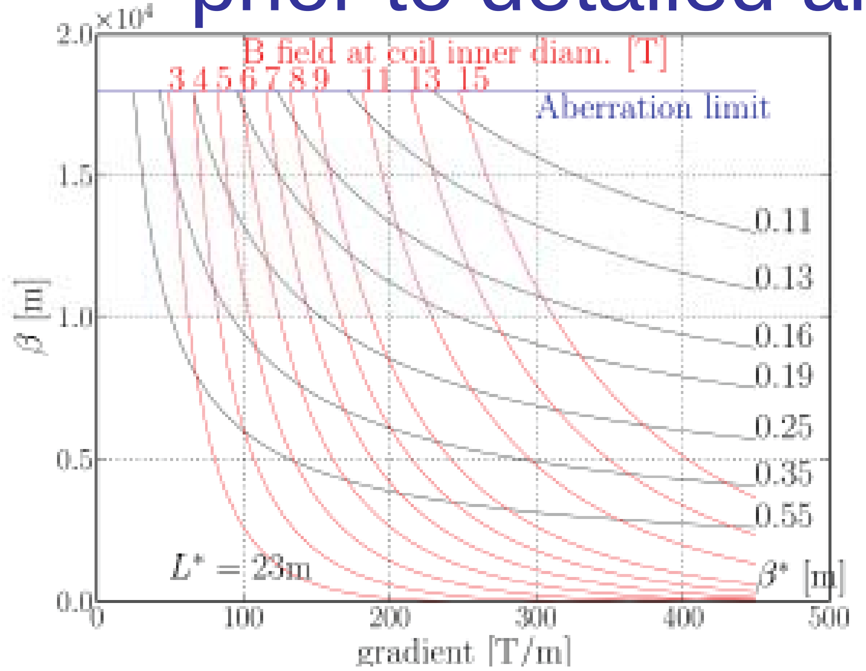
Twiss parameters vs. free parameters

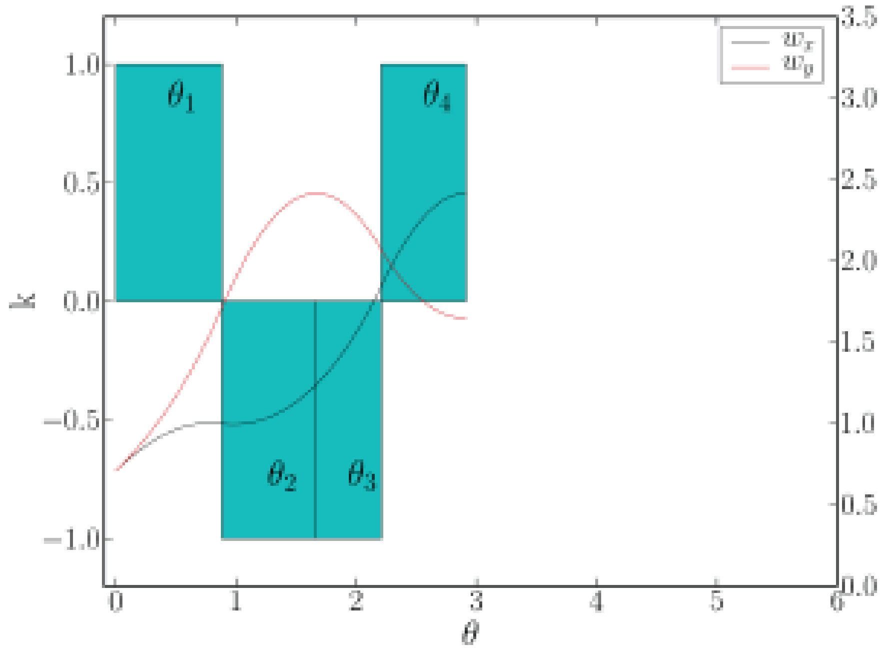


From E. Todesco, J.-P. Koutchouk, LUMI' 06 Proceedings.

The path to Phase 1 layout - III

- Huge parameter space: analytical approaches applied to a slightly simplified system to fix the overall optical parameters prior to detailed analysis are needed.





