LHC Upgrade Scenarios and Interaction Region Design

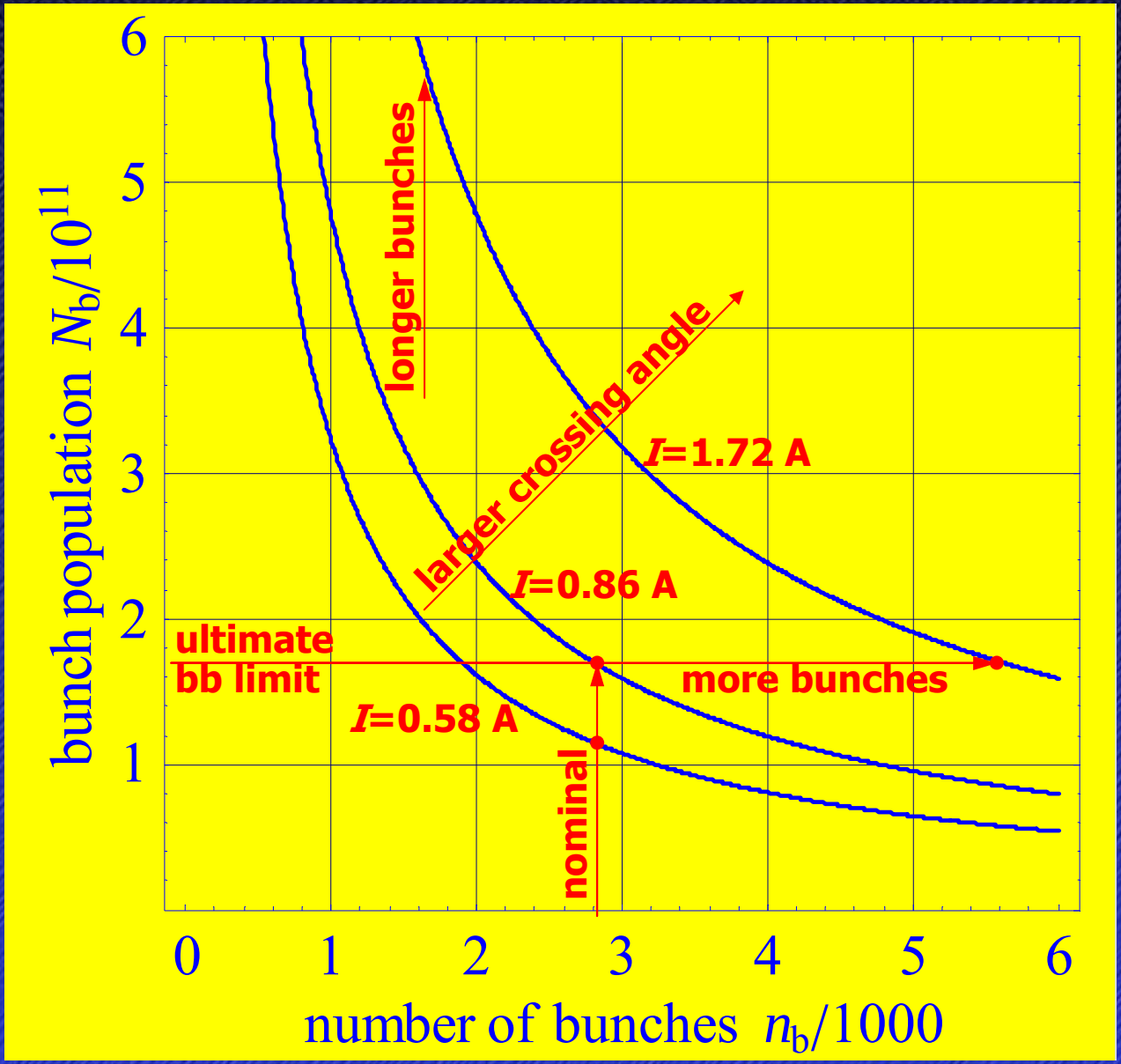
- Machine performance limitations
- Possible luminosity upgrade paths
- Scenarios for the IR upgrade
  - highlights from LHC-LUMI-05
  - minimum crossing angle and BBLR compensation
  - large crossing angle
    - Crab cavities or early beam separation
  - dipole-first (and flat beams) vs quadrupole first
- LHC luminosity upgrade studies: milestones and evolution towards a baseline design

http://care-hhh.web.cern.ch/CARE-HHH/

Nominal LHC parameters

collision energy	E_{cm}	2x7	TeV
dipole peak field	B	8.3	T
injection energy	E_{inj}	450	GeV
protons per bunch	N_b	1.15	10^{11}
bunch spacing	Δt	25	ns
average beam current	I	0.58	A
stored energy per beam		362	MJ
radiated power per beam		3.7	kW
normalized emittance	ε_n	3.75	μm
rms bunch length	σ_z	7.55	cm
beam size at IP1&IP5	σ^*	16.6	μm
beta function at IP1&IP5	β^*	0.55	m
full crossing angle	θ_c	285	μrad
luminosity lifetime	τ_L	15.5	h
peak luminosity	L	10^{34}	$cm^{-2}s^{-1}$
events per bunch crossing		19.2	
integrated luminosity	$\int L\,dt$	66.2	fb^{-1}/year

LHC upgrade paths/limitations



- Peak luminosity at the beam-beam limit $L \sim I/\beta^*$
- Total beam intensity I limited by electron cloud, collimation, injectors
- Minimum crossing angle depends on beam intensity: limited by triplet aperture
- Longer bunches allow higher bb-limit for N_b/ε_n: limited by the injectors
- Less ecloud and RF heating for longer bunches: ~50% luminosity gain for flat bunches longer than β^*
- Event pile-up in the physics detectors increases with N_b
- Luminosity lifetime at the bb limit depends only on β^*

Expected factors for the LHC luminosity upgrade

The peak LHC luminosity can be multiplied by:

- **factor 2.3** from nominal to ultimate beam intensity (0.58 $\Rightarrow$ 0.86 A)
- **factor 2** (or more?) from new low-beta insertions with $\beta^* = 0.25$ m

$T_{\text{turnaround}} \sim 10$ h $\Rightarrow \int L dt \sim 3$ x nominal $\sim$ 200/(fb*year)

Major hardware upgrades (LHC main ring and injectors) are needed to exceed ultimate beam intensity. The peak luminosity can be increased by:

- **factor 2** if we can double the number of bunches (maybe impossible due to electron cloud effects) or increase bunch intensity and bunch length

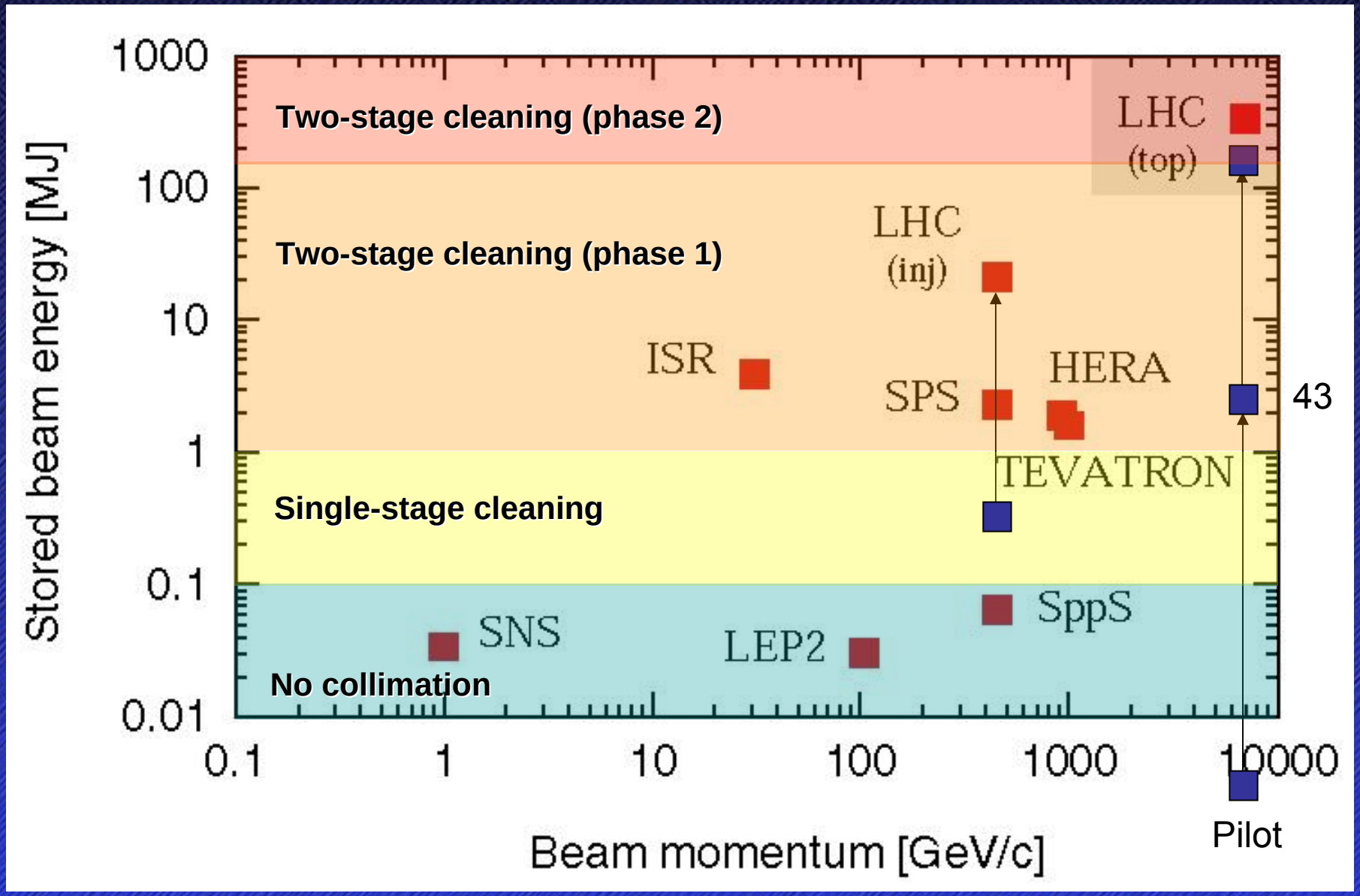
$T_{\text{turnaround}} \sim 10$ h $\Rightarrow \int L dt \sim 6$ x nominal $\sim$ 400/(fb*year)

Increasing the LHC injection energy to 1 TeV would potentially yield:

- **factor ~2** in peak luminosity (2 x bunch intensity and 2 x emittance)
- **factor 1.4** in integrated luminosity from shorter $T_{\text{turnaround}} \sim 5$ h

thus ensuring $L \sim 10^{35}$ cm^{-2} s^{-1} and $\int L dt \sim 9$ x nominal $\sim$ 600/(fb*year)

LHC Cleaning System



Luminosity optimization

$\sigma^* = \sqrt{\varepsilon\beta^*}$ transverse beam size at IP

$\varepsilon_n = \gamma\varepsilon = \gamma\dfrac{\sigma^2}{\beta}$ normalized emittance

$$L = \frac{n_b f_{rev} N_b^2}{4\pi\sigma^{*2}} = \frac{\gamma}{4\pi\beta^*}\frac{N_b}{\varepsilon_n} I$$

peak luminosity for head-on collisions

round beams, short Gaussian bunches

N_b/ε_n beam brightness

- head-on beam-beam
- space-charge in the injectors
- transfer dilution

$I = n_b f_{rev} N_b$ total beam current

- long range beam-beam
- collective instabilities
- synchrotron radiation
- stored beam energy

Collisions with full crossing angle θ_c

reduce luminosity by a geometric factor F

$$F \cong 1/\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}$$

maximum luminosity below beam-beam limit

⇒ short bunches and minimum crossing angle (baseline scheme)

H-V crossings in two IP's ⇒ no linear tune shift due to long range

total linear bb tune shift also reduced by F

$$\Delta Q_{bb} = \xi_x + \xi_y \cong \frac{N_b r_p}{2\pi\varepsilon_n} F$$

If bunch intensity and brightness are not limited by the injectors or by other effects in the LHC (e.g. electron cloud) ⇒ luminosity can be increased without exceeding beam-beam limit ΔQ_{bb}~0.01 by increasing the crossing angle and/or the bunch length

Express beam-beam limited brilliance N_b/ε_n in terms of maximum total beam-beam tune shift ΔQ_{bb}, then

$$L \cong \frac{\gamma}{2r_p}\frac{\Delta Q_{bb} I}{\beta^*} \cong \frac{\gamma \pi f_{rev}}{r_p^2}\frac{\Delta Q_{bb}^2 n_b \varepsilon_n}{\beta^*}\sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

