# HL-LHC: parameter space, constraints & possible options

Many thanks to
R. Assmann, C. Bhat, O. Brüning,
R. Calaga, R. De Maria,
S. Fartoukh, J.-P. Koutchouk,
S. Myers, L. Rossi, W. Scandale,
E. Shaposhnikova, R. Tomas,
J. Tuckmantel ,…

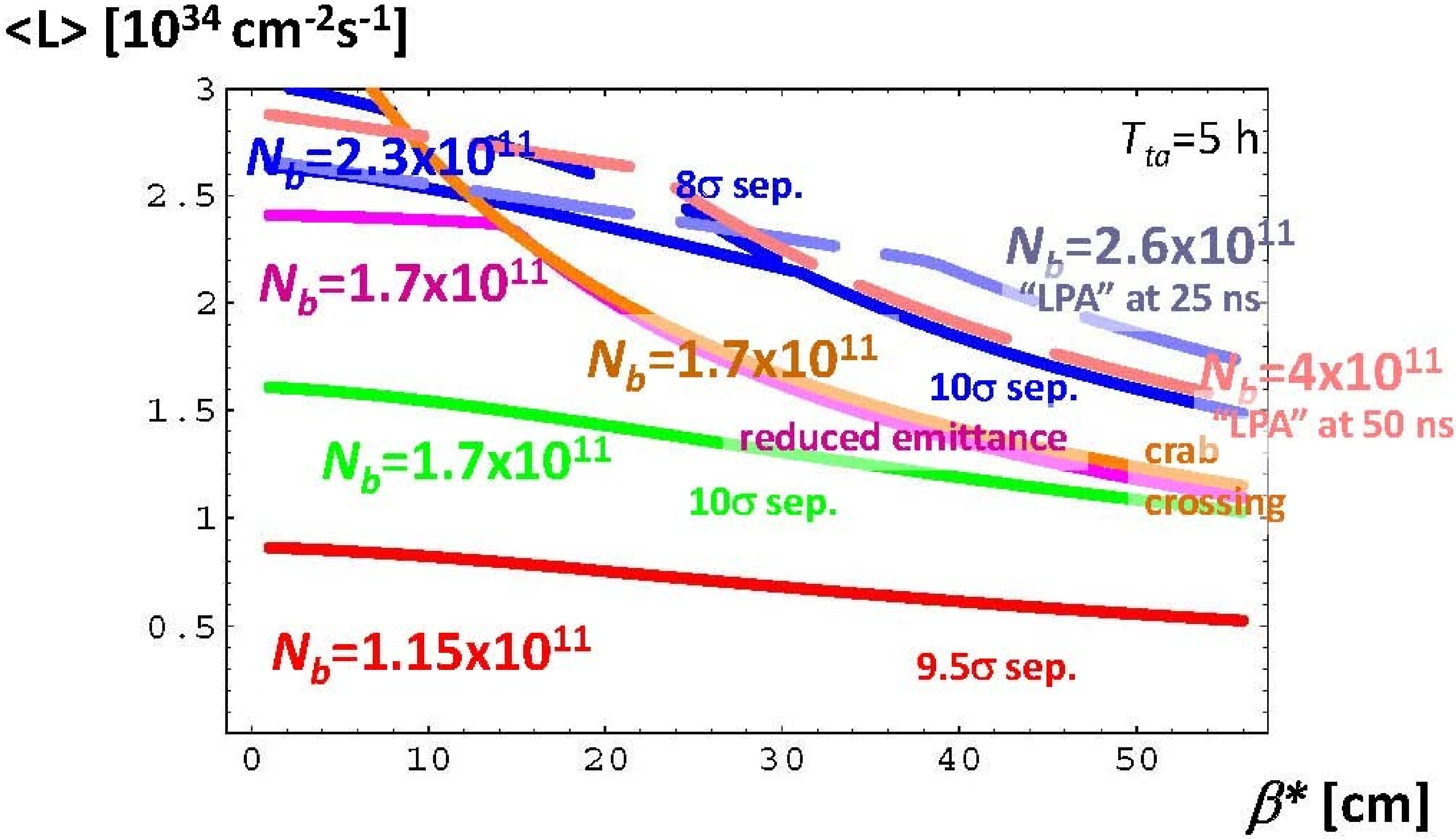
## Chamonix 2011

## LHC Performance Workshop

Frank Zimmermann

Photo: courtesy R. Assmann

# reminder -“key plot” from Chamonix ‘10



# *changes since Chamonix 2010*

- (head-on) beam-beam limit at least 2x higher
- possibility to operate with lower emittance & higher brightness
- we know HL-LHC will use leveling
- leveled luminosity is defined: $5 \times 10^{34}$ $cm^{-2}s^{-1}$
- “ATS optics” solution for $\beta^* < 30$ cm

