IR Upgrade Overview

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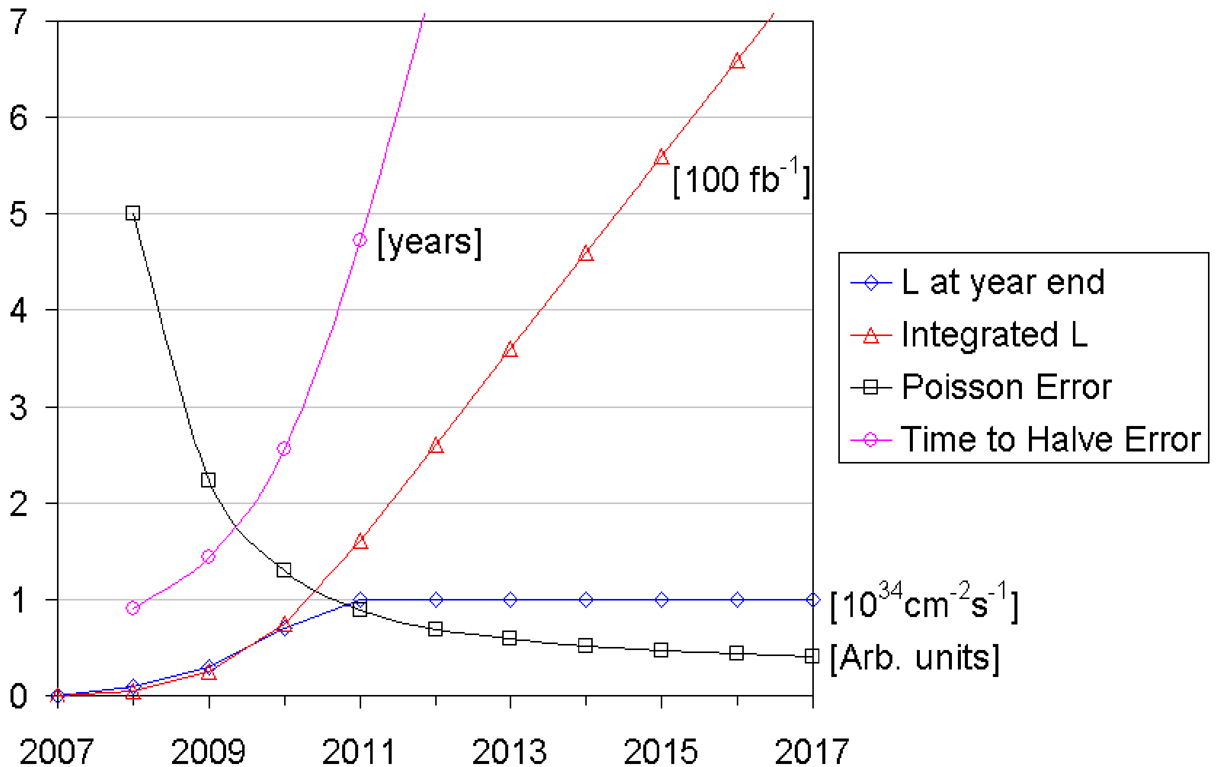
LHC Luminosity Upgrade
Why and When?

HEPAP* has set its highest priority on R&D for a luminosity upgrade:

The science of extending exploration of the energy frontier with the LHC accelerator and detector luminosity upgrades is *absolutely central*. The *R&D phase* for these will need to start soon if the upgrades are to be finished by the present target date of 2014.



*High-Energy Physics Facilities of the DOE Office of Science Twenty-Year Road Map, HEPAP report to the Director of the Office of Science, 17 March 2003.

LHC Upgrade Scenarios

- LHC Phase 0: maximum performance without hardware changes
- LHC Phase 1: maximum performance with the LHC arcs unchanged
- LHC Phase 2: maximum performance with 'major' hardware changes

The nominal LHC performance at 7 TeV corresponds to a total beam-beam tune spread of 0.01, with a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in IP1 and IP5 (ATLAS and CMS), halo collisions in IP2 (ALICE) and low-luminosity in IP8 (LHC-b). The steps to reach ultimate performance without hardware changes (LHC Phase 0) are:

1. collide beams only in IP1 and IP5 with alternating H-V crossing
2. increase N_b up to the beam-beam limit $\rightarrow L = 2.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
3. increase the dipole field to 9 T (ultimate field) $\rightarrow E_{max} = 7.54\,\mathrm{TeV}$

The ultimate dipole field of 9 T corresponds to a beam current limited by cryogenics and/or by beam dump considerations.