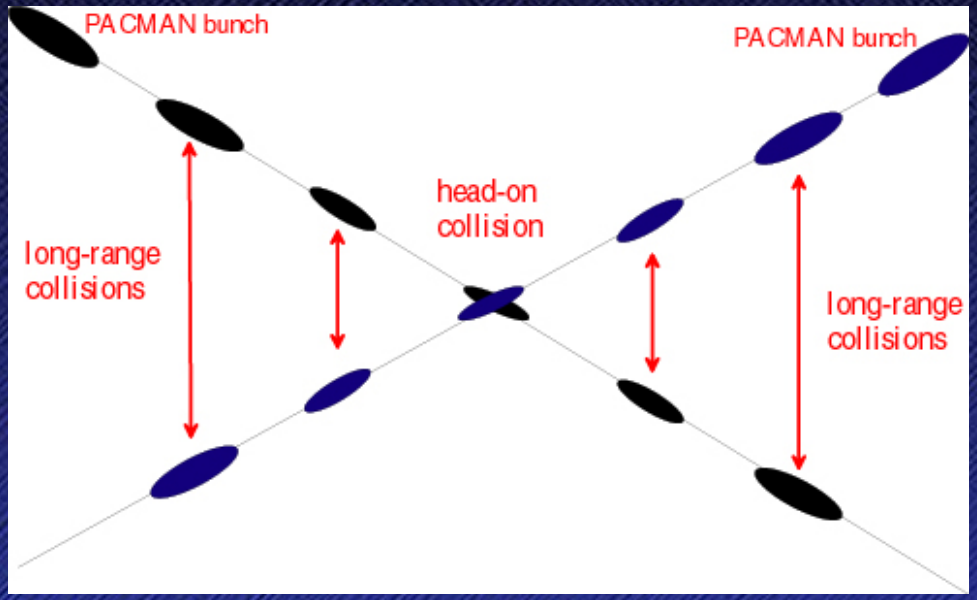
At high beam intensities or for large emittances, the performance will be limited by the angular triplet aperture

$$L \cong \frac{\gamma}{2r_p}\Delta Q_{bb} I \min\left\{\frac{1}{\beta^*}, \frac{1}{\varepsilon}\left(\frac{D_{tripl}/\ell^*}{20+\theta_c/\sigma_\theta}\right)^2\right\}$$

Minimum crossing angle

Beam-Beam Long-Range collisions:

- perturb motion at large betatron amplitudes, where particles come close to opposing beam
- cause 'diffusive' (or dynamic) aperture, high background, poor beam lifetime
- increasing problem for SPS, Tevatron, LHC, i.e., for operation with larger # of bunches



dynamic aperture caused by n_{par} parasitic collisions around two IP's

$$\frac{d_{da}}{\sigma} \approx \frac{\theta_c}{\sigma_\theta} - 3\sqrt{\frac{n_{par}}{32}\frac{N_b}{10^{11}}\frac{3.75\mu m}{\varepsilon_n}} \Rightarrow \frac{\theta_c}{\sigma_\theta} \approx 6 + 3\sqrt{\frac{I}{0.5A}\frac{3.75\mu m}{\varepsilon_n}}$$

$$\sigma_\theta = \sqrt{\frac{\varepsilon}{\beta^*}}$$ angular beam divergence at IP

higher beam intensities or smaller β^* require larger crossing angles to preserve dynamic aperture and shorter bunches to avoid geometric luminosity loss

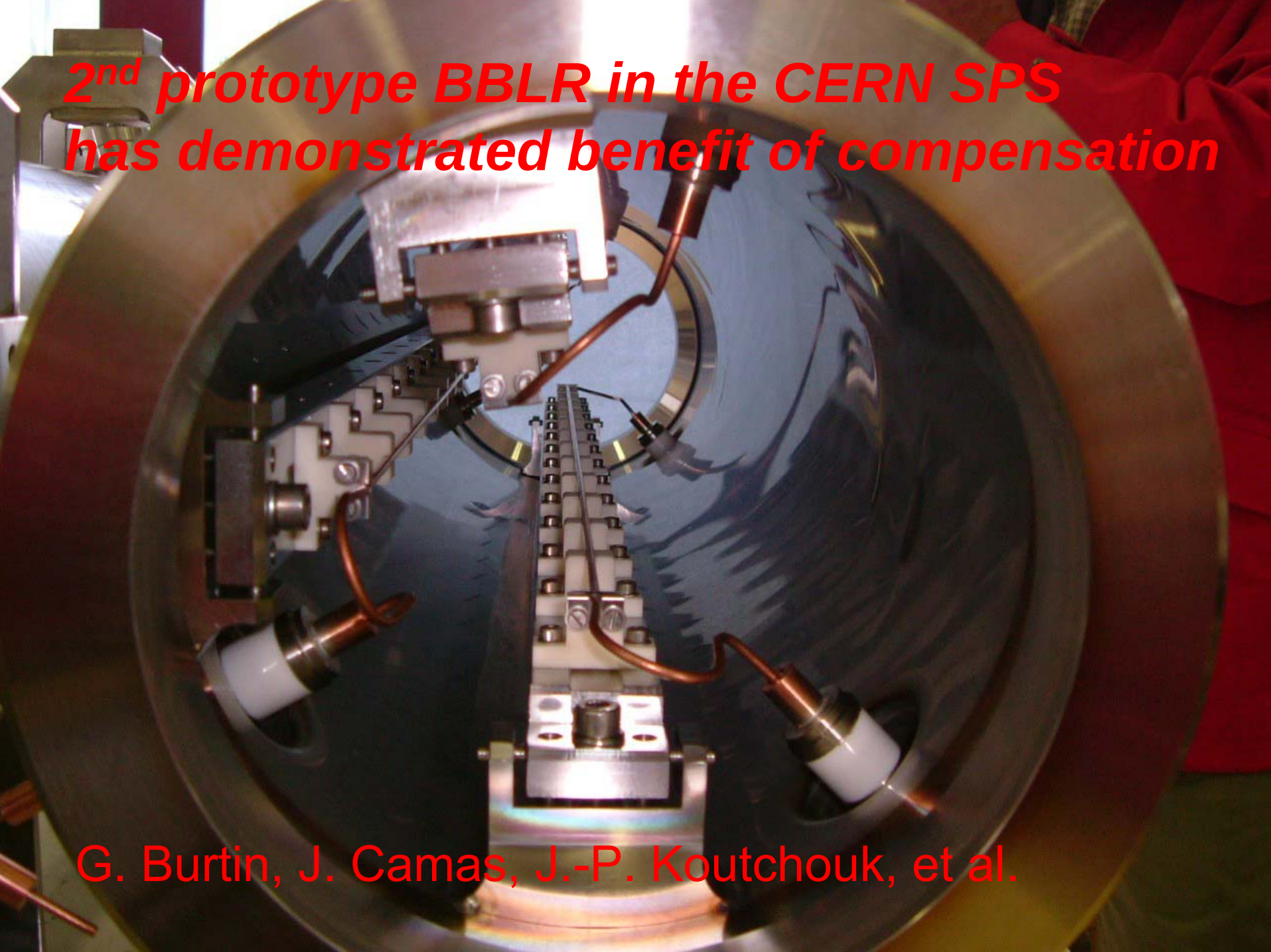
$\Rightarrow$ baseline scaling: $\theta_c \sim 1/\sqrt{\beta^*}$, $\sigma_z \sim \beta^*$

Alternative ways to avoid luminosity loss

1) **Reduce crossing angle and apply "wire" compensation of long range beam-beam effects**
2) **Crab cavities ⇒ large crossing angles to avoid long range bb effects w/o luminosity loss.** Potential of boosting the beam-beam tune shift (factor 2-3 predicted for KEKB, what about LHC?)
3) **Early beam separation by a "D0" dipole located a few metres away from the IP, as recently suggested by JPK at the LHC-LUMI-05 workshop.** The same effect could be obtained by tilted experimental solenoids, but the experiments don't seem to like the idea.

A potential drawback of 2) and 3) is that ΔQ_{bb} is no longer reduced by the geometric factor F ⇒ lower beam-beam limit?

2nd prototype BBLR in the CERN SPS has demonstrated benefit of compensation

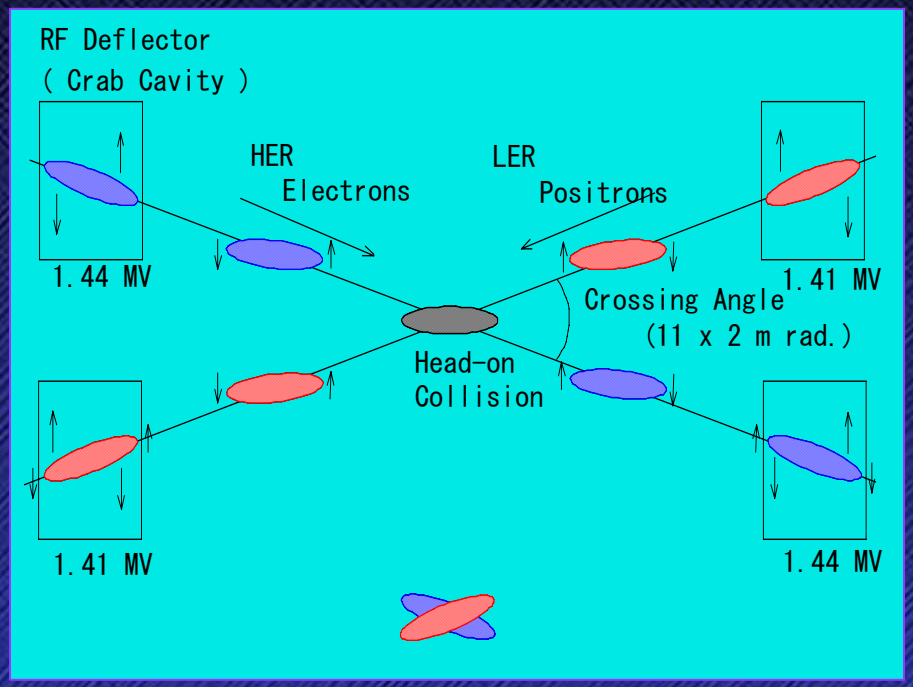


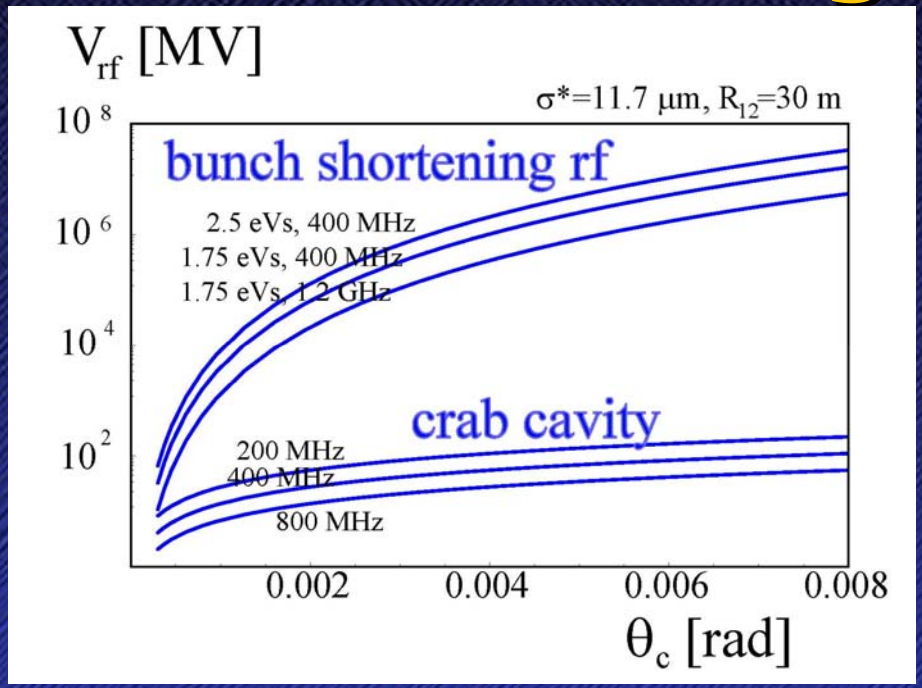
G. Burtin, J. Camas, J.-P. Koutchouk, et al.

LR beam-beam compensation: remarks and open issues

- Simulations of LR compensation with 2 wires indicate that lifetime is recovered over a wide tune range but not for all tunes.
- The measured SPS lifetime is 5 ms x $(d/\sigma)^5$. Extrapolation to LHC beam-beam distance (9.5 σ) would predict 6 minutes beam lifetime! Tevatron observations with electron lens show cubic dependence. Further SPS tests at different energy are needed.
- Lifetimes predicted by simulation codes are much larger than those observed, even though sensitivity to parameters seems correct. **Needs further understanding and beam tests, e.g. at RHIC.**
- For extreme PACMAN bunches there is overcompensation which causes the footprint to flip over or to increase instead of shrinking. **To avoid degraded lifetime for PACMAN bunches, the wire should be pulsed train by train.** It is rather challenging to make a pulsed wire for BB compensation: the required average pulse rate is 439 kHz and the turn-by-turn amplitude stability 10^{-4}.
- Experiments at RHIC (Fischer) **with a single LR encounter show that the BB effect is visible starting from a 5σ separation**, consistent with Tevatron and Daphne observations, but contrary to LHC simulations and possibly earlier observations at the SPS collider.