# luminosity leveling

run at constant luminosity during the store

motivations

→ reduced peak event pile up

→ reduced peak IR power deposition

→ maximized integrated luminosity

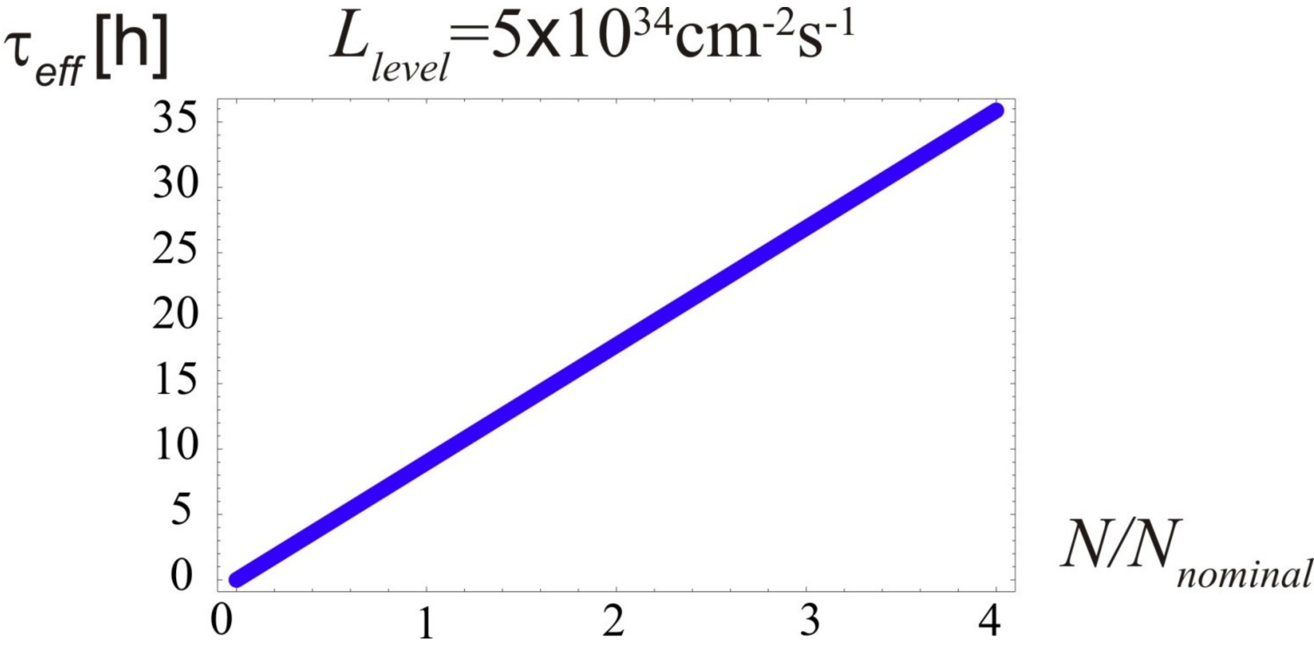
# effective beam lifetime

for given luminosity

$\tau_{\text{eff}}$ scales with total beam current

$$\frac{dN_{tot}}{dt} = -\frac{N_{tot}}{\tau_{eff}} = -n_{IP}\sigma L_{lev}$$ ($\sigma$=100 mbarn)

$$\tau_{eff} = \frac{N_{tot}}{n_{IP}\sigma L_{lev}}$$



# luminosity formulae with leveling

$$L = \frac{f_{rev} n_b N_b^2}{4\pi\beta^* \varepsilon} F\left(\phi_{piw}, \Delta x, \ldots\right)$$

*F*: geometric reduction from crossing angle and/or offset

$$L_{lev} = f_{lev}(t) L_{\max}(t)$$

*$f_{lev}$*: time-dependent leveling factor, $f_{lev} \leq 1$

define virtual “potential peak luminosity”

$$\hat{L} \equiv L_{\max}(0) = \frac{f_{rev} n_b N_b^2(0)}{4\pi\beta^*(0)\varepsilon} F\left(\phi_{piw,\min}(0)\right) = \frac{L_{lev}}{f_{lev}(0)}$$

# leveling schemes

- vary beam offset $\Delta x$ (successful in 2010)

$$L_{lev} = \hat{L} \exp\left( -\left( \frac{\Delta x}{2\sigma^*} \right)^2 \right); \; \Delta Q_{lev} = \Delta \hat{Q} 2 \left( \left[ \exp\left( -\frac{(\Delta x)^2}{2\sigma^{*2}} \right) - 1 \right] \frac{\sigma^{*2}}{(\Delta x)^2} + \exp\left( -\frac{(\Delta x)^2}{2\sigma^{*2}} \right) \right)$$

- vary Piwinski angle $\phi_{piw}$ ,that is $\sigma_z$, $\theta_c$, or $V_{crab}$

$$L_{lev} \approx \hat{L} \frac{1}{\sqrt{1+\phi_{piw}^2}}; \quad \Delta Q_{lev} \approx \Delta \hat{Q} \frac{1}{\sqrt{1+\phi_{piw}^2}}$$

for two IPs with alternating crossing

- vary IP beta function $\beta^*$ e.g. at constant $\phi_{piw}$

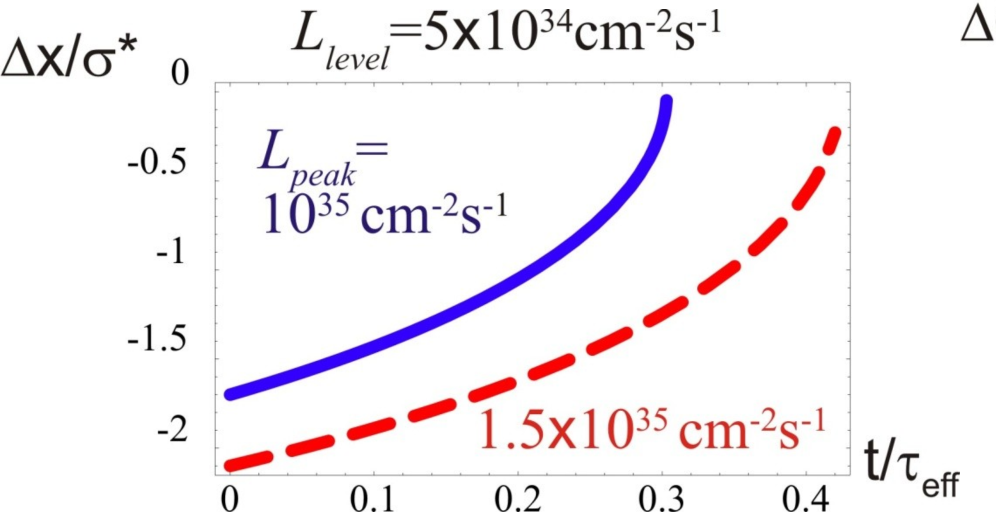
$$L_{lev} \approx \hat{L} \frac{\hat{\beta}^*}{\beta_{lev}^*}; \qquad \Delta Q_{lev} \approx \Delta \hat{Q}$$