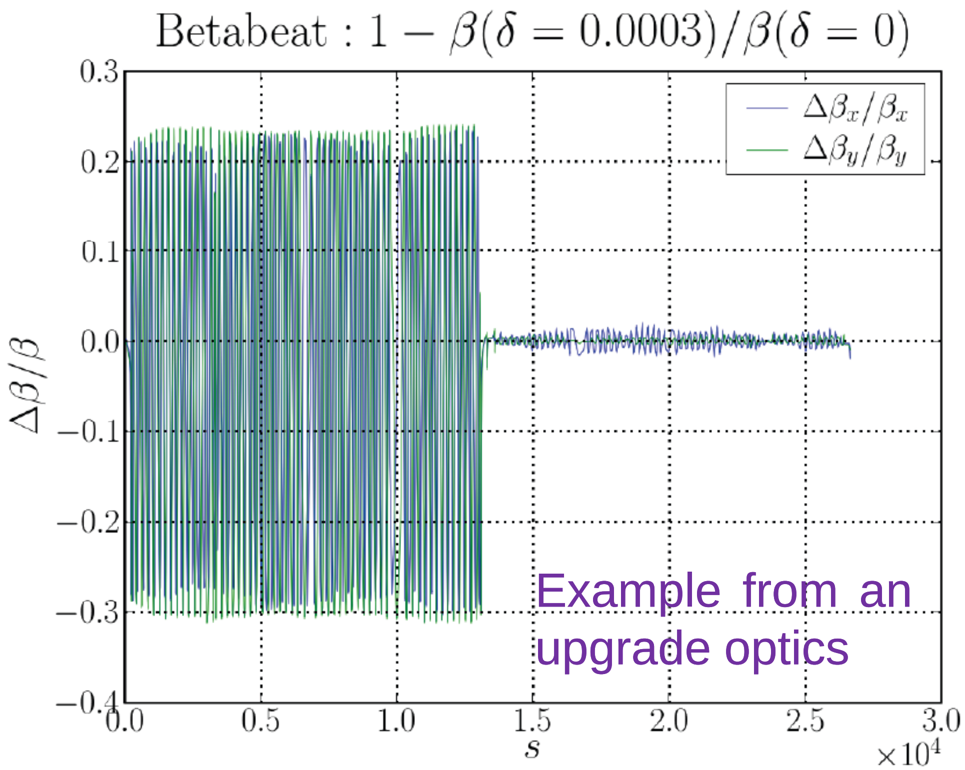
R. De Maria, LHC Project Report 1051.

The path to Phase 1 layout - IV

- Guidelines for the optical design:
  - Aperture is the first requirement. General criterion:
    - 33 σ + 12 mm needed in the triplets
    - Open question: how much aperture margin do we need? And what is the best use of it, e.g.
      - Mitigation of energy deposition issues (still to be studied in details, see presentation by E. Wildner).
      - Mitigation (but not solution!!!) of impedance issues due to collimators.
  - Keep βmax under control (impact on chromaticity, off-momentum beta-beating and single-particle dynamic aperture).

The path to Phase 1 layout - V

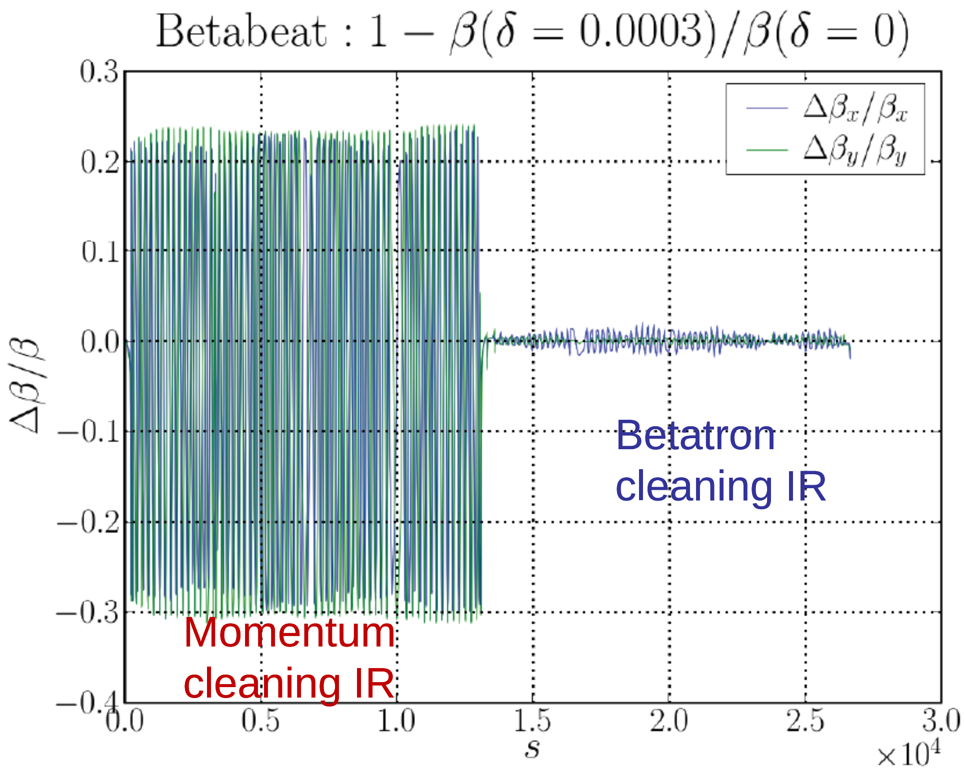
- A word on off-momentum beta-beating:
  - Nominal LHC:
    - 3/8 10^{-4} $\Delta p/p$ -> 10%/30%
    - Correction means (see S. Fartoukh LHC Project Report 308)
      - Phasing IPs
      - Chromatic sextupoles (32 families/beam)
    - NB: off-momentum beta-beating can be corrected only in one half of the machine.



The path to Phase 1 layout - VI

- Apart on aperture, off-momentum beta-beating has an impact on collimation performance.
- How to chose in which half of the machine the beating has to be corrected?
  - Driving criterion: avoid that a secondary collimator becomes a primary one.

FOR the nominal LHC the correction should be made between IR5 and IR1.