Crab cavities vs bunch shortening





Crab cavities combine advantages of head-on collisions and large crossing angles

require lower voltages compared to bunch shortening RF systems

but tight tolerance on phase jitter to avoid emittance growth

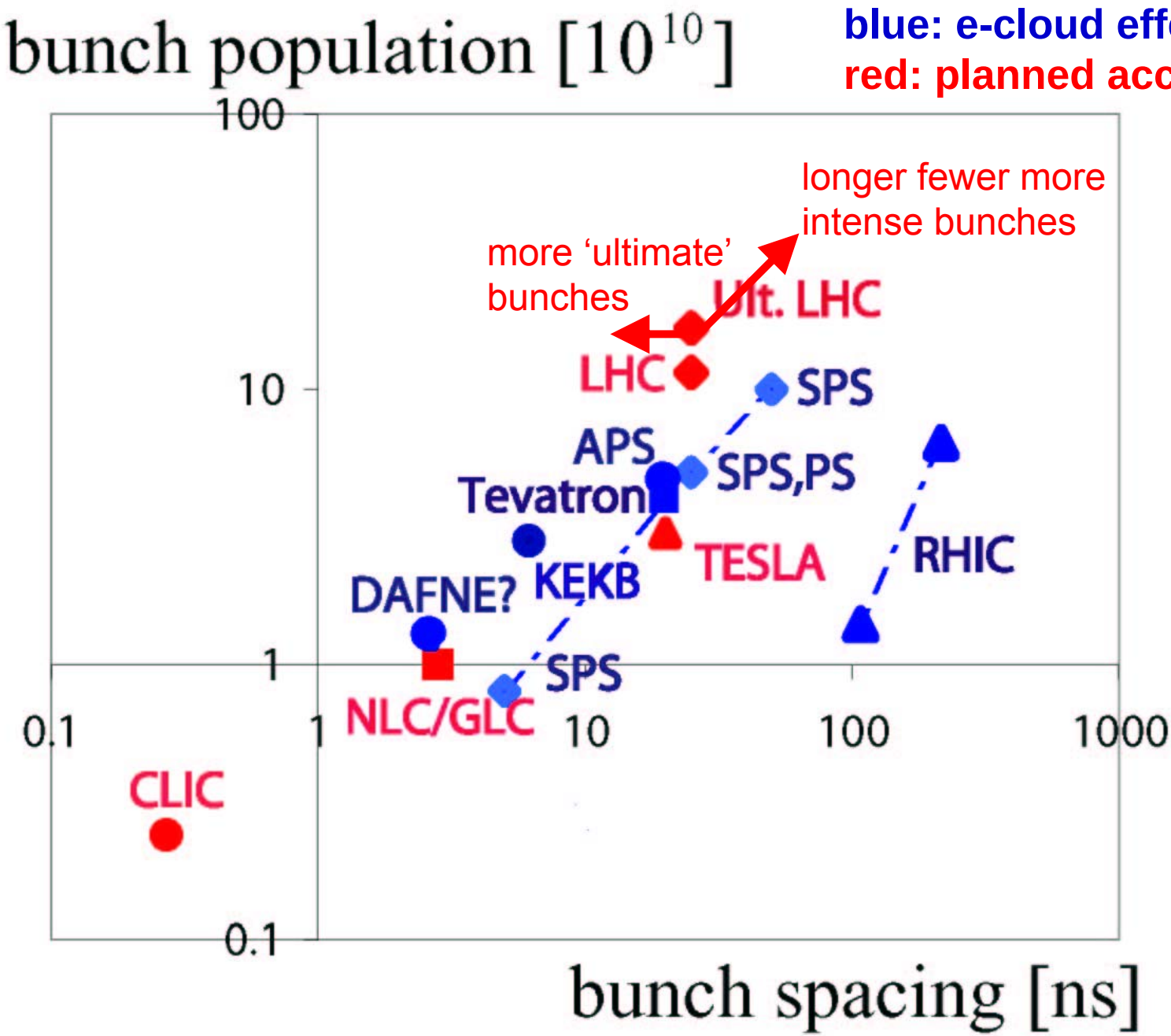
Comparison of timing tolerances

	KEKB	Super-KEKB	ILC	Super-LHC
σ_x*	100 μm	70 μm	0.24 μm	11 μm
θ_c	+/- 11 mrad	+/-15 mrad	+/-5 mrad	+/- 0.5 mrad
Δt	6 ps	3 ps	**0.03 ps**	**0.08 ps**

Tentative milestones for future machine studies

- **2006**: installation and test of a beam-beam long range compensation system at RHIC to be validated with colliding beams
- **2006/2007**: new SPS experiment for crystal collimation, complementary to recent (exciting!) Tevatron results
- **2006**: installation and test of Crab cavities at KEKB to validate higher beam-beam limit and luminosity with large crossing angles
- **2007**: if KEKB test successful, test of Crab cavities in a hadron machine (RHIC?) to validate low RF noise and emittance preservation

Scaling of electron cloud effects

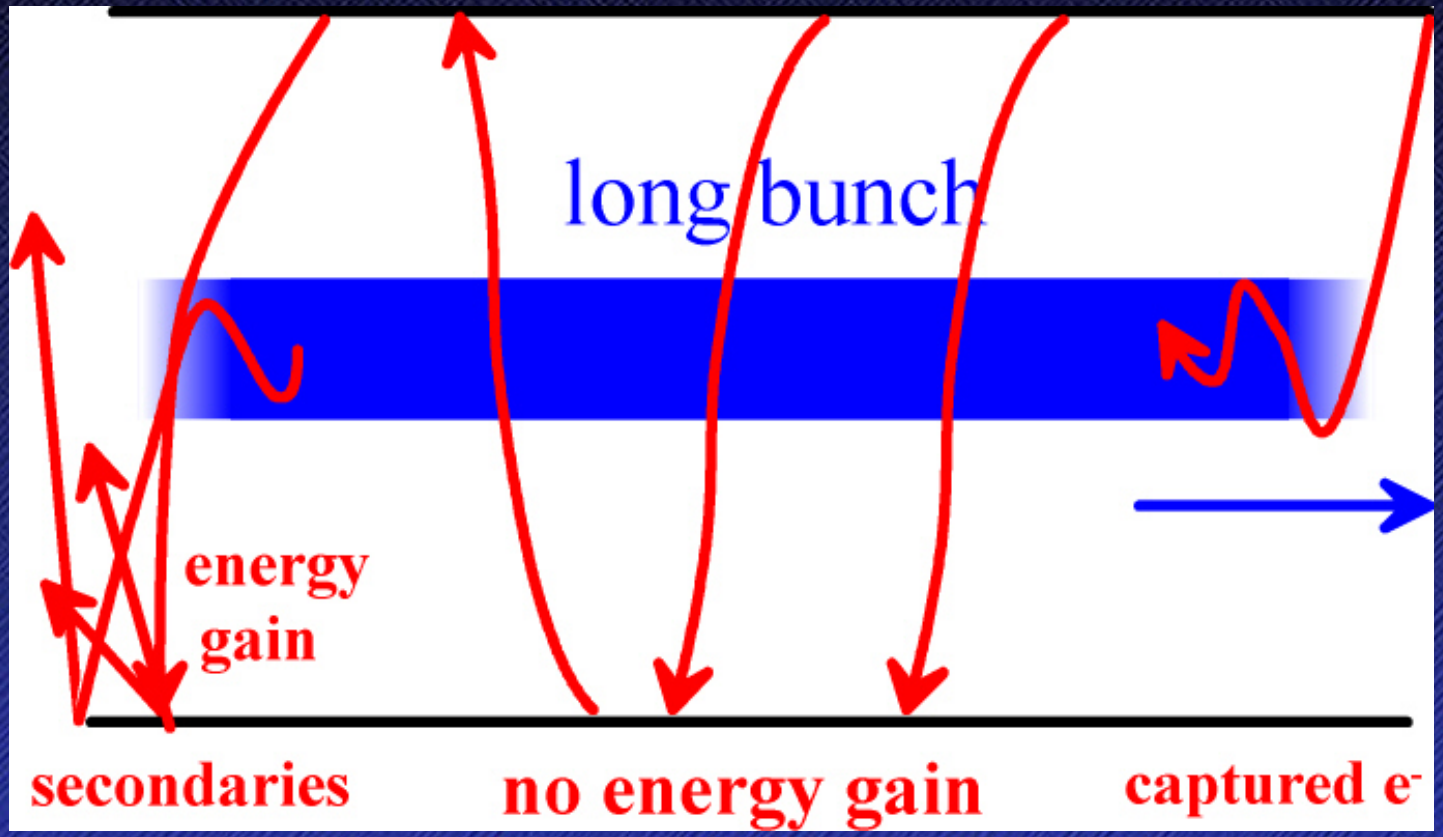


blue: e-cloud effect observed

red: planned accelerators

experience at several storage rings suggests that the e-cloud threshold scales as $N_b \sim \Delta t_{sep}$

possible LHC upgrades consider either smaller Δt_{sep} with constant N_b, or they increase Δt_{sep} in proportion to N_b



Schematic of reduced electron cloud build up for a long bunch. Most electrons do not gain any energy when traversing the chamber in the quasi-static beam potential

negligible heat load [after V. Danilov]

Scenarios for the luminosity upgrade

- ultimate performance without hardware changes (phase 0)
- maximum performance with only IR changes (phase 1)
- maximum performance with "major" hardware changes (phase 2)

Nominal LHC performance ⇒
- beam-beam tune spread of 0.01
- $L = 10^{34}$ cm^{-2}s^{-1} in ATLAS and CMS
- Halo collisions in ALICE
- Low-luminosity in LHCb

Phase 0: steps to reach ultimate performance without hardware changes:

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

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

Scenarios for the luminosity upgrade

Phase 1: steps to reach maximum performance with only IR changes

1) Modify the insertion quadrupoles and/or layout $\Rightarrow$ $\beta^* = 0.25$ m
2) Increase crossing angle θ_c by $\sqrt{2}$ $\Rightarrow$ $\theta_c = 445$ μrad
3) Increase N_b up to ultimate intensity $\Rightarrow$ $L = 3.3 \times 10^{34}$ cm^{-2}s^{-1}
4) Halve σ_z with high harmonic RF system $\Rightarrow$ $L = 4.6 \times 10^{34}$ cm^{-2}s^{-1}
5) Double the no. of bunches n_b (and increase θ_c) $\Rightarrow$ $L = 9.2 \times 10^{34}$ cm^{-2}s^{-1}
   excluded by electron cloud? **Step 5 belongs to Phase 2**

☹ Step 4) requires a new RF system providing
- an accelerating voltage of 43 MV at 1.2 GHz
- a power of about 11 MW/beam
- longitudinal beam emittance reduced to 1.8 eVs
- horizontal Intra-Beam Scattering (IBS) growth time decreases by ~ $\sqrt{2}$

☹ Operational consequences of step 5) $\Rightarrow$ exceeding ultimate beam intensity
- upgrade LHC cryogenics, collimation, RF and beam dump systems
- the electronics of all LHC beam position monitors should be upgraded
- possibly upgrade SPS RF system and other equipment in the injectors

Various LHC upgrade options

parameter	symbol	nominal	ultimate	shorter bunch	longer bunch
no of bunches	n_b	2808	2808	5616	936
proton per bunch	N_b [10^{11}]	1.15	1.7	1.7	6.0
bunch spacing	Δt_{sep} [ns]	25	25	12.5	75
average current	I [A]	0.58	0.86	1.72	1.0
normalized emittance	ε_n [μm]	3.75	3.75	3.75	3.75
longit. profile		Gaussian	Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
ß* at IP1&IP5	β^* [m]	0.55	0.50	0.25	0.25
full crossing angle	θ_c [μrad]	285	315	445	430
Piwinski parameter	$\theta_c\, \sigma_z/(2\sigma^*)$	0.64	0.75	0.75	2.8
peak luminosity	L [10^{34} cm^{-2} s^{-1}]	1.0	2.3	9.2	8.9
events per crossing		19	44	88	510
luminous region length	σ_{lum} [mm]	44.9	42.8	21.8	36.2

Injector chain for 1 TeV proton beams

injecting at 1 TeV into the LHC reduces dynamic effects of persistent currents, i.e.:

- persistent current decay during the injection flat bottom
- snap-back at the beginning of the acceleration $\Rightarrow$ easier beam control

$\Rightarrow$ decreases turn-around time and hence increases integrated luminosity

$$T_{\text{run}}\ (\text{optimum}) \Rightarrow \begin{cases} 1 + \dfrac{T_{\text{run}} + T_{\text{turnaround}}}{\tau_{\text{L}}} = e^{\frac{T_{\text{run}}}{\tau_{\text{L}}}} \\ \displaystyle\int_0^{T_{\text{run}}} L dt = \frac{L_0}{\tau_{\text{L}}} \times \frac{T_{\text{run}} + T_{\text{turnaround}}}{T_{\text{run}} + T_{\text{turnaround}} + \tau_{\text{L}}} \end{cases}$$

with τ_{gas} = 85 h and

$\tau^{\times}_{\text{IBS}}$= 106 h (nom) $\Rightarrow$ 40 h (high-L)

L_0 [cm^{-2}s^{-1}]	τ_L [h]	$T_{\text{turnaround}}$ [h]	T_{run} [h]	$\int_{200\ \text{days}} L\,dt$ [fb^{-1}]	gain
10^{34}	15	10	14.6	66	x1.0
10^{34}	15	5	10.8	85	x1.3
10^{35}	6.1	10	8.5	434	x6.6
10^{35}	6.1	5	6.5	608	x9.2

LHC injector complex upgrade

- CERN is preparing a road map for an upgrade of its accelerator complex to optimize the overall proton availability in view of the LHC luminosity upgrade and of all other physics users
- Scenarios under consideration include a new proton linac (Linac 4, 160 MeV) to overcome space charge limitations at injection in the PS Booster and a new Superconducting PS reaching an energy of 50-60 GeV
- This would open the possibility of a more reliable production of higher-brightness beams for the LHC, with lower transmission losses in the SPS thanks to the increased injection energy
- It would also offer the opportunity to develop new fast pulsing SC magnets in view of a Super-SPS, injecting at 1 TeV into the LHC