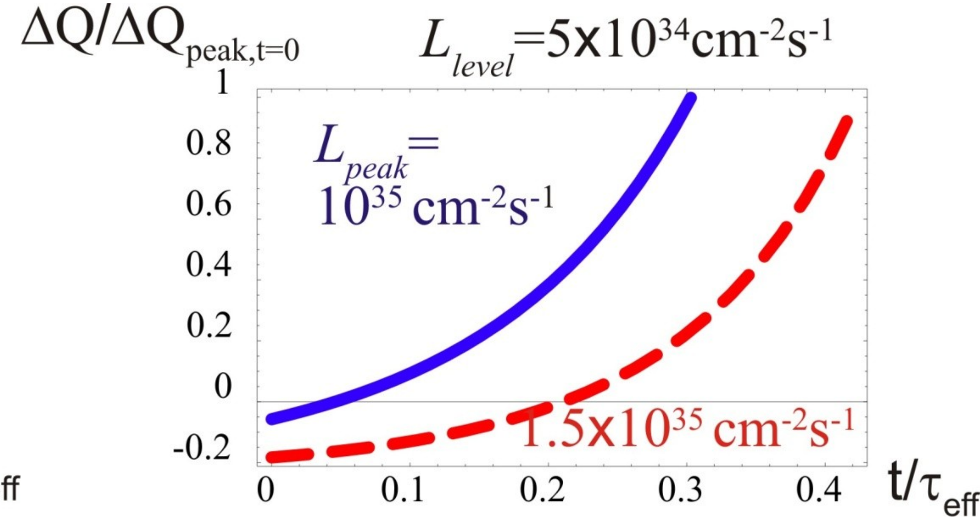
formulae above assume round beams

# leveling with $\Delta x$

example: $L_{peak}$=1.0 (1.5) x$10^{35}$ cm$^{-2}$s$^{-1}$

initially $\phi_{piw}$=1.7 (2.1) mrad to get $L_{lev}$=5x$10^{34}$ cm$^{-2}$s$^{-1}$





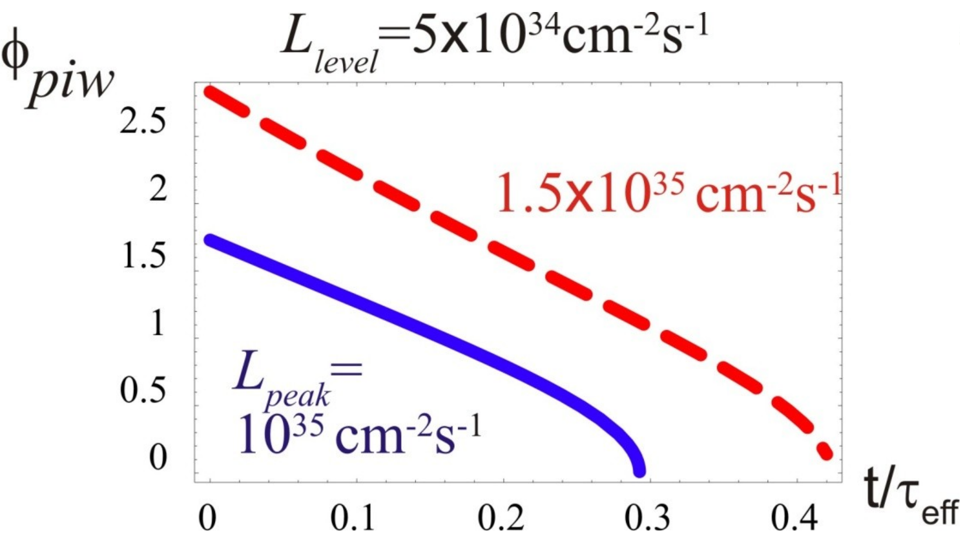
alternating offset $\Delta x$, $\Delta y$

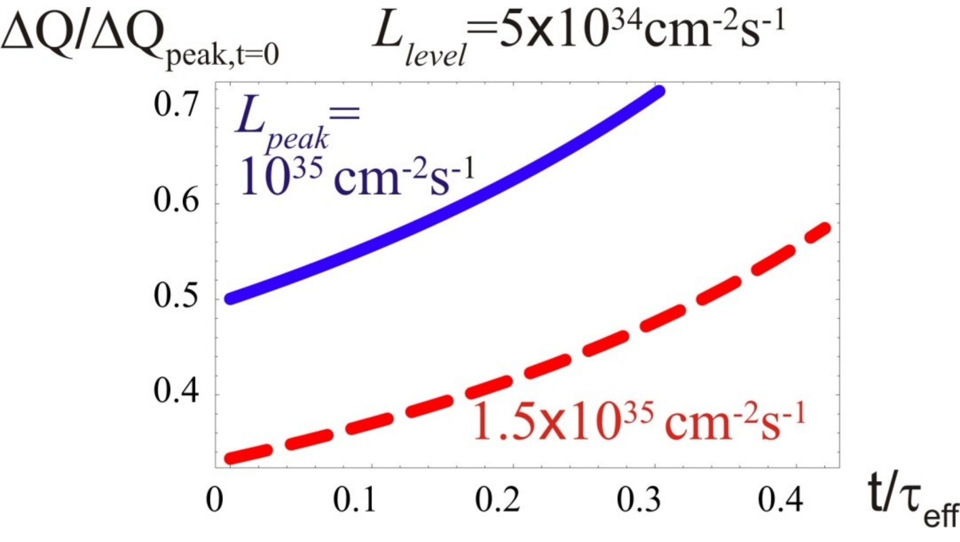
maximum leveling time = 0.3 (0.42) $\tau_{eff}$

tune shift changes sign during the store

# leveling with $\theta_c$ or $V_{crab}$

example: $L_{peak}$=1.0 (1.5) x$10^{35}$ cm$^{-2}$s$^{-1}$
initially $\phi_{piw}$=1.7 (2.8) $\sigma$ to get $L_{lev}$=5x$10^{34}$ cm$^{-2}$s$^{-1}$