The path to Phase 1 layout - VII

- Concerning field quality issues, it is worth mentioning that:
  - Recently a useful result was obtained concerning the dependence of the triplets field quality on aperture (E. Todesco et al. LHC Project report 1010).

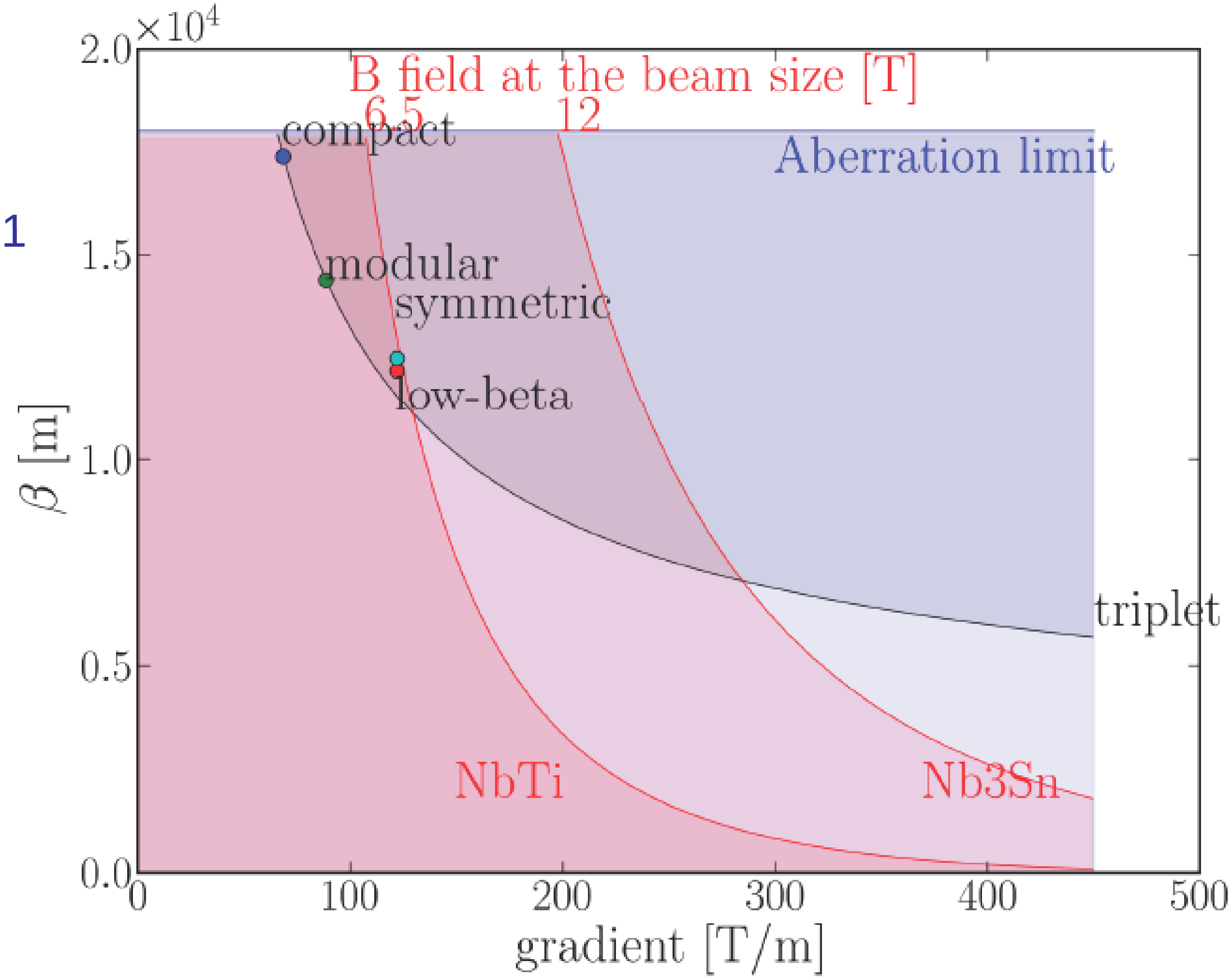
$$\sigma(b_n, a_n; \alpha\phi, d, \alpha R_{ref}) = \frac{1}{\alpha}\sigma(b_n, a_n; \phi, d, R_{ref})$$

  - The impact of these scaling laws on dynamic aperture clearly observed (see presentation by R. Tomás).
- Hardware constraints such as modularity (optimize the tooling and the spares) have to be considered.

The path to Phase 1 layout - VIII

- Putting everything together:

Detailed discussion of the four optics under consideration for the Phase 1 upgrade by R. de Maria.



From R. de Maria LIUWG presentation 18/10/07

The path to Phase 1 layout - IX

- Usually the focus is always on the triplets, but the long straight section needs also revision and detailed analysis (see S. Fartoukh LIUWG presentation 27/09/07):
  - D1 (warm design): its aperture has to be increased!
    - Modification to the current design proposed (J.-P. Koutchouk and D. Tommasini): very cost-effective.
    - Should a cold D1 be considered?
  - D2, Q4, Q5: a rotation of the beam screens should fix the aperture issues. Possibility of designing a two-aperture Q4 with increased aperture assessed (E. Todesco).
  - The rest of the long straight section is essentially compatible with Phase 1 upgrade requirements.