Interaction Region upgrade

goal: reduce β^* by at least a factor 2

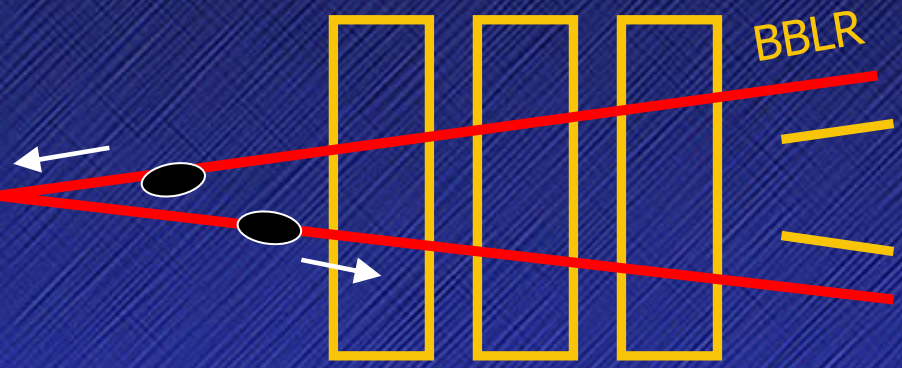
options: NbTi 'cheap' upgrade, NbTi(Ta), Nb_3Sn
new quadrupoles
new separation dipoles

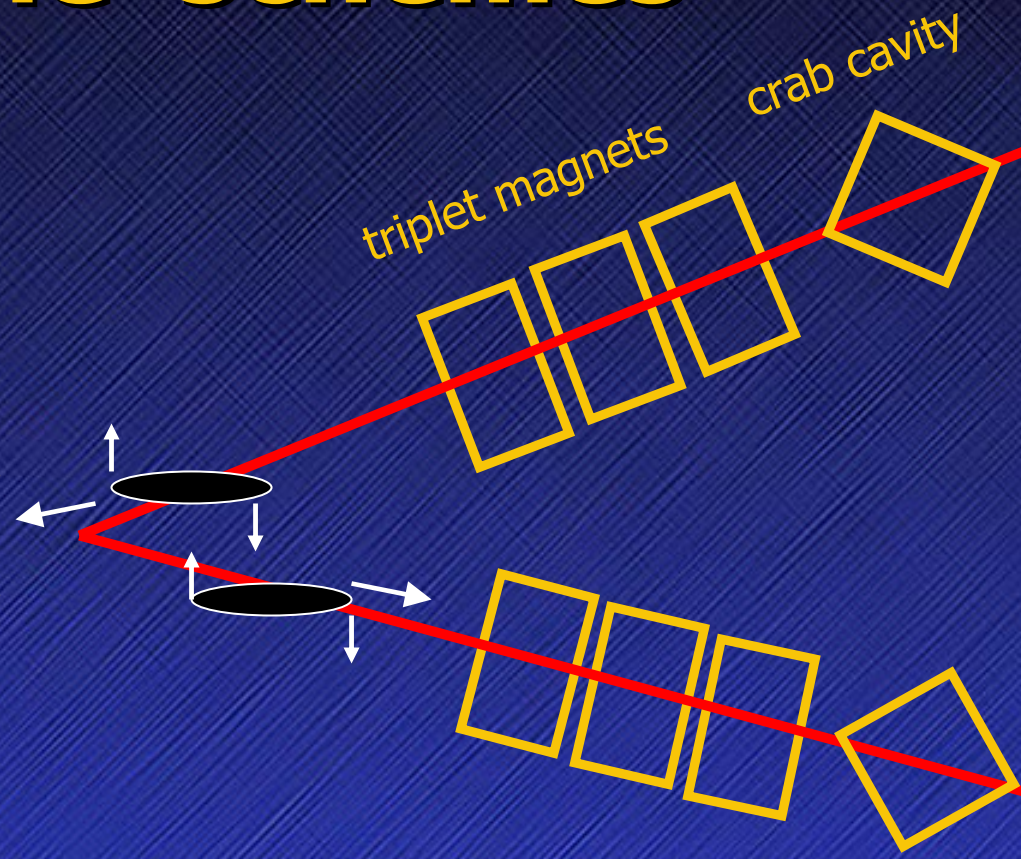
factors driving IR design:

maximize magnet aperture,
minimize distance to IR

- minimize β^*
- minimize effect of LR collisions
- large radiation power directed towards the IRs
- accommodate crab cavities and/or beam-beam compensators. Local Q' compensation scheme?
- compatibility with upgrade path

IR 'baseline' schemes

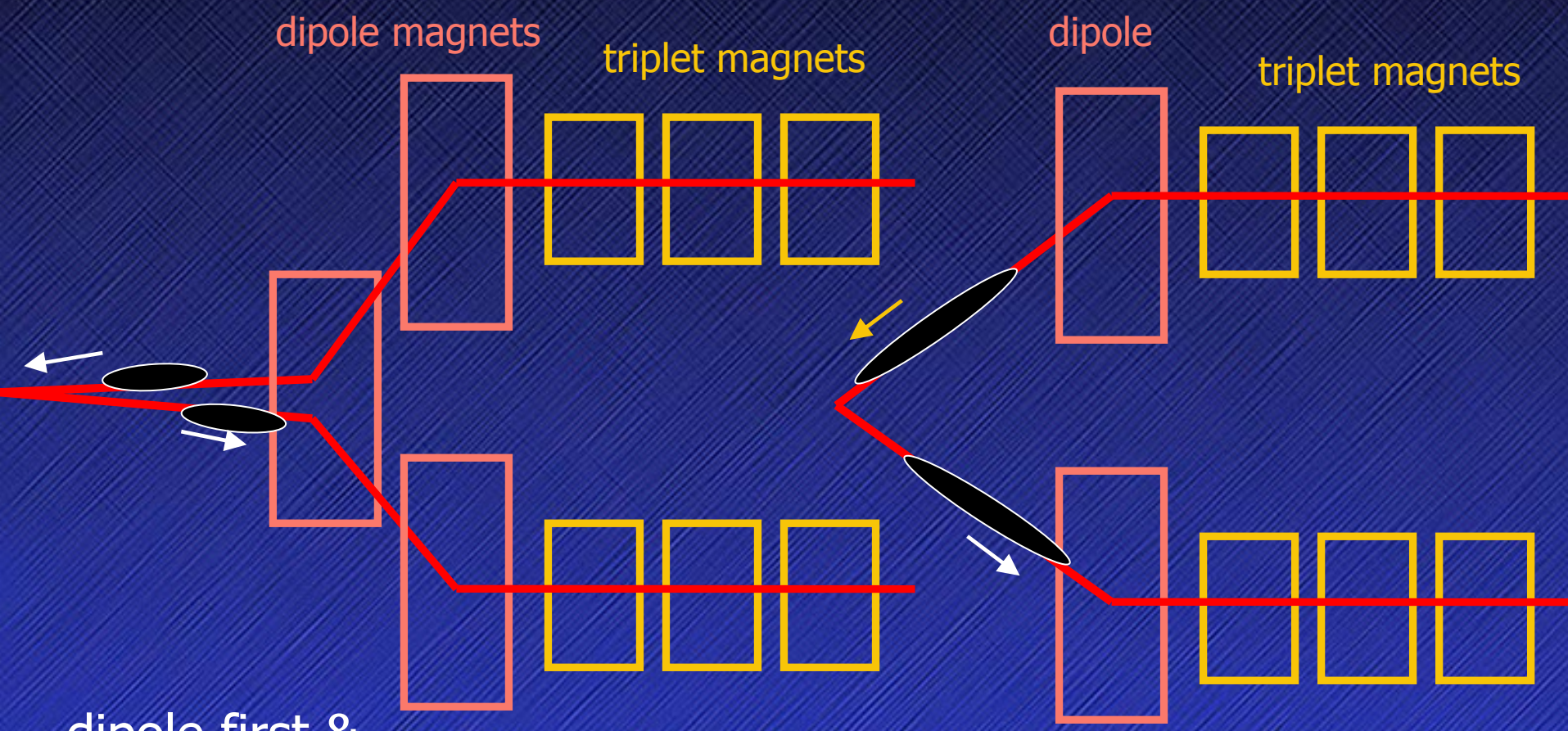




short bunches &
minimum crossing angle &
BBLR

crab cavities &
large crossing angle
(what is minimum crossing angle for separate channels?)

alternative IR schemes

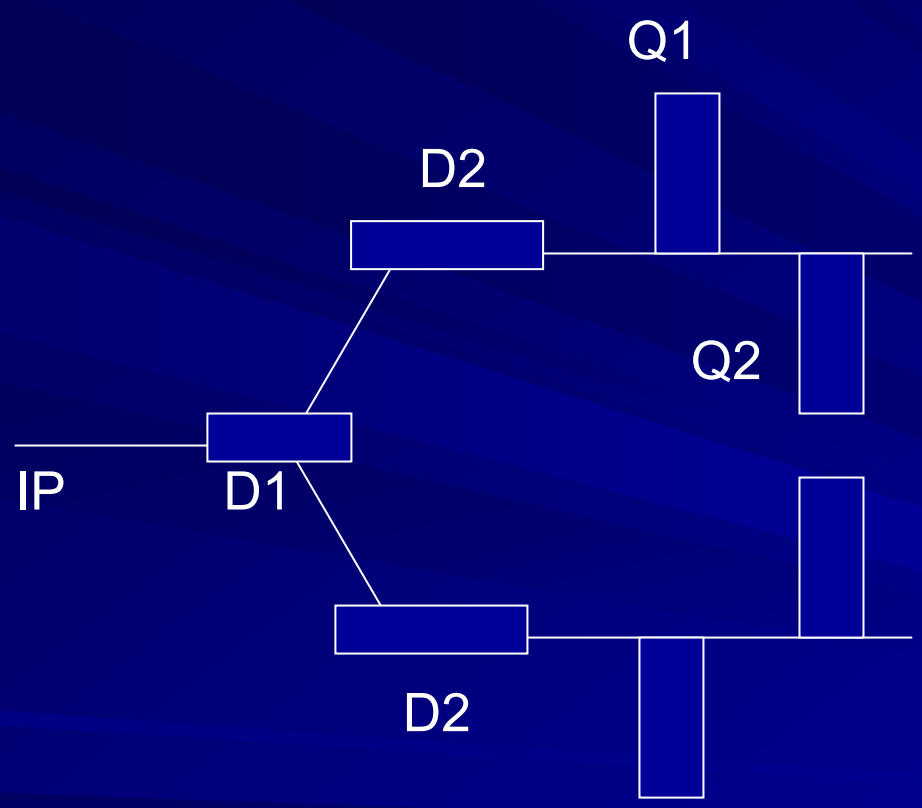


dipole first &
small crossing angle

reduced # LR collisions
collision debris hit D1

dipole first &
large crossing angle &
long bunches or crab cavities

Dipoles first and doublet focusing



Focusing symmetric about IP

Features

- Requires beams to be in separate focusing channels
- Fewer magnets
- Beams are not round at the IP
- Polarity of Q1 determined by crossing plane – larger beam size in the crossing plane to increase overlap
- Opposite polarity focusing at other IR to equalize beam-beam tune shifts
- Significant changes to outer triplet magnets in matching section.

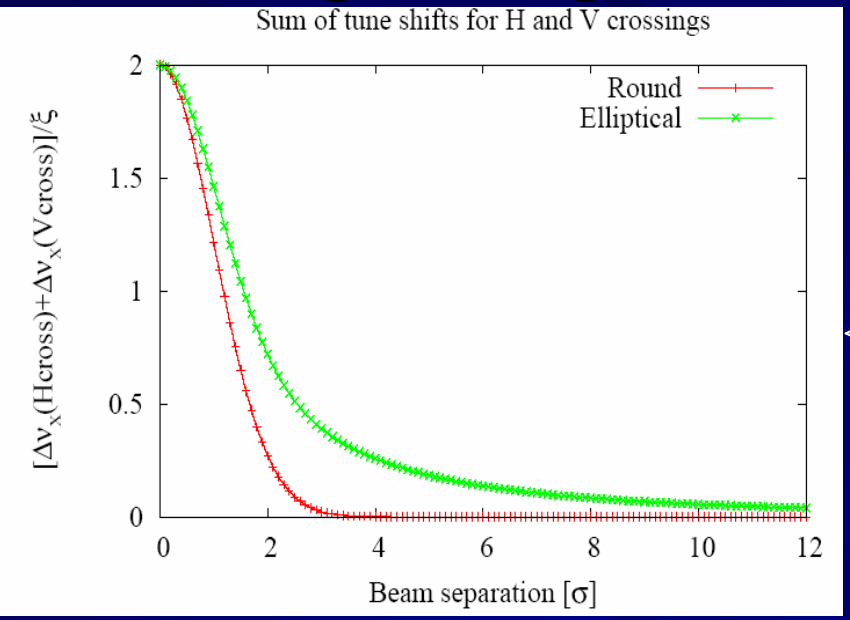
Features of this doublet optics

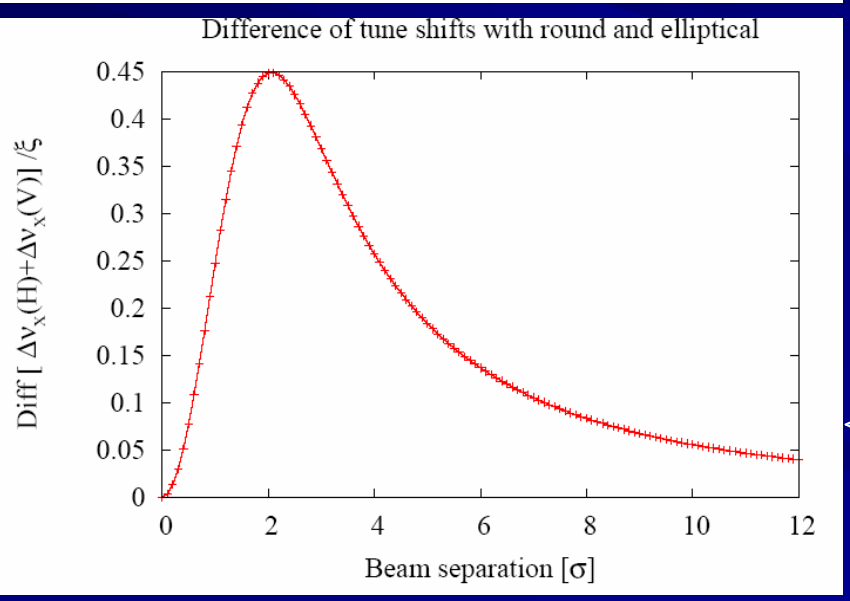
- Symmetric about IP from Q1 to Q3, anti-symmetric from Q4 onwards
- Q1, Q2 are identical quads, Q1T is a trim quad (125 T/m). L(Q1) = L(Q2) = 6.6 m
- Q3 to Q6 are at positions different from baseline optics
- All gradients under 205 T/m
- Phase advance preserved from injection to collision
- At collision, β^*_x= 0.462m, β^*_y = 0.135m, β^*_{eff}= 0.25m
- Same separation in units of beam size with a smaller crossing angle $\Phi_E = \sqrt{(\beta^*_R / \beta^*_E)}\, \Phi_R = 0.74\, \Phi_R$
- Luminosity gain compared to round beam