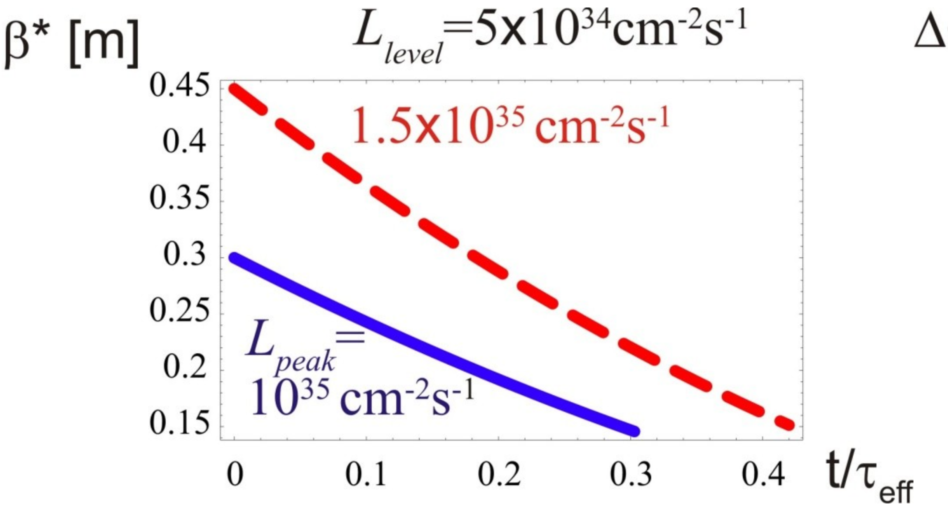


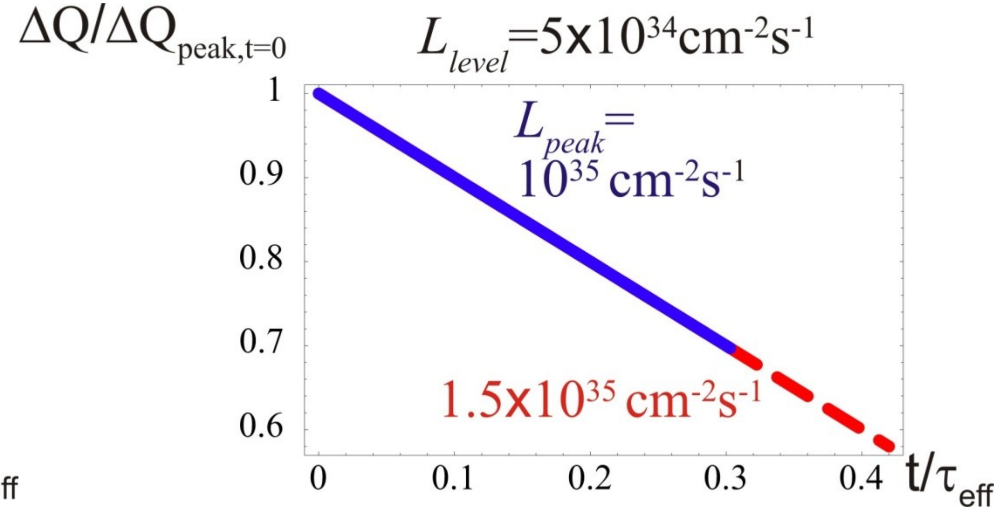
maximum leveling time = 0.3 (0.42) $\tau_{eff}$

tune shift increases during the store

# leveling with $\beta^*$

example: $L_{peak}$=1.0 (1.5) x$10^{35}$ cm$^{-2}$s$^{-1}$ at $\beta^*$=0.15 m
initially $\beta^*$=0.3 (0.45) m to get $L_{lev}$=5x$10^{34}$ cm$^{-2}$s$^{-1}$