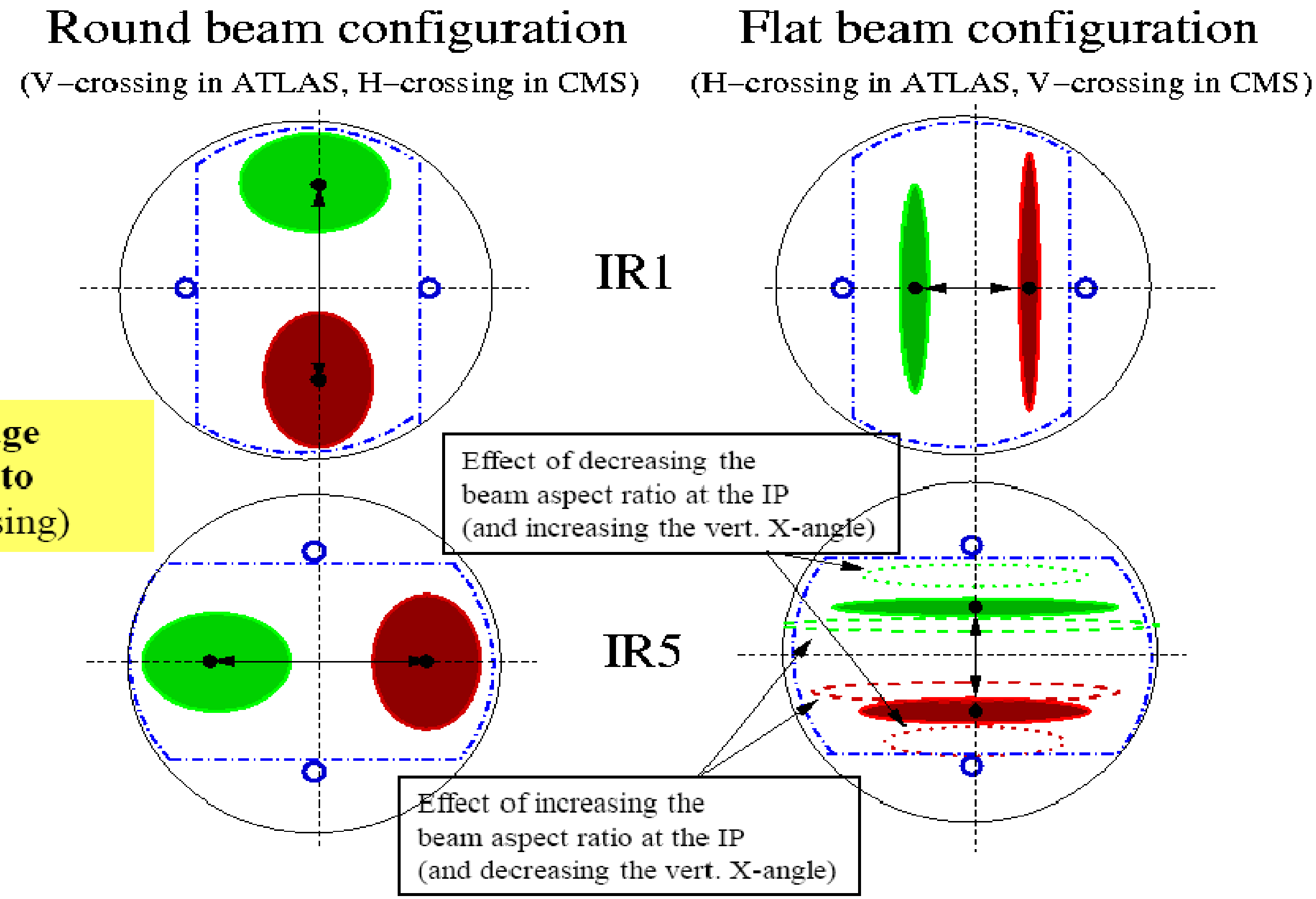
The path to Phase 1 layout - X

- Next steps:
  - Convergence to a smaller number of optics candidates (two). Each should be studied in terms of:
    - Overcome the observed limitations in the optics.
    - Provide a complete solution compatible with the hardware constraints (cryostats parameters, instrumentation).
    - Study tunability of the optics.
    - Study injection optics.
    - Study squeeze sequence.
    - Evaluate the performance of a flat beam option.
    - Beam-beam simulations.
    - Collimation performance.

The beneficial effect of flat beams - I

Potential of Flat Beam: Aperture

- Triplet beam screen orientation for H/V crossing



→ In all cases, the **average b-b separation is set to 9.5*$\sigma_{x/y}$** (for H/V crossing)

→Find the optimum between beam-screen and beam aspect ratio

S. Fartoukh, LHC-MAC, 16 June 2006, p. 3/20

The beneficial effect of flat beams - II

Conclusions

- The LHC experimental insertions are very **flexible**.
- Extremely good **Field Quality** of the triplet magnets.

→ will allow **to produce and test a large variety of flat beam collision optics**: $\sqrt{\beta_x^* / \beta_y^*} \equiv r \;\; = 1/2 \rightarrow 2$ (range given by the triplet beam screen aperture).