$$\frac{\mathcal{L}_E}{\mathcal{L}_R} = \left[\frac{1 + (\phi_R \sigma_s / \sigma^*_{x,R})^2}{1 + (\beta^*_{x_R}/\beta^*_{x_E})^2 (\phi_R \sigma_s / \sigma^*_{x,R})^2}\right]^{1/2} = 1.38$$

Including the hourglass factor, $\frac{\mathcal{L}_E}{\mathcal{L}_R} = 1.33$

Long-range beam-beam tune shifts





- Vertical crossing at IP1 and horizontal crossing at IP5

Round beams

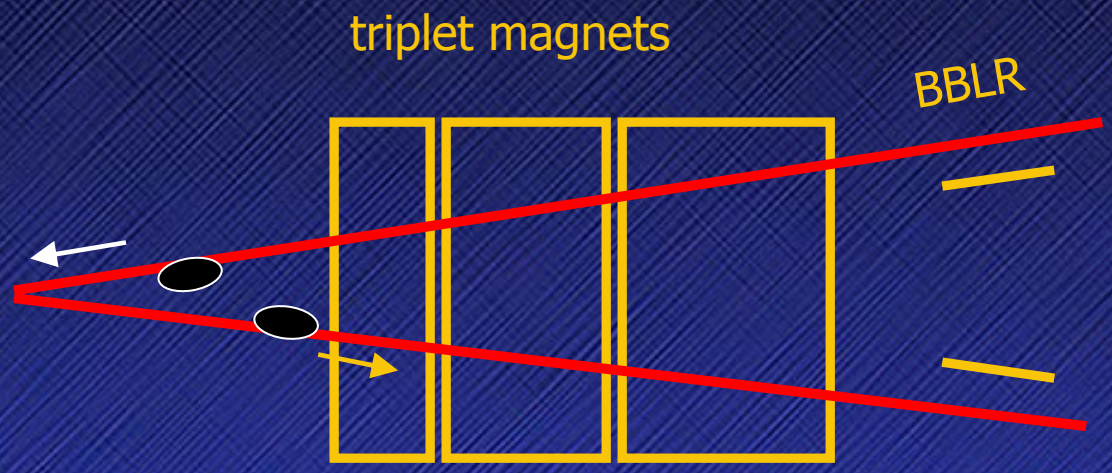
- Cancellation of tune shifts is very good (< 0.001 ξ) for separations beyond 4σ

Elliptical beams

- Doublet optics, beam vertically large at IP1 ($\sigma_y/\sigma_x = 2$) with vertical crossing and horizontally large ($\sigma_y/\sigma_x = 0.5$) at IP5 with horizontal crossing
- Sum of tune shifts from IP1 and IP5 < 0.1 ξ for separations > 7σ
- Difference in long-range tune shifts between round and elliptical beams < 0.07 ξ for separations > 9σ
- Could be a source of concern if difference persists with all parasitics included.

‘cheap’ IR upgrade

in case we need to double LHC luminosity earlier than foreseen



short bunches &
minimum crossing angle &
BBLR

each quadrupole individually optimized (length & aperture)
reduced IP-quad distance from 23 to 22 m
conventional NbTi technology: β^*=0.25 m seems possible

Triplet aperture requirements

The minimum coil aperture D_{min} of the low-β quadrupoles for the baseline scheme can be roughly estimated by assuming:

- 9σ beam envelope
- 7.5σ beam separation (at mid of Q2 -> $\theta_c \sim 9.5\text{-}10\ \sigma_\theta$)
- 3-4 mm spurious dispersion orbit d_s (depending on θ_c)
- 20% β-beating
- 3 mm peak orbit excursion
- 1.6 mm mechanical tolerances
- 10 mm margin for beam tube and beam screen

$$D_{min} \geq 1.1*(7.5+ 2*9)\sigma + 2*(d_s + 3\text{mm}+1.6\text{mm}) + 10\text{mm}$$

Nominal LHC: $\beta^* = 0.5$ m, $\sigma = 1.54$ mm $\Rightarrow D_{min} \sim 68$ mm

Baseline upgrade: $\beta^* = 0.25$ m, $\sigma = 2.2$ mm $\Rightarrow D_{min} \sim 89$ mm

- Drop 7.5σ beam separation for separate channels (e.g. dipole-first)
- Add safety margin from heat deposition $\Rightarrow$ approximate scaling?
- Add $1.5\text{-}2\sigma$ beam separation for $I = 1.7$ A (12.5 ns spacing, no BBLR)
- Multiply σ by $\sqrt{2}$ for 2 x bunch intensity and 2 x emittance (Super-SPS)

Quadrupole-first layout: an example

Main parameters of the quadrupoles at 7 TeV in different arrangements of the low-β triplet. The spacing between the quadrupoles is 2 m and ℓ^* is 23 m (Table 2 from R. Ostojic et al, PAC05 and CARE Conf-05-005-HHH).

The short Q1 in the last column assumes Nb_3Sn cable, all others NbTi.

	LHC triplet		Symmetric triplet		Long Q3		Short Q1	
	Q2, Q3	Q1	Q2, Q3	Q1	Q2, Q3	Q1	Q2, Q3	Q1
β^* [m]	0.50	0.50	0.25	0.25	0.25	0.25	0.25	0.25
β_{peak} [m]	4750	1265	11520	5400	11840	5440	9500	3600
θ_c [μrad]	315	315	445	445	445	445	445	445
σ [mm]	1.5	0.8	2.4	1.6	2.4	1.6	2.2	1.3
d_s [mm]	2.8	1.4	4.2	2.9	4.3	2.9	3.9	2.4
D_{min} [mm]	67.6	44.2	94.5	70.8	95.5	70.9	87.6	61.3
g [T/m]	198.5	198.5	151.8	151.8	137.8	161.1	151.8	338.6
L [m]	5.5/6.3	6.3	8.0	8.0	8.0/10.0	8.0	8.0	4.0

LHC-LUMI-05: Highlights for the IR Upgrade

main points from Pantaleo Raimondi's presentation I:

-local chromaticity correction via dispersion inside the triplet magnets and two pairs of sextupoles (one inside at the location of dispersion and one with phase advance of π) can correct chromaticity and geometric aberrations

➔ works well for linear collider final focus (cancellation up to forth order)

➔ Frank Zimmermann showed that the concept can be applied to circular collider

From ILC to LHC (1)

Much smaller chromaticity:

$W_{max}=L^*/\beta y^*=4/0.0001=40000$ for ILC

$W_{max}=L^*/\beta^*=50/0.025=2000$ for LHC

Much larger emittance and sizes

300nm/3nm for ILC

4μm/4μm for LHC

Much larger D allowed at the Final Quads:

D=0.2m for ILC

D>2m for LHC (increase in the size at the Quads negligible)

Much smaller energy acceptance

De=+-2% for ILC

De=+-0.1% for LHC

Very weak and long bends needed for ILC to reduce blow-up from SR.

From ILC to LHC (2)

Much easier task overall

Much weaker sexupoles

Much smaller second order geometric aberrations and spurious higher order residual aberrations.

A possible strategy for LHC:

Look for a solution that can be implemented (and removed) anytime simply rematching betas and Ds and chromaticity by varying quads and sexupoles (Safest approach)

Summary of Working Group I

main points from Riccardo de Marias's presentation:

-matched optics solution for dipole first layout for Beam1 and Beam2 with squeeze and tunability study:

- ➔ 18 km β-max requires additional Q' correction
- ➔ dispersion of 15 cm from D1/D2 arrangement for free
- ➔ could be increased for D' = 0 at the IP
- ➔ dispersion changes sign left and right from IP
- ➔ SF: kissing scheme could allow equal signs of D but vertical D is quite small

Summary of Working Group I

main points from Riccardo de Marias's presentation:

-optics study relies on Nb_3Sn technology:

➔ 10 m long dipole magnets with B = 15 T

➔ quadrupole magnets with 260 T/m and 80 mm aperture ➔ 11 T coil field

➔ IR layout provides magnetic TAS for "free"

Summary of Working Group I

main points from Oliver Brüning's presentation:

-proposal of a low gradient solution that could be realized with NbTi technology

➔ 18 km β-max requires additional Q' correction

➔ maximum gradient of 70 T/m allows more than 200mm diameter with a peak coil field of 5.5 T

➔ Dispersion inside the triplet could be increased for D' = 0 at the IP

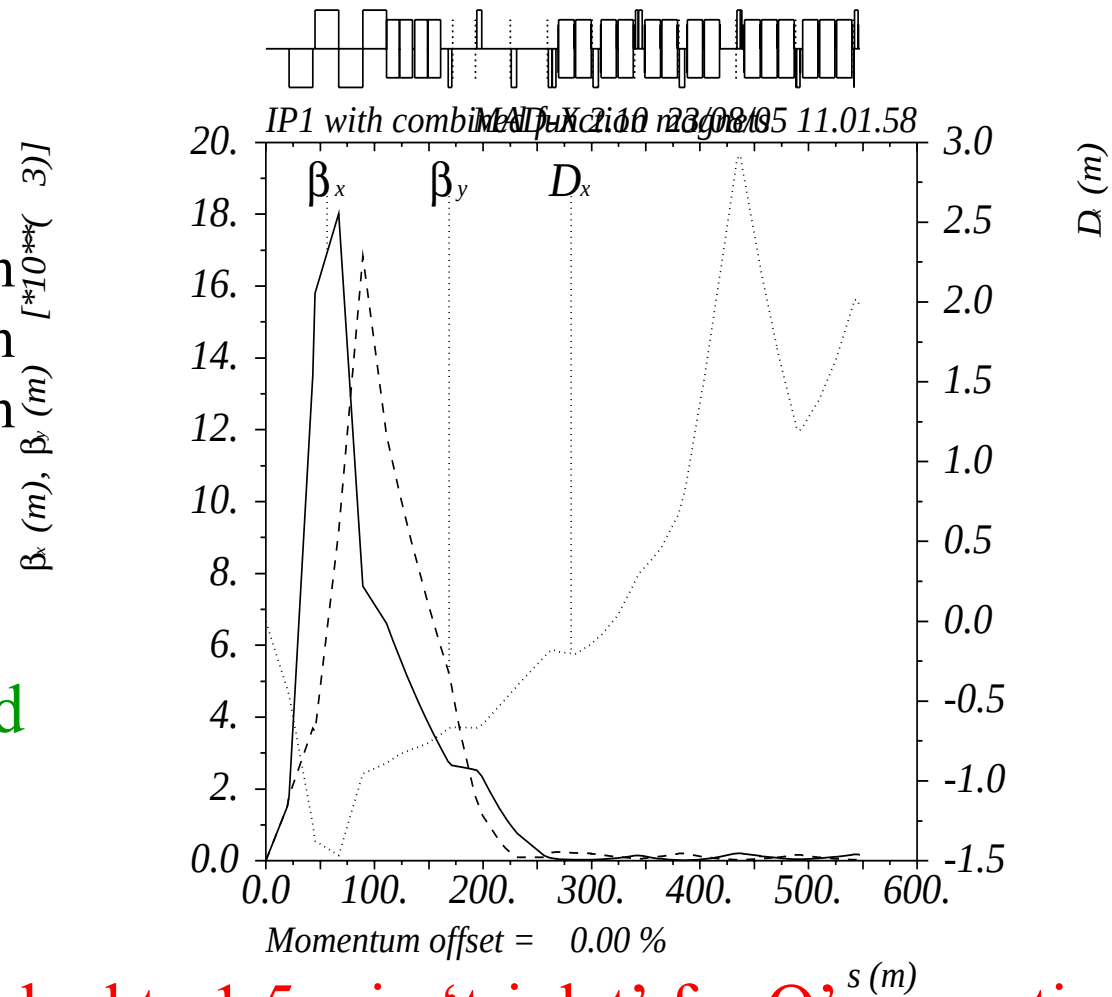
➔ Layout still requires an improved TAS absorber

Options for a Quadrupole First Layout

Layout and optics derived from Combined function solution:

D1/D1 ➔ 3.7 T
Q1 ➔ 47T/m ➔ d = 212mm
Q2 ➔ 70T/m ➔ d = 143mm
Q3 ➔ 47T/m ➔ d = 212mm
Q3b ➔ 6T/m

➔ aperture estimate assumes a peak coil field of 5 T!