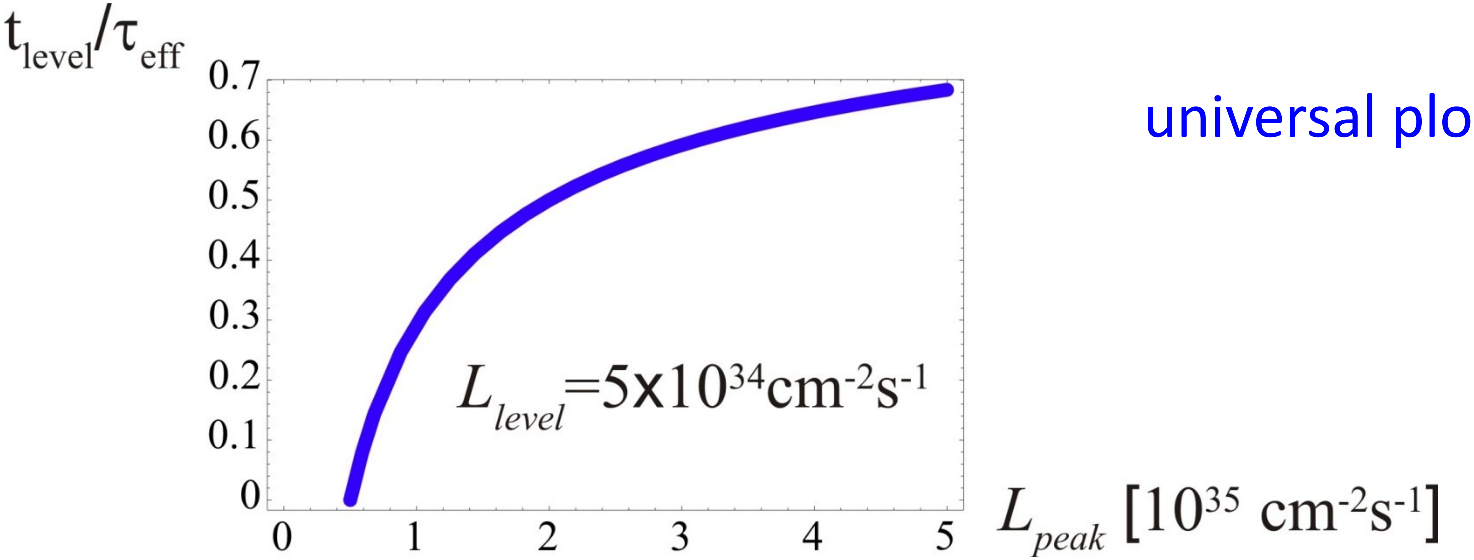


maximum leveling time = 0.3 (0.42) $\tau_{eff}$

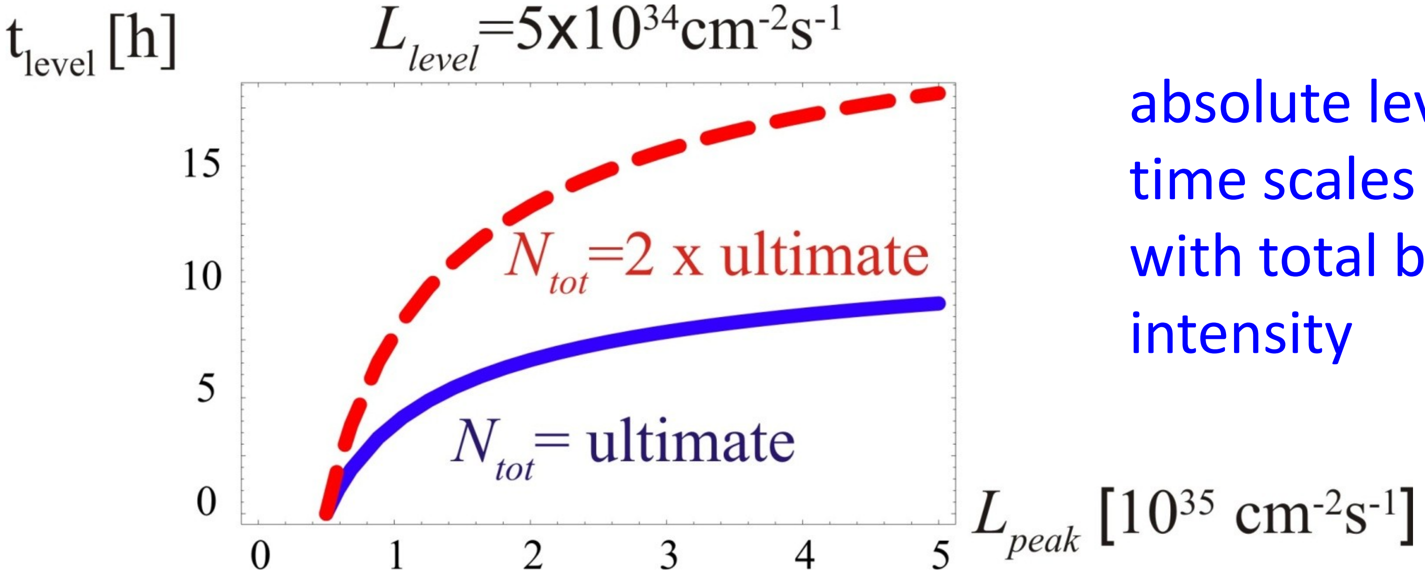
***independent of leveling scheme***

tune shift decreases during store

# maximum leveling time



universal plot



absolute leveling time scales linearly with total beam intensity

# estimating integrated luminosity

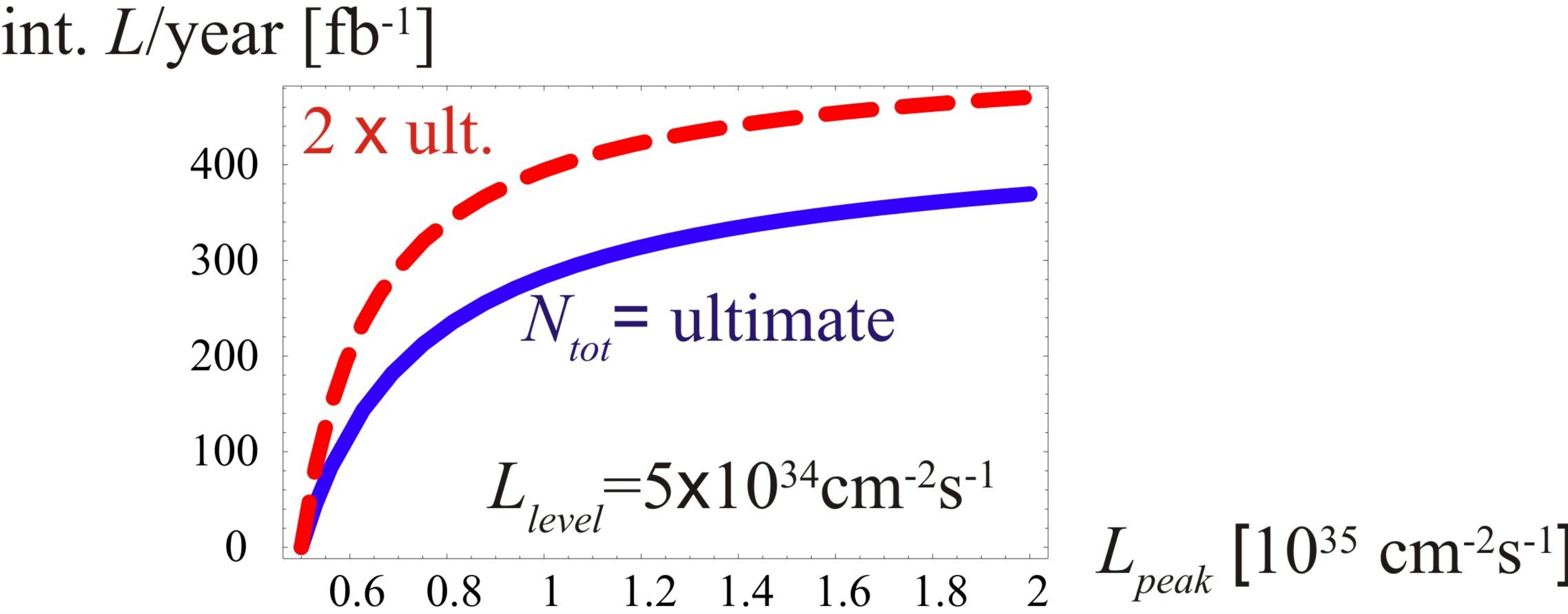
assumptions

- two high-luminosity collision points