O. Bruning, et al., LHC Project Report 626, December 2002.

Phase 0 – Maximum $\mathcal{L}$ without Major Upgrades

parameter	symbol	units	nominal	ultimate	Piwinski
number of bunches	n_b		2808	2808	2808
bunch spacing	Δt_{sep}	ns	25	25	25
protons per bunch	N_b	10^{11}	1.1	1.7	2.6
aver. beam current	I_{av}	A	0.56	0.86	1.32
norm. tr. emittance	ε_n	μm	3.75	3.75	3.75
long. emittance	ε_L	eV s	2.5	2.5	4.0
peak RF voltage	V_{RF}	MV	16	16	3/1
RF frequency	f_{RF}	MHz	400.8	400.8	200.4/400.8
r.m.s. bunch length	σ_z	cm	7.55	7.55	15.2
r.m.s. energy spread	σ_E	10^{-4}	1.13	1.13	0.9
IBS growth time	$\tau_{x,IBS}$	h	111	72	87
beta at IP1-IP5	β^*	m	0.5	0.5	0.5
full crossing angle	θ_c	μrad	300	315	345
lumi at IP1-IP5	L	$10^{34}/\text{cm}^2\,\text{s}$	1.0	2.3	3.6

F. Ruggiero CERN Nominal and ultimate LHC parameters at 7 TeV

LHC Phase 1: Luminosity Upgrade

Possible steps to increase the LHC luminosity with hardware changes only in the LHC insertions and/or in the injector complex include the following baseline scheme:

or smaller!

1. modify insertion quadrupoles and/or layout $\rightarrow \beta^* = 0.25\,\mathrm{m}$
2. increase crossing angle by $\sqrt{2} \rightarrow \theta_c = 445\,\mu\mathrm{rad}$
3. increase N_b up to ultimate intensity $\rightarrow L = 3.3 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$
4. halve σ_z with high harmonic RF system $\rightarrow L = 4.6 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$
5. double number of bunches (and increase θ_c!) $\rightarrow L = 9.2 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$
   excluded by electron cloud?

Step 4 is not cheap since it requires a new RF system with 43 MV at 1.2 GHz and a power of about 11 MW/beam (estimated cost 56 MCHF). The changeover from 400 to 1200 MHz is assumed at 7 TeV, or possibly at an intermediate flat top, where stability problems may arise in view of the reduced longitudinal emittance of 1.78 eVs. The horizontal Intra-Beam Scattering growth time decreases by about $\sqrt{2}$.