➔ dispersion matched to 1.5m in 'triplet' for Q' correction!

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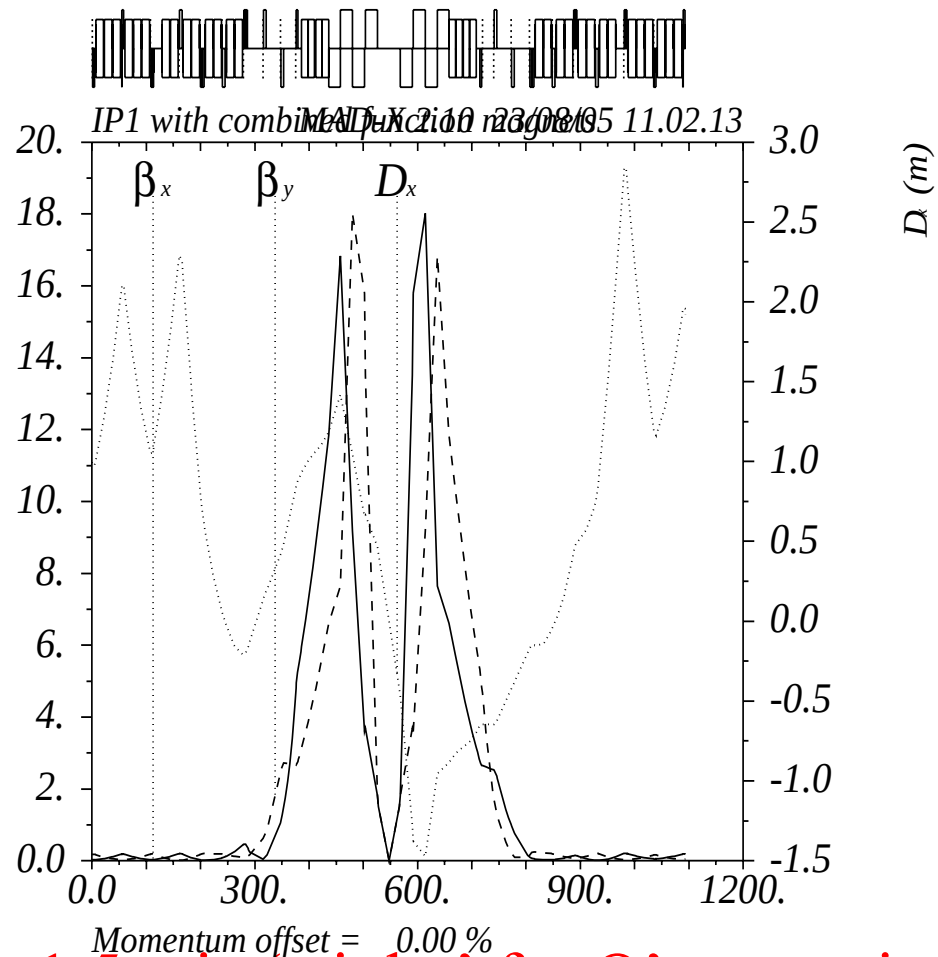


➔ dispersion matched to 1.5m in 'triplet' for Q' correction!

Summary of Working Group I

-repository with optics solutions is very desirable! (linked to HHH CARE WWW page?) ➔ we should all use the same input format (MADX)

-identified three layout options that should be studied in more detail:

1) dipole first based on Nb_3Sn technology with L* = 19m
2) quad first layout based on Nb_3Sn technology L* = 19m
3) low gradient quad first layout based on NbTi technology

Summary of Working Group I

-we desperately need to fix L* and required length for TAS upgrade (inflation of solutions)!

➔ this point was already raised at HHH workshop in 2004!

➔ Tanaji promised an answer for the TAS after October US-LARP workshop in Fermilab!

➔ Emmanuel Tsesmelis will clarify the L* options with the LHC integration team (we agreed to assume L* = 19 m for now as a reasonable estimate)

➔ the goal is to have an update of the 3 proposals by **end 2005**

Several LHC IR upgrade options are currently being explored: we need to converge to a baseline configuration and identify a few alternative options

- quadrupole-first and dipole-first solutions based on conventional NbTi technology and on high-field Ni_3Sn magnets, possibly with structured SC cable
- energy deposition, absorbers, and quench limits
- schemes with Crab cavities as an alternative to the baseline bunch shortening RF system at 1.2 GHz to avoid luminosity loss with large crossing angles
- early beam separation by a "D0" dipole located a few metres away from the IP (or by tilted experimental solenoids?) may allow operation with a reduced crossing angle. Open issues: compatibility with detector layout, reduced separation at first parasitic encounters, energy deposition by the collision debris
- local chromaticity correction schemes
- flat beams, i.e. a final doublet instead of a triplet. Open issues: compensation of long range beam-beam effects with alternating crossing planes

Towards a baseline design

Following the approach proposed by Barry Barish for the ILC, I suggest to:

- **Define a Baseline, i.e. a forward looking configuration which we are reasonably confident can achieve the required LHC luminosity performance and can be used to give an accurate cost estimate by mid-end 2006 in a "Reference Design Report."**
- **Identify Alternative Configurations and rate them in terms of technological and operational risks/advantages**
- **Identify R&D (at CERN and elsewhere)**
  - **To support the baseline**
  - **To develop the alternatives**

What are Alternatives and Why?

Alternates: technologies or concepts, which may provide a significant cost reduction, improved performance (or both), but which will not be mature enough to be used in the baseline by end 2006

Alternatives will be part of the RDR, will form an important element in the R&D program and are the key to evolving the design

Reference LHC Luminosity Upgrade: workpackages and tentative milestones

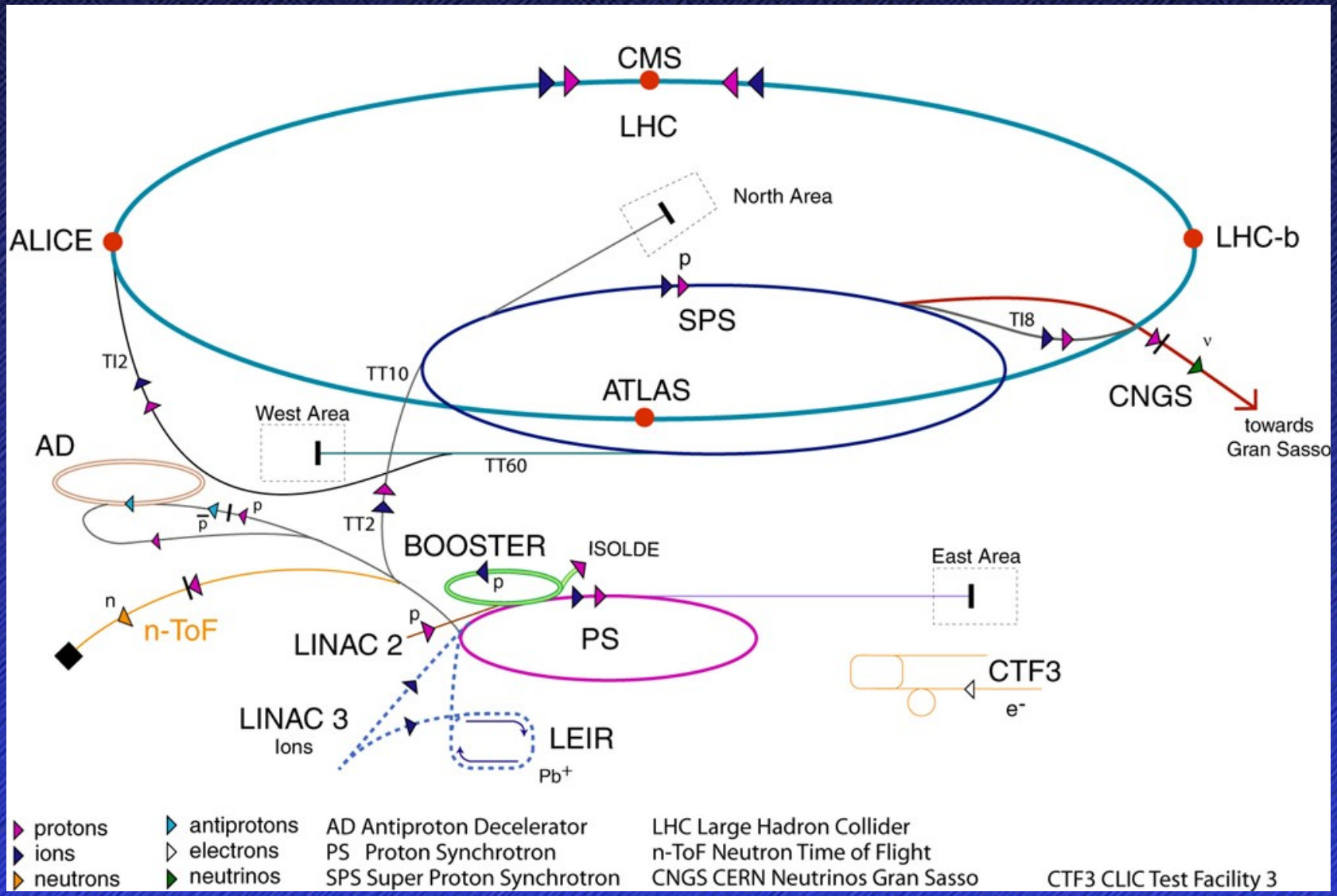
accelerator	WorkPackage	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	after 2015
LHC Main Ring	Accelerator Physics											
	High Field Superconductors											
	High Field Magnets											
	Magnetic Measurements											
	Cryostats											
	Cryogenics: IR magnets & RF											
	RF and feedback											
	Collimation&Machine Protection											
	Beam Instrumentation											
	Power converters											
SPS	SPS kickers											
	Tentative Milestones	Beam-beam compensation test at RHIC	SPS crystal collimation test	LHC collimation tests	LHC collimation tests	Install phase 2 collimation	LHC tests: collimation & beam-beam			Install new SPS kickers	new IR magnets and RF system	
	Other Tentative Milestones	Crab cavity test at KEKB	Low-noise crab cavity test at RHIC	**LHC Upgrade Conceptual Design Report**		LHC Upgrade Technical Design Report	Nominal LHC luminosity 10^34			Ultimate LHC luminosity 2.3x10^34	beam-beam compensation	Double ultimate LHC luminosity 4.6x10^34
		LHC Upgrade Reference Design Report										

R&D - scenarios & models	
specifications & prototypes	
construction & testing	
installation & commissioning	

Reference LHC Upgrade scenario: peak luminosity 4.6x10^34/(cm^2 sec)
Integrated luminosity 3 x nominal ~ 200/(fb*year) assuming 10 h turnaround time
new superconducting IR magnets for beta*=0.25 m
phase 2 collimation and new SPS kickers needed to attain ultimate LHC beam intensity of 0.86 A
beam-beam compensation may be necessary to attain or exceed ultimate performance
new superconducting RF system: for bunch shortening or Crab cavities
hardware for nominal LHC performance (cryogenics, dilution kickers, etc) not considered as LHC upgrade
R&D for further luminosity upgrade (intensity beyond ultimate) is recommended: see Injectors Upgrade

Additional Slides

CERN: the World's Most Complete Accelerator Complex (not to scale)



Injector chain for 1 TeV proton beams

injecting in LHC more intense proton beams with constant brightness, within the same physical aperture

$\Longrightarrow$ will increase the peak luminosity proportionally to the proton intensity

$$L \approx \gamma \Delta Q_{bb}^2 \frac{\pi \varepsilon_n f_{rep}}{r_p^2 \beta^*} \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*} \right)^2}$$