→ if needed, will allow **V-H, H-V, V-V or H-H crossing scheme** with **round-round, flat-flat, round-flat or flat-round** beam optics in IR1 and IR5.

- While **strong (parasitic) beam-beam limitations** occur at **nominal intensity**, **staging the IP beam aspect ratio with intensity** allows
  1. To **push the lumi by up to 20%** at max. β* (aperture saturated) and medium intensity: **< 60% of nom. intensity** → see flat beam case 4, with *r* ~ *1.7*.
  2. **Up to ~ 80% of the nominal intensity,** to **enlarge the triplet aperture by 15%** (*n1* =8 instead of 7) at constant lumi, e.g. in case of direct or indirect problem (impedance) related to collimation → see case 5a, with *r* ~ *1.45*.
  3. To **enlarge the b-b separation by ~ 15-20%** at **full intensity**, constant aperture but slightly reduced lumi, e.g. in case of unexpected beam-beam related difficulties → see case 5b, with *r* ~ *1.45* and b-b sep. of ~11σ.

Phase 2: introduction - I

- Current studies look for a 10-fold increase in the peak luminosity. Two options (doubling the bunch number not possible):
  - **ES (25 ns):** Low β^* (11 cm – 14 cm) with ‘ultimate’ beam parameters requiring significant hardware modifications in the IR & detector regions.
  - **LPA (50 ns):** operation with larger than ‘ultimate’ beam intensities and ‘flat bunches’ but without modifications in the detector regions.

Phase 2: introduction - II

- Additional measured required for a Phase 2 upgrade:
  - Upgrade of the cryogenic plants for IR1 and IR5 (additional new plants).
  - Improved shielding and protection of triplet magnets.
  - Both Phase 2 options require additional measures that go beyond magnet.
  - R&D and that could benefit already the Phase 1 upgrade.

distance to IP	l^*	(m)	23	13
quad length	$l(Q1\text{-}Q3)$	(m)	7.3	9.3
quad length	$l(Q2)$	(m)	6.5	6.8
total quad length	l_q	(m)	27.5	32.1
triplet length	l_t	(m)	34.1	38.7
Gradient Q1	G_1	(T/m)	166	169
Gradient Q2	G_2	(T/m)	166	169
Gradient Q3	G_3	(T/m)	166	141
B peak estimate	B_p	(T)	13.7	13.5
Aperture	ϕ	(m)	0.150	0.145
β funct. in IP	β^*	(m)	0.142	0.112
Max β funct. in Q1-Q3	β_{max}	(m)	18700	16800

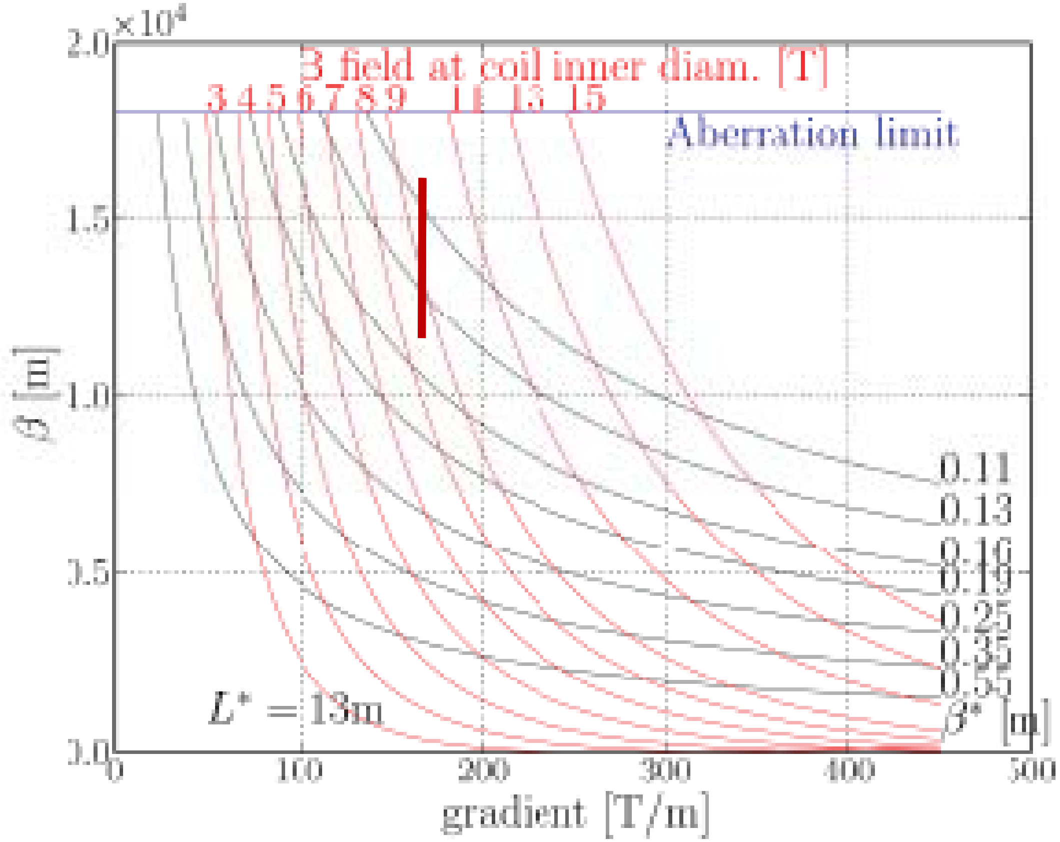
J.-P. Koutchouk *et al.*, PAC07.