- beam & *L* lifetime from *p* consumption
- 200 physics days of proton run per year

  (w/o restart, w/o TS's, w/o MD periods)
- 5 h turnaround time
- 75% machine availability

  [Nov. 2010: 80%, W. Venturini, Evian]

# integrated luminosity w leveling

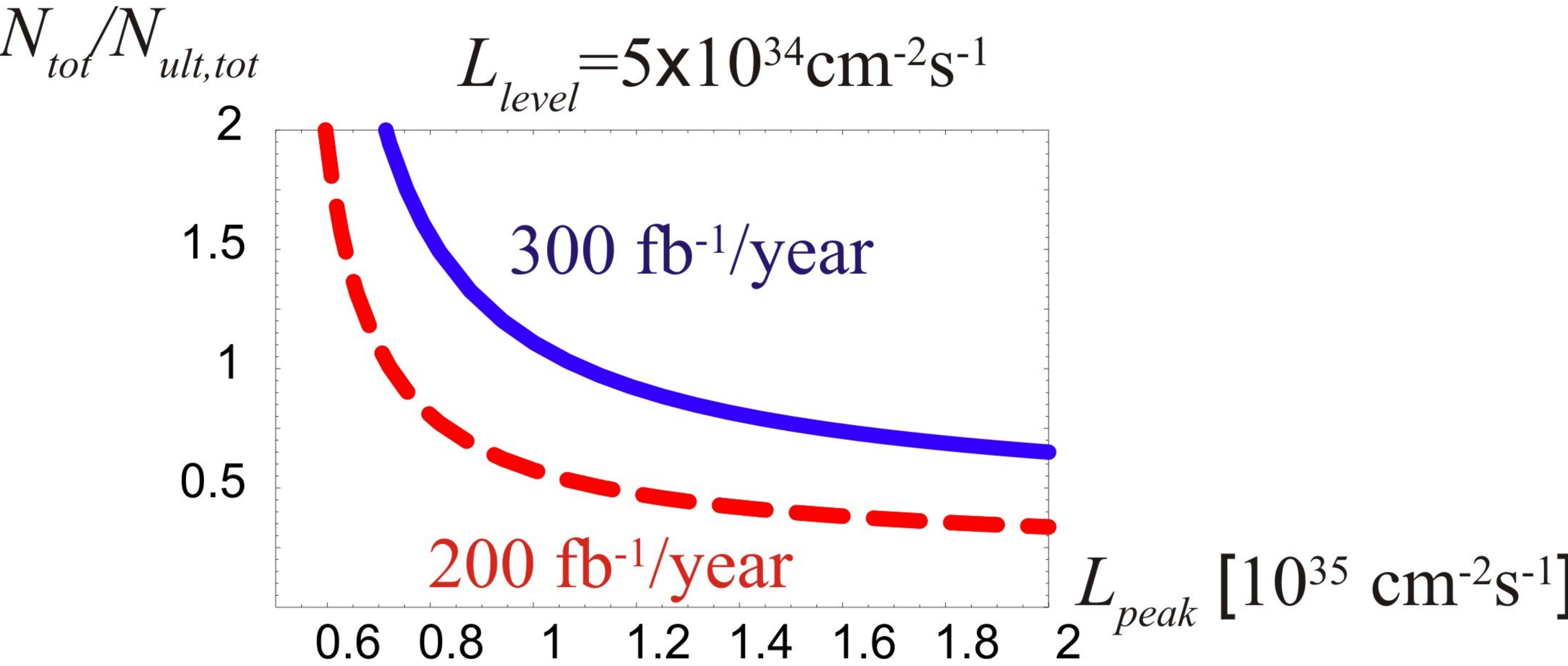


e.g. to get 300 $\mathrm{fb}^{-1}$ per year:

at ultimate intensity we need $L_{peak}$=1.10x$10^{35}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