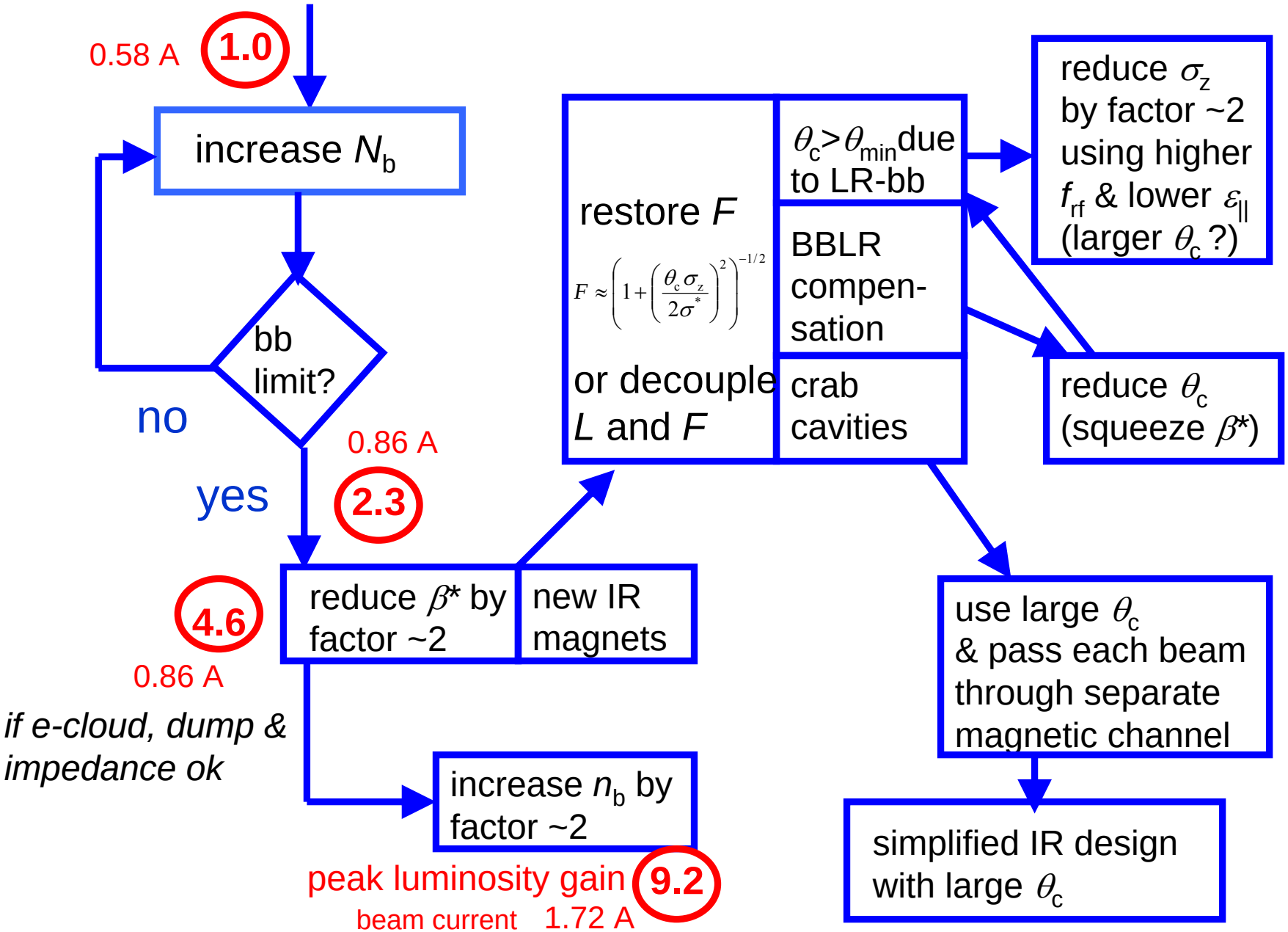
$$\frac{d_{sep}}{\sigma} \approx \theta_c \sqrt{\frac{\gamma \beta^*}{\varepsilon_n}}$$

- at the beam-beam limit, peak luminosity L is proportional to normalized emittance $\varepsilon_n = \gamma\varepsilon$, unless limited by the triplet aperture
- an increased injection energy (Super-SPS) allows a larger normalized emittance ε_n in the same physical aperture, thus more intensity and more luminosity at the beam-beam limit.
- the transverse beam size at 7 TeV would be larger and the relative beam-beam separation correspondingly lower: long range beam-beam effects have to be compensated.

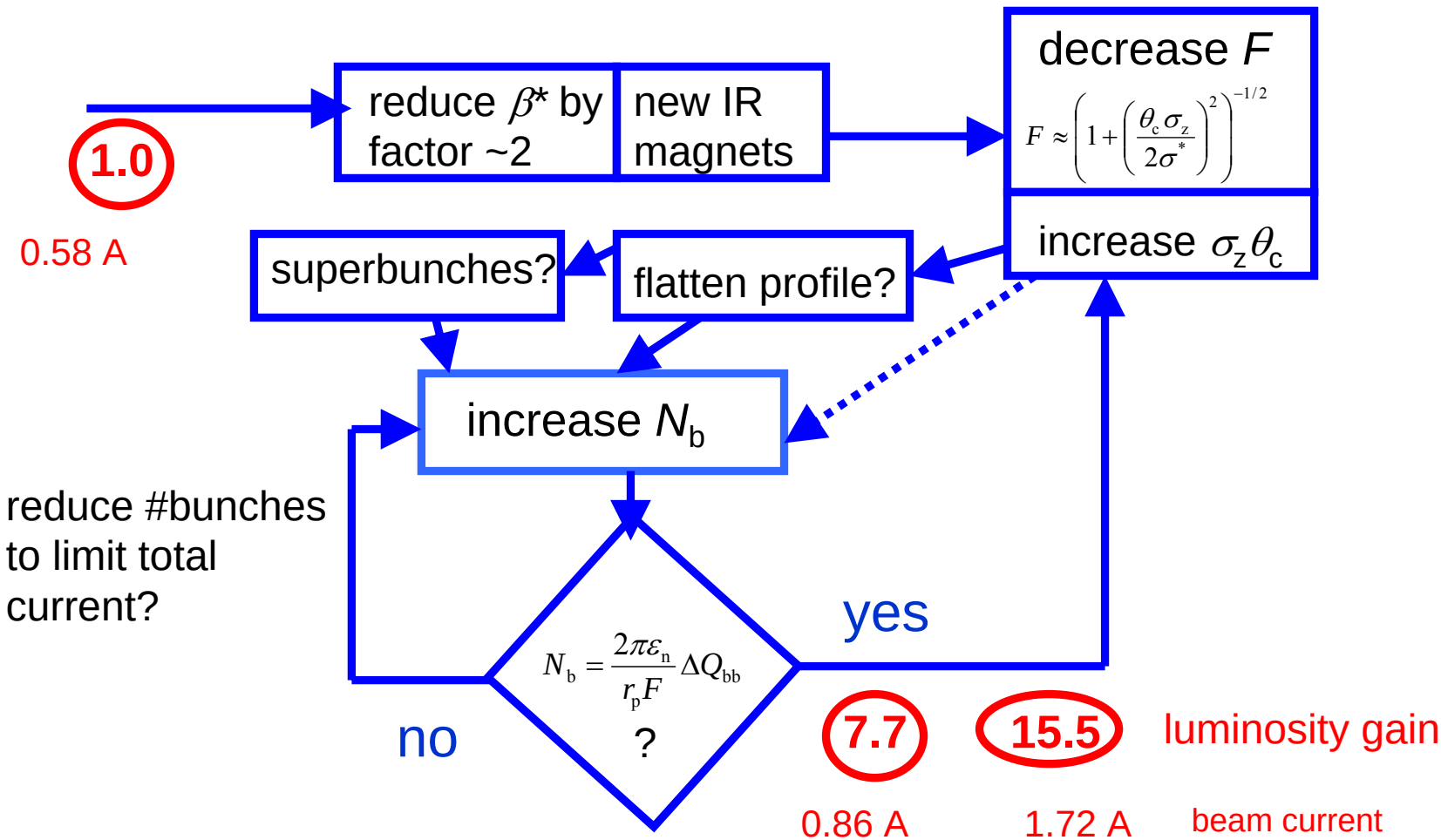
Chronology of LHC Upgrade studies

- **Summer 2001**: two CERN task forces investigate physics potential (CERN-TH-2002-078) and accelerator aspects (LHC Project Report 626) of an LHC upgrade by a factor 10 in luminosity and 2-3 in energy
- **March 2002**: LHC IR Upgrade collaboration meeting
  http://cern.ch/lhc-proj-IR-upgrade
- **October 2002**: ICFA Seminar at CERN on
  "Future Perspectives in High Energy Physics"
- **2003**: US LHC Accelerator Research Program (LARP)
- **2004**: CARE-HHH European Network on **High Energy High Intensity Hadron Beams**
- **November 2004**: first CARE-HHH-APD Workshop (HHH-04) on
  "Beam Dynamics in Future Hadron Colliders and Rapidly Cycling High-Intensity Synchrotrons", CERN-2005-006
- **September 2005**: CARE-HHH Workshop (LHC-LUMI-05) on
  "Scenarios for the LHC Luminosity Upgrade"
  http://care-hhh.web.cern.ch/CARE-HHH/LUMI-05/

luminosity upgrade: baseline scheme



luminosity upgrade: Piwinski scheme



beam-beam: tune shift

tune shift from head-on collision (primary IPs)

$$\xi_{HO} \equiv \frac{N_b r_p}{4\pi\gamma\varepsilon_{x,y}}$$

limit on ξ_{HO} limits $N_b/(\gamma\varepsilon)$

tune shift from long-range collisions

$$\xi_{LR} = 2 n_{par} \frac{\xi_{HO}}{d^2}$$

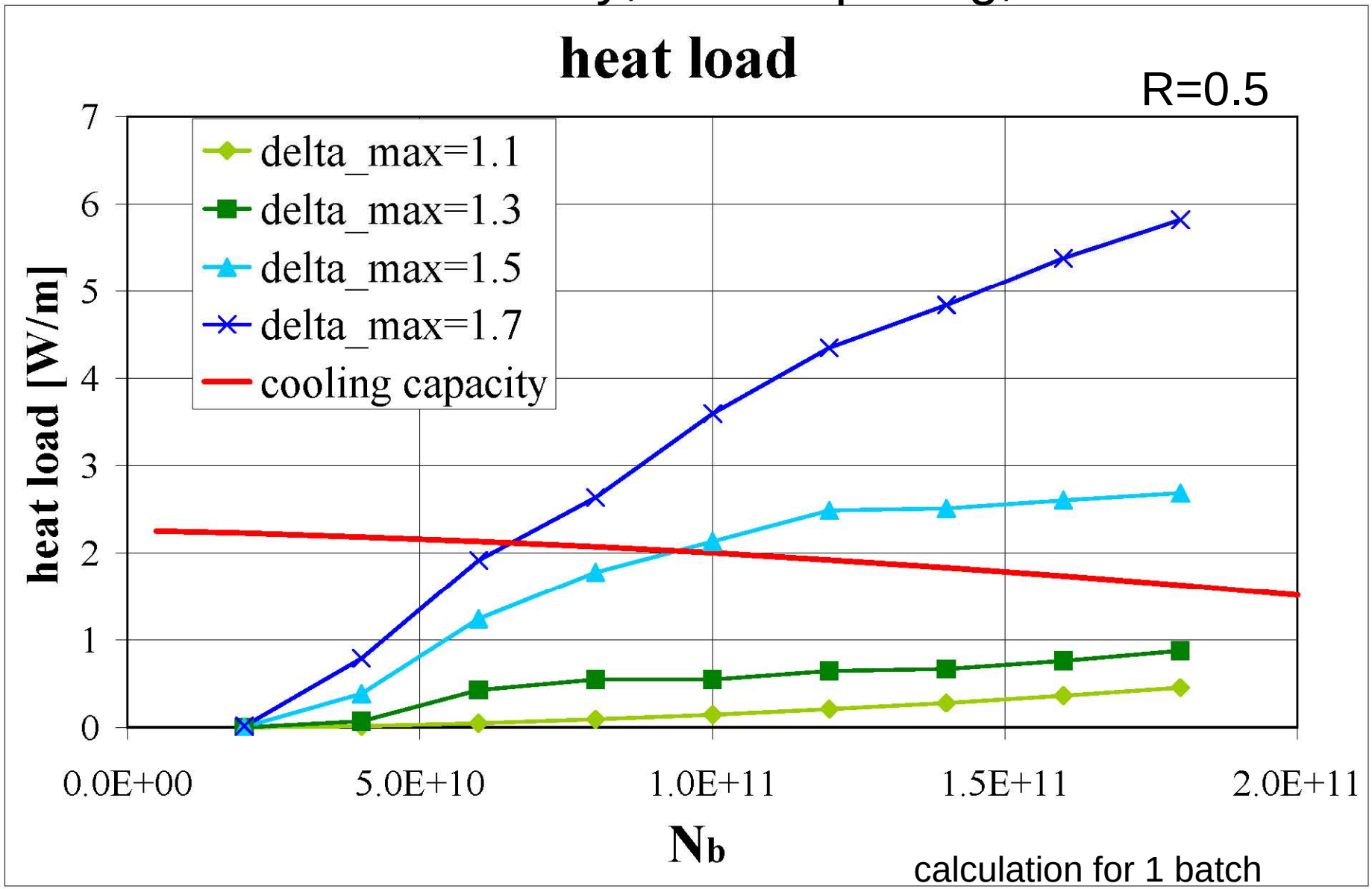
increases with reduced bunch spacing or crossing angle

d: normalized separation, $d \propto \theta_c$

	ξ_{HO} / IP	no. of IPs	ΔQ_{bb} total
SPS	**0.005**	**3**	**0.015**
Tevatron (pbar)	**0.01-0.02**	**2**	**0.02-0.04**
RHIC	**0.002**	**4**	**~0.008**
LHC (nominal)	**0.0034**	**2 (4)**	**~0.01**