Phase 2: optics concept

R. De Maria, LHC Project Report 1051

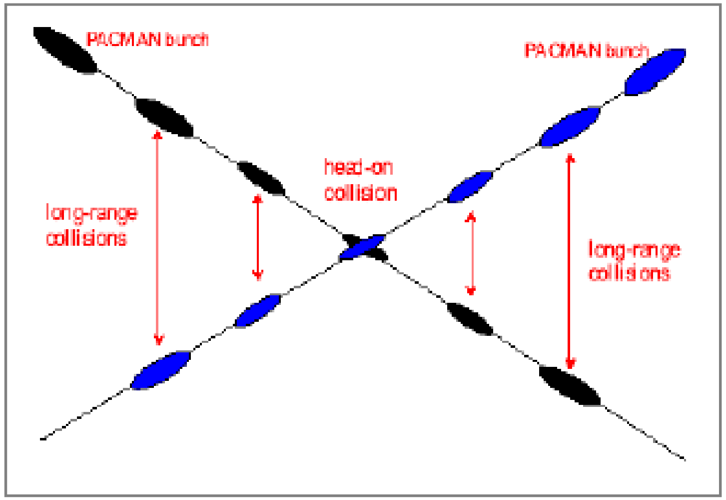
Additional changes in the long straight section (see S. Fartoukh LIUWG presentation 27/09/07):

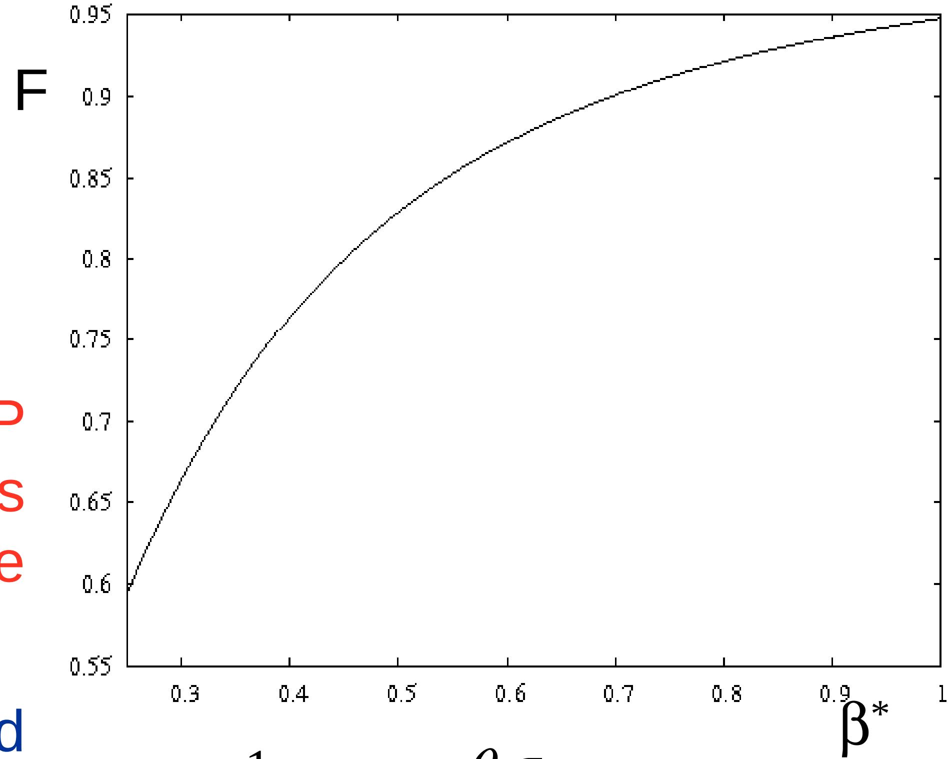
- Beam screen rotation in D2, Q4, Q5.
- Q4, Q5 must be replaced with large aperture magnets.
- 120-130 mm gap requested for D1 (cold D1 might be the only possible option).
- 95-100 mm aperture requested for D2 (Warm D2, e.g. MBW type, might be the only possible option).



Additional measures for Phase 2 - I

Minimizing the luminosity loss due to the crossing angle:





The crossing angle results at the IP in an increase of the effective cross section and thus a reduction of the luminosity.