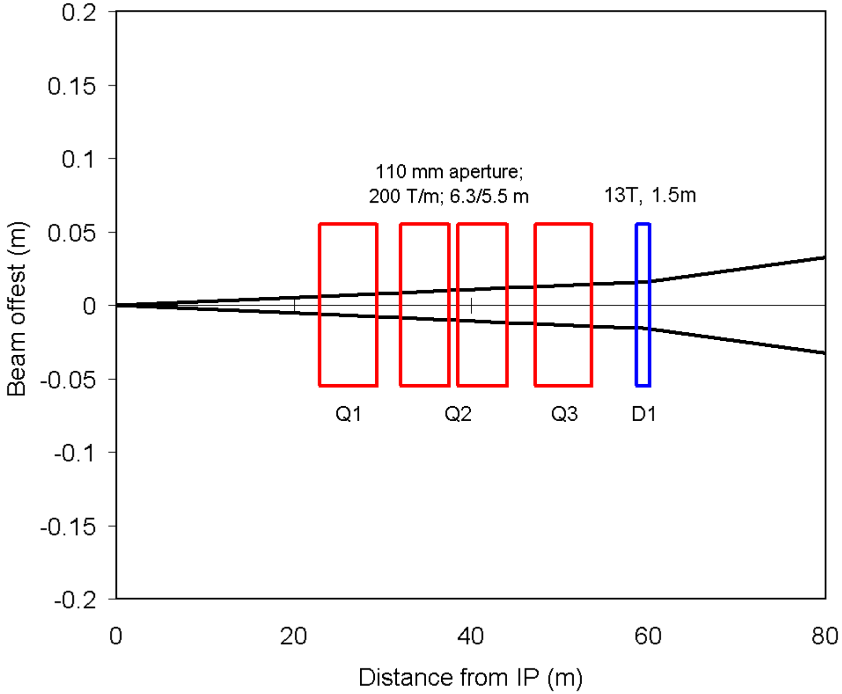
Additional $\mathcal{L}$ Upgrade Routes

parameter	symbol	units	baseline	Piwinski	super-bunch
number of bunches	n_b		2808	2808	1
bunch spacing	Δt_{sep}	ns	25	25	
protons per bunch	N_b	10^{11}	1.7	2.6	5600
aver. beam current	I_{av}	A	0.86	1.32	1.0
norm. tr. emittance	ε_n	μm	3.75	3.75	3.75
long. emittance	ε_L	eV s	1.78	2.5	15000
peak RF voltage	V_{RF}	MV	43	16	3.4
RF frequency	f_{RF}	MHz	1202.4	400.8	10
r.m.s. bunch length	σ_z	cm	3.78	7.55	7500
r.m.s. energy spread	σ_E	10^{-4}	1.60	1.13	5.8
IBS growth time	$\tau_{x,IBS}$	h	42	46	63
beta at IP1-IP5	β^*	m	0.25	0.25	0.25
full crossing angle	θ_c	μrad	445	485	1000
lumi at IP1-IP5	L	$10^{34}/\mathrm{cm}^2\,\mathrm{s}$	4.6	7.2	9.0

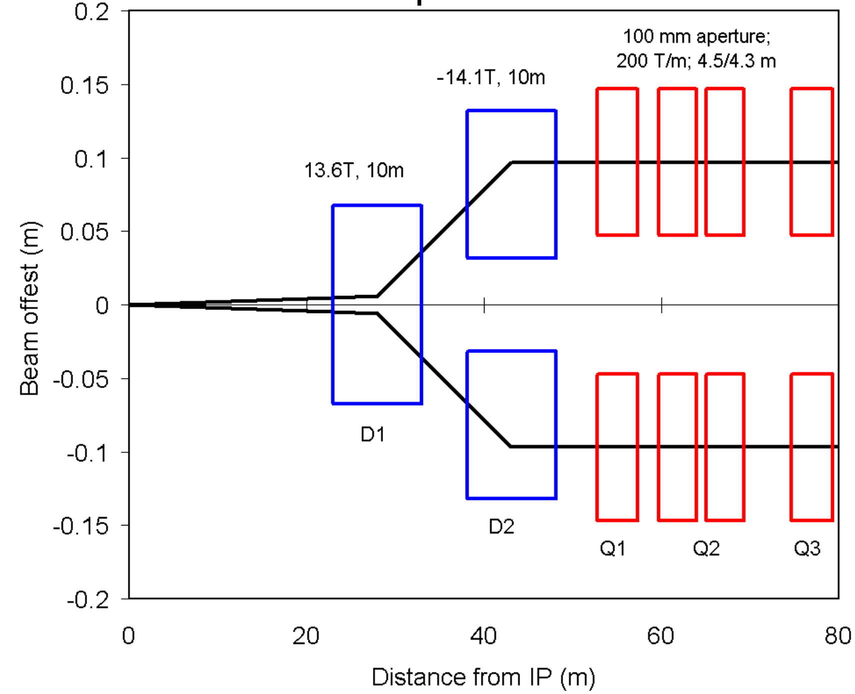
F. Ruggiero CERN Luminosity upgrade scenarios: LHC parameters at 7 TeV