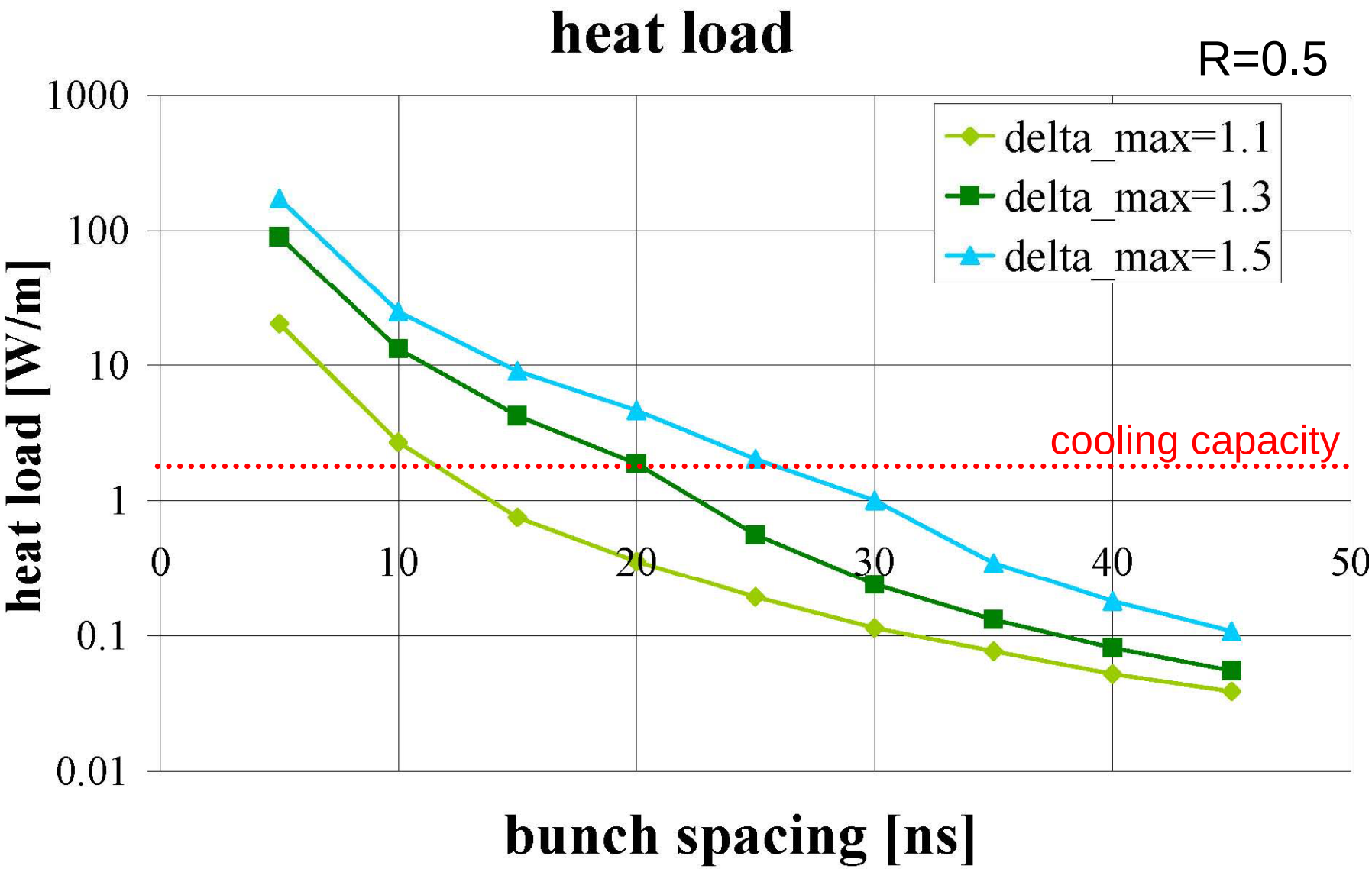
conservative value for total tune spread based on SPS collider experience

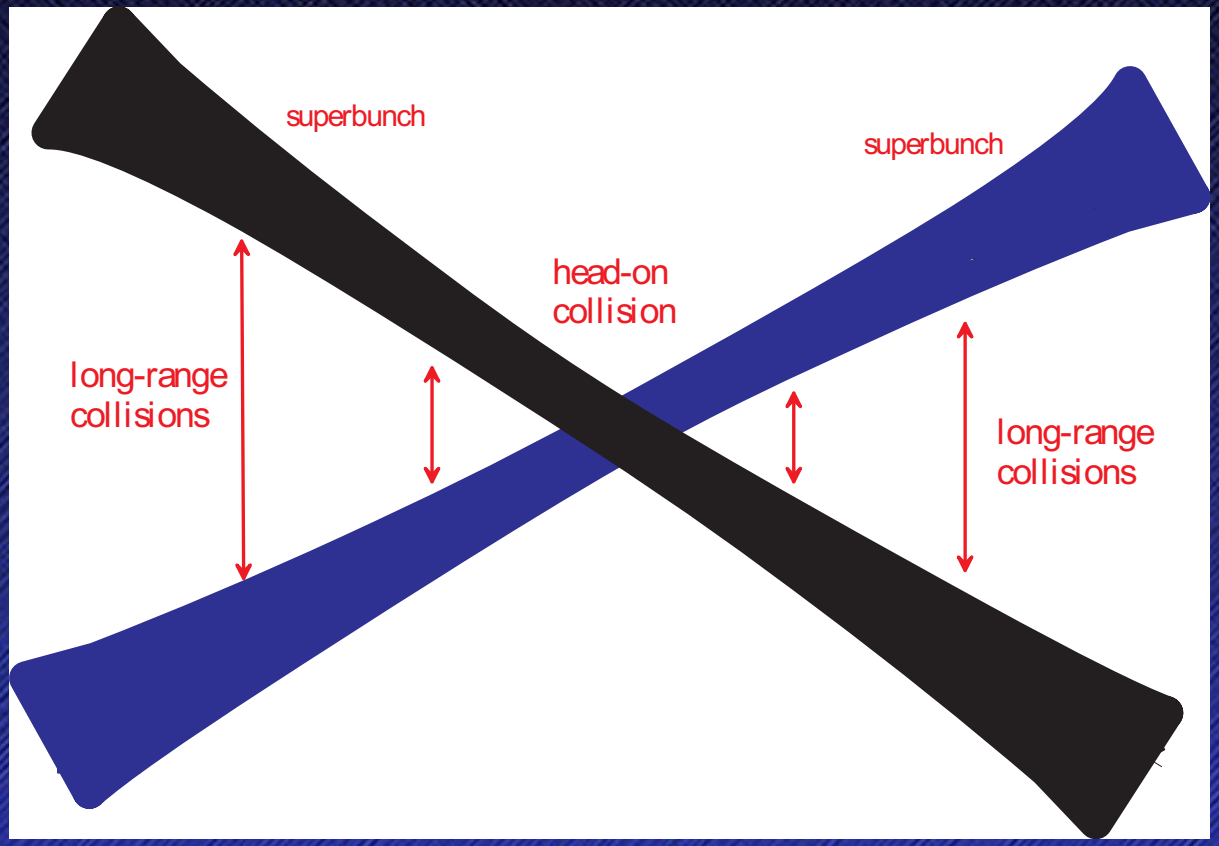
arc heat load vs. intensity, 25 ns spacing, ‘best’ model



heat load for quadrupoles higher in 2nd batch; still to be clarified

arc heat load vs. spacing, N_b=1.15x10^{11}, 'best' model





Schematic of a **super-bunch collision**, consisting of 'head-on' and 'long-range' components. The luminosity for long bunches having flat longitudinal distribution is ~1.4 times higher than for conventional Gaussian bunches with the same beam-beam tune shift and identical bunch population (see LHC Project Report 627)

Events per bunch crossing and beam lifetime due to nuclear p-p collisions

$$\frac{\text{events}}{\text{X-ing}} = \frac{L}{n_b}\frac{\sigma_{bb}}{f_{rev}}$$

σ_{bb}=60 mb total inelastic cross section

$$\tau_N = \frac{n_b N_b / L}{2\sigma_{TOT}}$$

beam intensity halving time due to nuclear p-p collisions at two IP's with total cross section σ_{TOT}=110 mb

$$\frac{L}{n_b N_b} \cong \frac{\gamma f_{rev}}{2 r_p}\frac{\Delta Q_{bb}}{\beta^*}$$

nuclear scattering lifetime at the beam-beam limit depends only on β^*!

$$\tau_L = \frac{1}{\frac{1}{2\tau_{IBS}^x} + \frac{2}{\tau_{gas}} + \frac{1.54}{\tau_N}}$$

luminosity lifetime: assumes radiation damping compensates diffusion

exponential luminosity lifetime due to nuclear p-p interactions

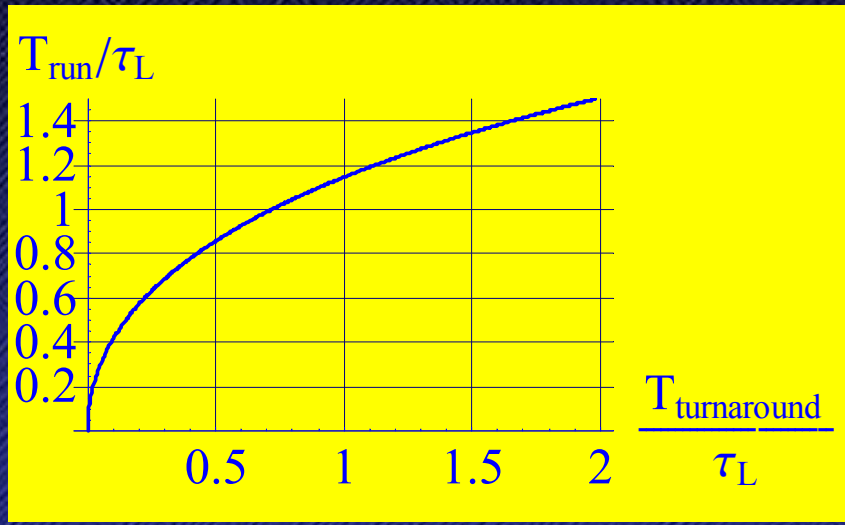
$$(\sqrt{e}-1)\tau_N \cong \frac{\tau_N}{1.54}$$

Optimum run time and effective luminosity

$$\frac{\tau_L + T_{run} + T_{turnaround}}{\tau_L} = e^{\frac{T_{run}}{\tau_L}}$$

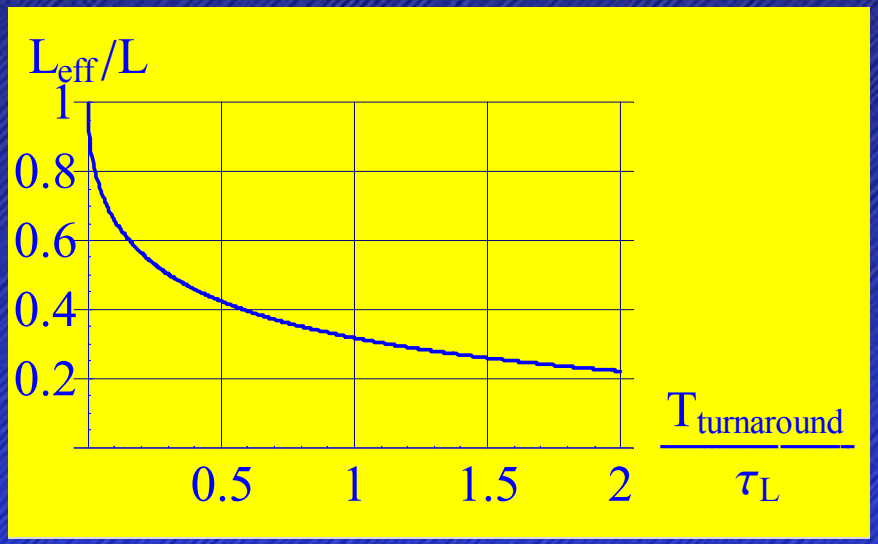
The optimum run time and the effective luminosity are universal functions of $T_{turnaround}/\tau_L$

$$\frac{T_{run}}{\tau_L} = -1 - \frac{T_{turnaround}}{\tau_L} - \text{ProductLog}[-1, -e^{-1-\frac{T_{turnaround}}{\tau_L}}]$$



$$\frac{L_{eff}}{L} = \frac{\tau_L}{\tau_L + T_{run} + T_{turnaround}} = -\frac{1}{\text{ProductLog}[-1, -e^{-1-\frac{T_{turnaround}}{\tau_L}}]}$$

where $w = \text{ProductLog}[z] \Leftrightarrow z = we^w$



When the beam lifetime is dominated by nuclear proton-proton collisions, then $\tau_L \sim \tau_N/1.54$ and the effective luminosity is a universal functions of $T_{turnaround}/\beta^*$

Effective luminosity for various upgrade options

parameter	symbol	nominal	ultimate	shorter bunch	longer bunch
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	6.0
bunch spacing	Δt_{sep} [ns]	25	25	12.5	75
average current	I [A]	0.58	0.86	1.72	1.0
longitudinal profile		Gaussian	Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
ß* at IP1&IP5	β^* [m]	0.55	0.50	0.25	0.25
full crossing angle	θ_c [μrad]	285	315	445	430
Piwinski parameter	$\theta_c \sigma_z/(2\sigma^*)$	0.64	0.75	0.75	2.8
peak luminosity	L [10^{34} cm^{-2} s^{-1}]	1.0	2.3	9.2	8.9
events per crossing		19	44	88	510
IBS growth time	τ^*_{IBS} [h]	106	72	42	75
nuclear scatt. lumi lifetime	$\tau_N/1.54$ [h]	26.5	17	8.5	5.2
luminosity lifetime (τ_{gas} =85 h)	τ_L [h]	15.5	11.2	6.5	4.5
effective luminosity	L_{eff} [10^{34} cm^{-2} s^{-1}]	0.4	0.8	2.4	1.9
($T_{turnaround}$=10 h)	T_{run} [h] optimum	14.6	12.3	8.9	7.0
effective luminosity	L_{eff} [10^{34} cm^{-2} s^{-1}]	0.5	1.0	3.3	2.7
($T_{turnaround}$= 5 h)	T_{run} [h] optimum	10.8	9.1	6.7	5.4