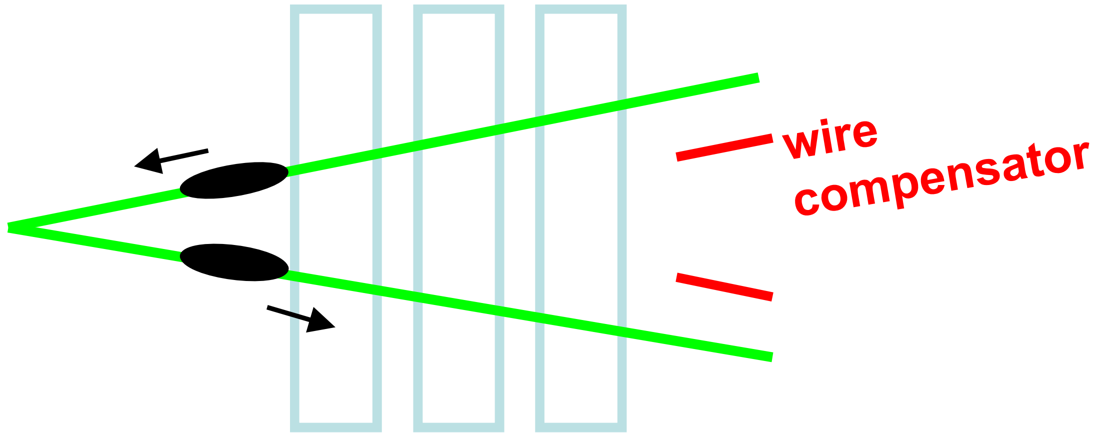
$$F = \frac{1}{\sqrt{1+\phi^2}}; \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$ Piwinski angle

Assuming a constant normalized beam separation the reduction factor decreases with decreasing β^*!

Additional measures for Phase 2 - II

Minimizing the luminosity loss due to the crossing angle at the IP:

Compensate the long range beam-beam effects, thus allowing a smaller angle

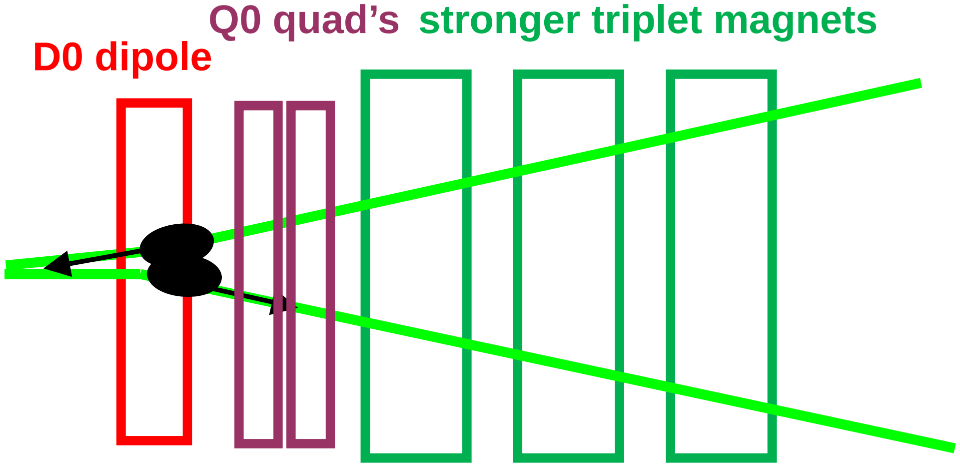


- New proposal and technology, requiring MDs (USLARP & CERN[@])
- Could potentially reduce the required crossing angle
- Similar proposal for head-on collisions: electron lens

Additional measures for Phase 2 - III

Minimizing the luminosity loss due to the crossing angle at the IP:

Reduce the crossing angle at the IP via dipole magnets deep inside the detectors (slim dipole option)

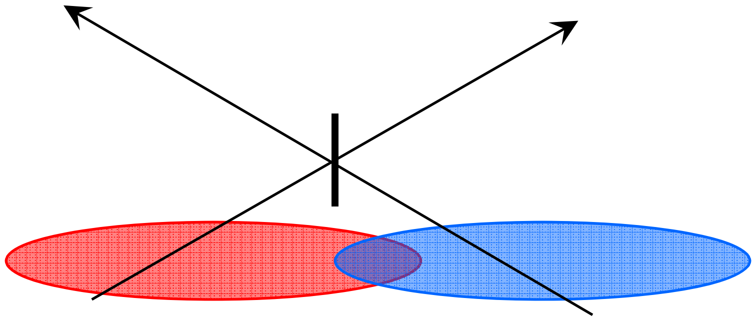


- Requires magnet integration inside the detectors.
- Impact on detector performance and physics reach.
- Requires new magnet technology.
- Implies beam-beam studies (numerical and experimental).

Additional measures for Phase 2 - IV

Minimizing the luminosity loss due to the crossing angle at the IP:

Bunch rotation via crab cavities. It implies a new technology for protons.

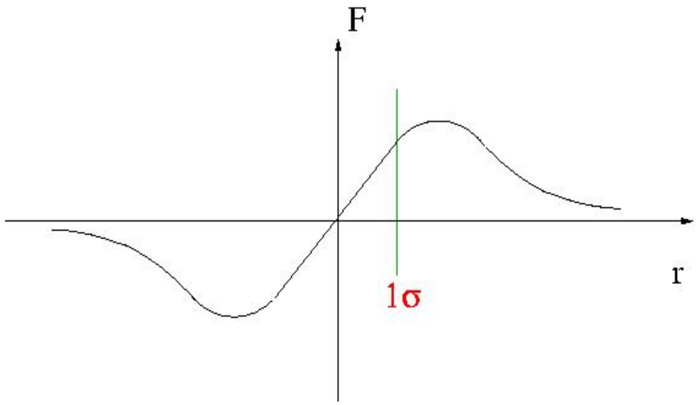


- Requires high precision RF technology and control.
- Currently used in KEK B-factory.
- No experience with operation in proton machines (noise).
- Requires prototyping and machine studies (lead time and resources).