New IRs:
“Straightforward” Designs

Quads 1st



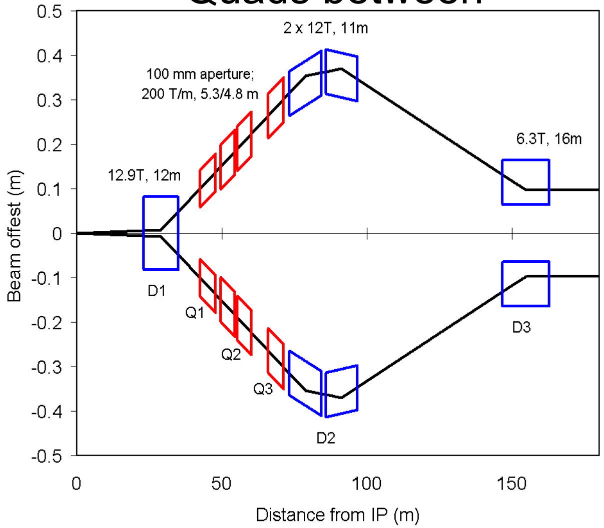
Dipoles 1st



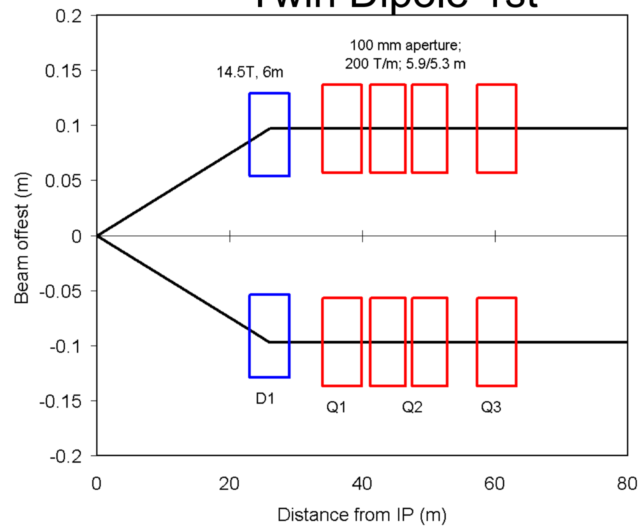
J. Strait, et al., Towards a New LHC Interaction Region Design for a Luminosity Upgade, PAC 2003.

New IRs:
Alternate Designs

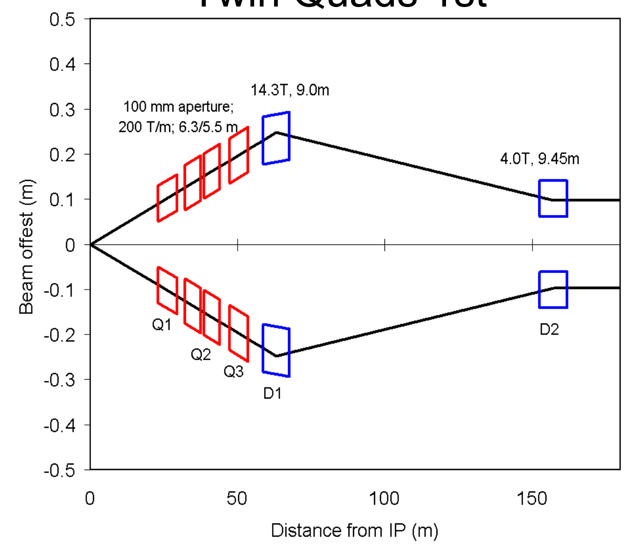
Quads between



Twin Dipole 1st



Twin Quads 1st



Preliminary IR Design Studies

Table 1: IR Parameters

	Base-line	Quad 1st	Dipoles 1st	Quad between	Twin D 1st	Twin Q 1st
IP to Q1 (m)	23	23	52.8	42.5	34	23
D_{quad} (mm)	70	110	100	100	100	100
β^*_{min} (cm)	50	16	26	19	15	10
β_{max} (km)	5	15	23	23	23	23
B_{D1} (T)	2.75	15.3	15	14.6	14.5	14.3
L_{D1} (m)	9.45	1.5	10	12	6	9
D_{D1} (mm)	80	110	135	165	75	105
θ_{cross} (mrad)	0.30	0.53	0.42	0.49	7.5	7.8

IR Upgrade Questions and Issues

IR design concepts shown reduce β^* by x2 – x5 w.r.t. baseline design.