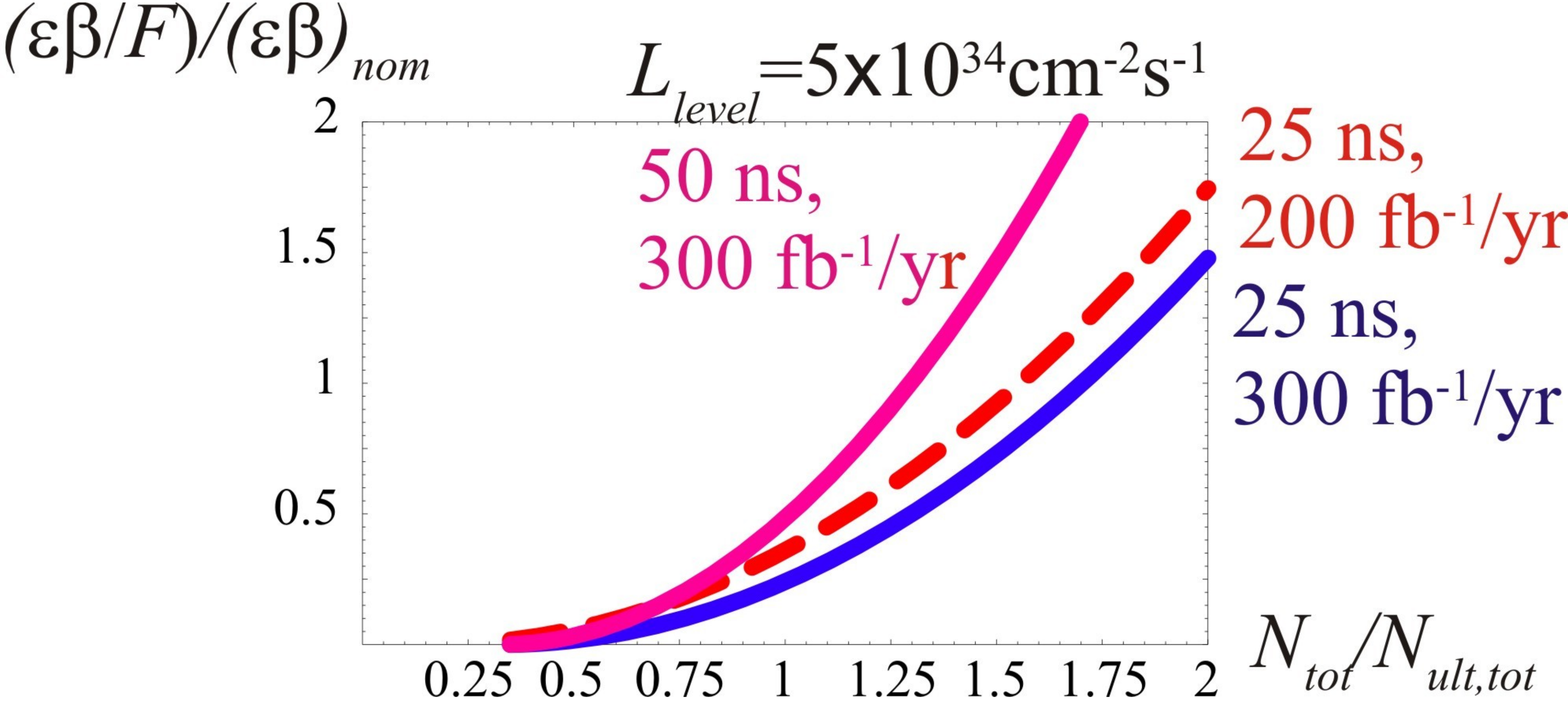
At 2x ultimate intensity $L_{peak}$=0.71x$10^{35}$$\mathrm{cm}^{-2}\mathrm{s}^{-1}$

# intensity vs “peak” luminosity



peak luminosity scales with (intensity)$^2$

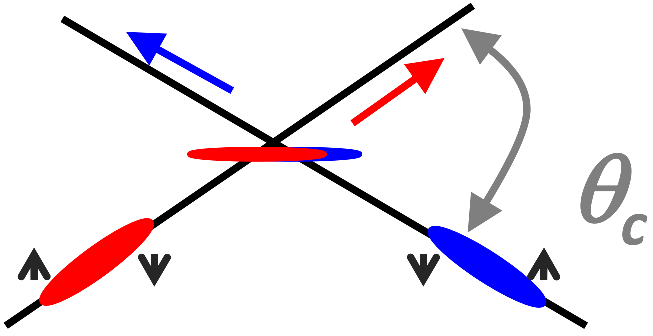
# *how much do we need to squeeze?*



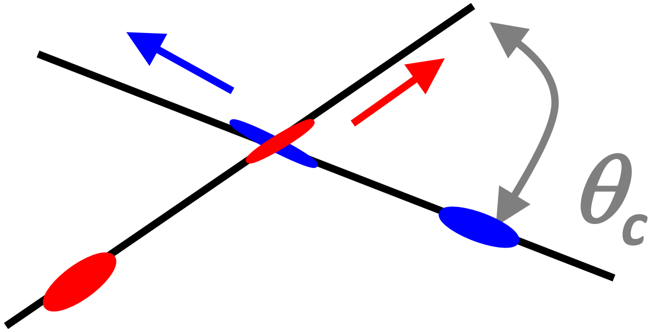
e.g. to get 300 fb$^{-1}$ per year:
at $N_b$=2x10$^{11}$ & 25 ns we need *to* reduce *($\beta\varepsilon$)*/F *by* x0.38
at $N_b$=3.4x10$^{11}$ & 50 ns we need to reduce ($\beta\varepsilon$)/F by x0.48

# approaches to boost LHC luminosity

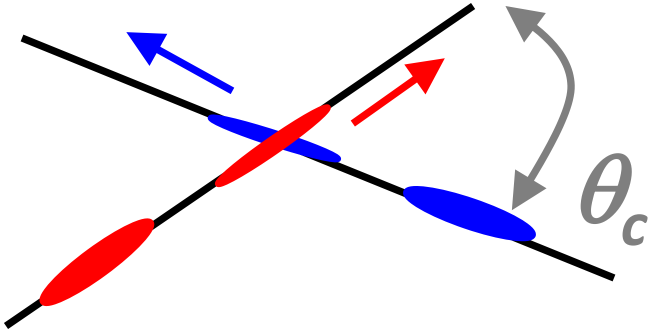
- low β* & crab cavities (80 MV)



- low β* & higher harmonic RF (7.5 MV @800 MHz) + LR compensation



- large Piwinski angle (& “flat” bunch shape) + LR-BB compensation



always pushing intensity to “limit”