Additional measures for Phase 2 - V

Minimizing the luminosity loss due to the crossing angle at the IP:

Bunch rotation via crab cavities. It implies a new technology for protons.



Compensate the head-on beam-beam force by additional e^-/p^+ interactions (opposite sign of the p^+/p^+ beam-beam force).

- Development of a prototype 'electron lens' at FNAL.
- This new tool is currently studied / tested in Tevatron (and RHIC in 2008).
- Still open issues: Tevatron observes significant operation improvements (lens as a fast quadrupole), but no successful operation as beam-beam lens.

Additional measures for Phase 2 - VI

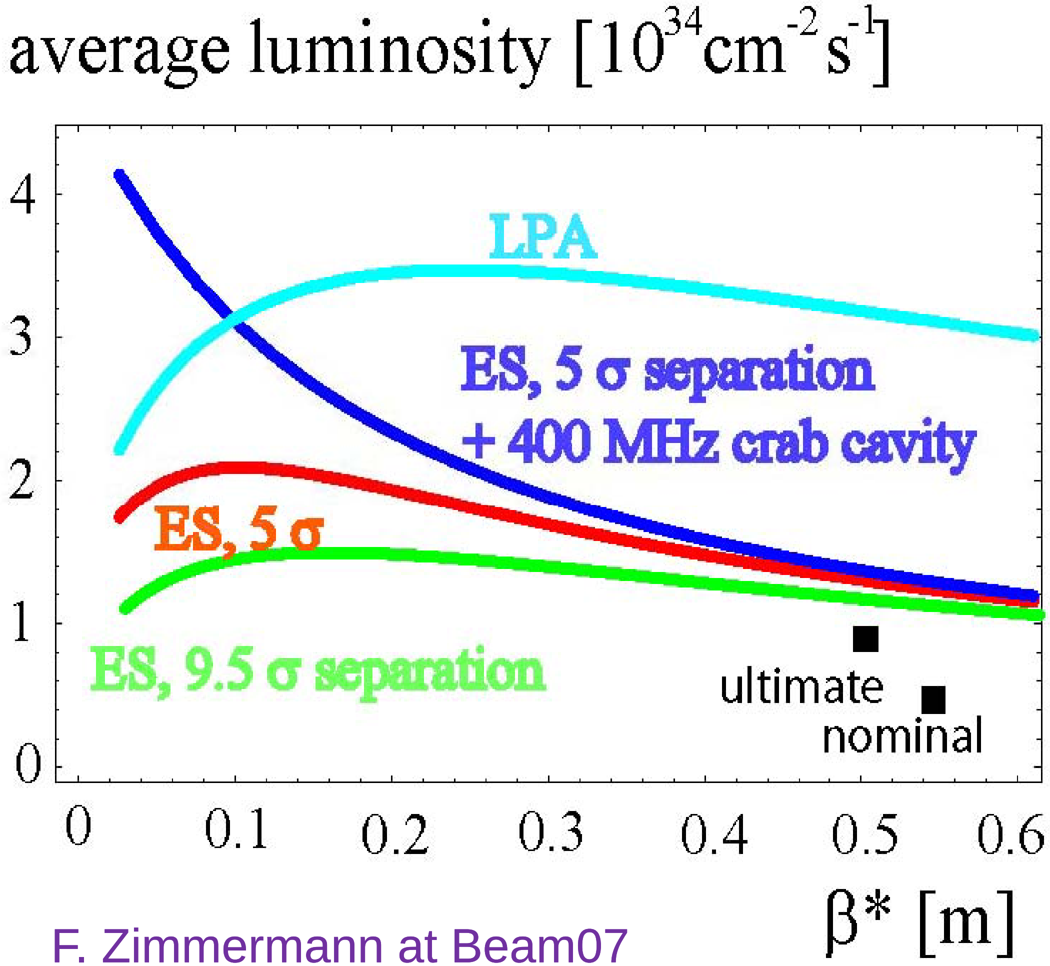
Operation with large Piwinski angle:

- 40% higher luminosity for flat bunch profile.
  - Increased luminosity lifetime.
  - Does the flat bunch remain flat (proved in injectors for short times)?

Luminosity leveling (see talks by J.-P. Koutchouk and G. Sterbini):

- Can it be performed in real operation?

Phase 2 luminosity potential reach



F. Zimmermann at Beam07

- Average luminosity over one physics run assuming optimum run length.
- Estimates done without luminosity leveling.
- Phase 2 might provide average luminosity increase by a factor 3 to 4 in most optimistic scenario.

Conclusions and outlook

- Phase 1:
  - Essentially new magnets are required, only.
- Phase 2:
  - New magnets are required and (not all together):
    - wire compensators
    - integrated dipole magnets
    - crab cavities
    - electron lens
    - Flat beam operation
    - Luminosity leveling
    - Magnets TAS, absorbers, and masks

All additional measures for the Phase 2 upgrade could benefit the Phase 1 upgrade. They should be launched before Phase 2!