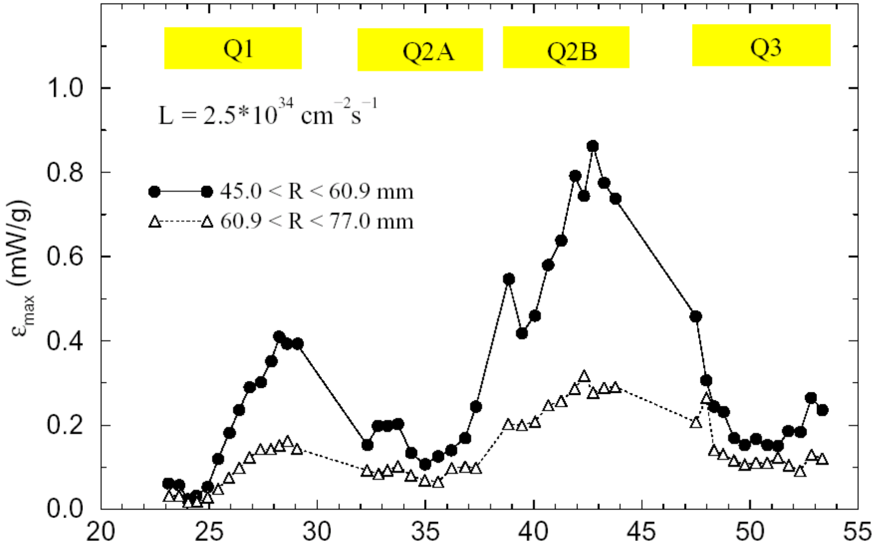
But…

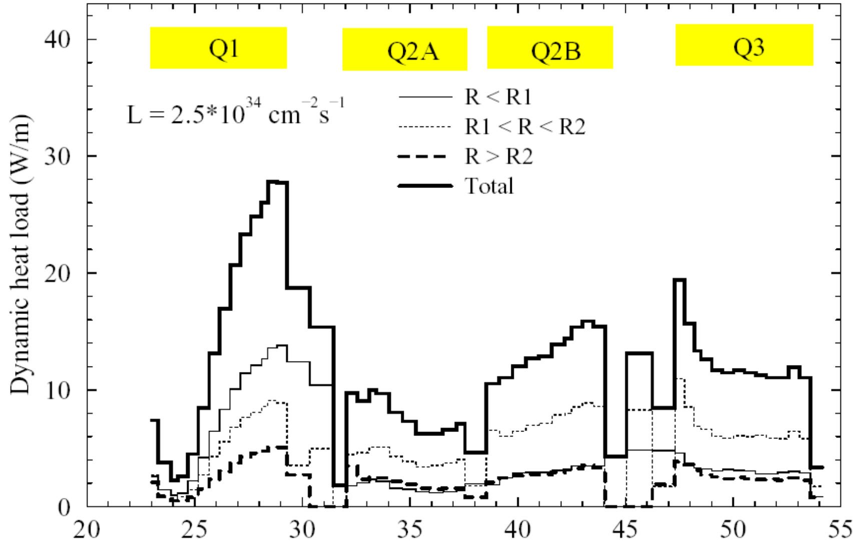
- Larger $\phi_{crossing}$ and larger beam divergence limit the increase in $\mathcal{L}$.
  - Shorten bunches with more RF? (Expensive even for x2 reduction.)
  - Crab crossing? (Difficult to provide enough crab cavity voltage. Any imperfections in crab system will blow up ε_{xy} .)
  - Increase bunch current? (Other factors may limit beam current below what it needed.)
- Factors limiting luminosity won't be fully understood without LHC running experience.
- Other developments may influence design choice. (E.g. active beam-beam compenstion; requirements by the experiments….)

Energy Deposition

Energy deposition and radiation are *major* issues for new IRs.

- In quad-first IR, E_{dep} increases both with L and with quad aperture.
  - ε_{max} > 4 mW/g, $(P/L)_{max}$ > 120 W/m, $P_{triplet}$ >1.6 kW for $\mathcal{L} = 10^{35}$ cm^{-2} s^{-1}.
  - Radiation lifetime for G11CR < 6 months at hottest spots.

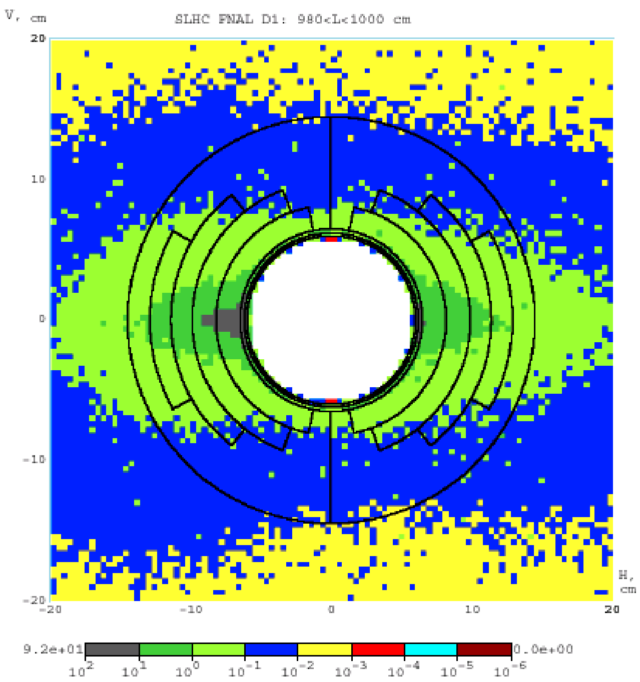


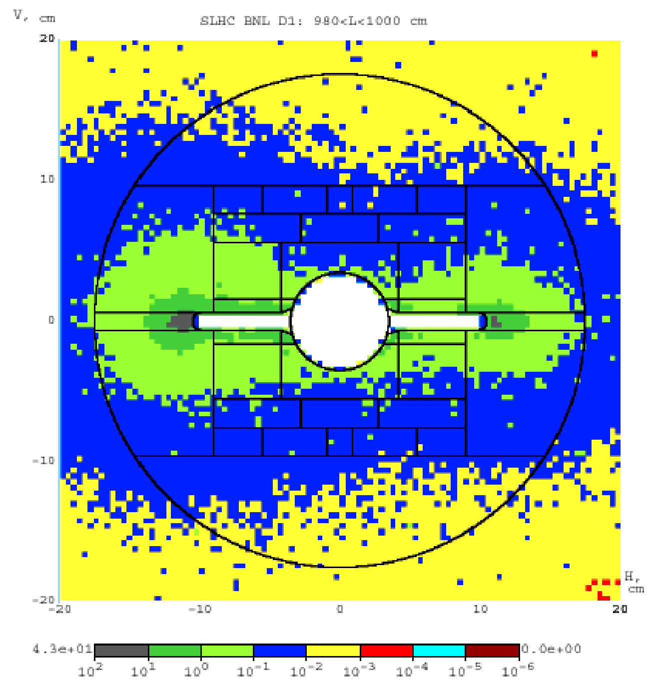


T. Sen, et al., Beam Physics Issues for a Possible 2nd Generation LHC IR, EPAC 2002.

Energy Deposition

- Problem is even more severe for dipole-first IR.
  - ε_{max} on mid-plane ~ 50 mW/g; P_{dipole} ~3.5 kW for $\mathcal{L} = 10^{35}$ cm^{-2} s^{-1}.
  - "Exotic" magnet designs may be required, whose feasibility is not known.





N.V. Mokhov, et al., Energy Dep.Limits in a Separation Dipole in Front of the LHC High-L Inner Triplet, PAC 2003.

Other Beam Physics Questions

- Are the (very) large crossing angle schemes (twin-aperture dipole or quad first) in any way feasible?
- Can dispersion suppressors be designed for the non-parallel axis quadrupole cases?
- Can triplet errors be adequately corrected given the very large β-functions?
- Other beam physics issues… see Tanaji's talk.
- Main goal now is not to design an optimal IR upgrade, but to provide input and guidance to the magnet R&D program.

Magnet R&D Questions

- What is the maximum D_{quad} for G>200 T/m?
- What is the maximum D_{quad} in a dual-bore quadrupole with 194 mm spacing?
- Can dipoles be made to operate as high as 15 T in the extreme radiation environment at very high luminosity?
- How can the many kW of beam power be removed from the cryogenic magnets for a tolerable cost?
- Are non-parallel axis dual-bore quadrupoles feasible?
- Can good field quality be maintained over the full operating range in very high field, dual-bore dipoles with parallel field directions?
- How can the required very strong correctors (linear and non-linear) correctors be made?