# Crab Cavities

**benefits**

- **improving geometric overlap** (main motivation)
- **boosting beam-beam limit** (potential additional benefit) [next slides]
- **luminosity leveling** (main motivation)
- **avoiding off-center collisions from beam loading** (additional benefit)

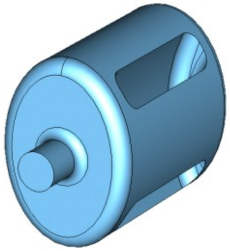
**concerns:**

- **emittance growth from RF noise, impedance, field nonlinearity**
- **machine protection, trip rate, technical challenges, time line**

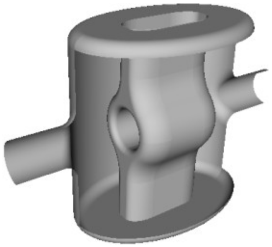
**status & plan:**

- **SPS/LHC prototype beam tests from ~2015, before final decision**
- **4-5 promising compact cavity designs**

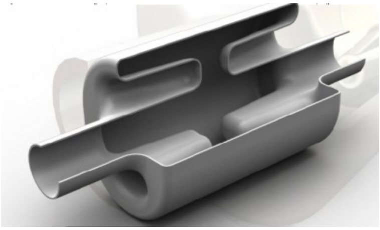
Parallel bar elliptical TEM cavity (JLAB)



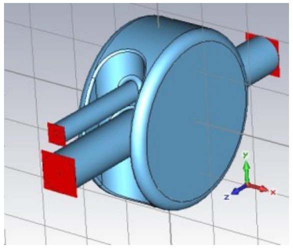
Half wave spoke resonator (SLAC)



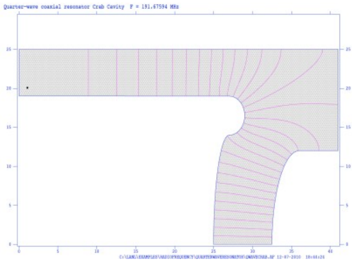
Four rod compact crab cavity (Cockcroft)



Rotated pill-box cavity (KEK)



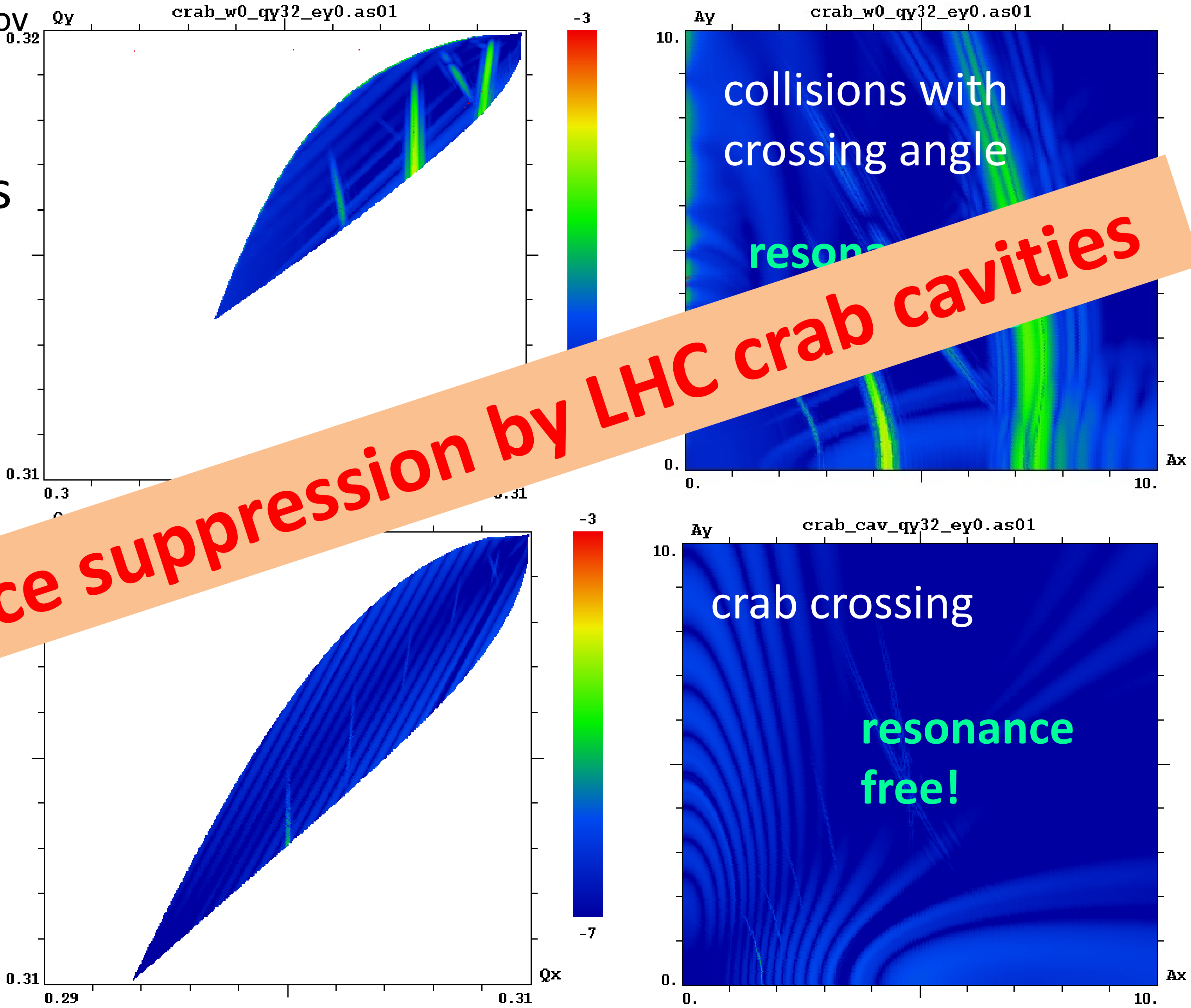
Quarter-wave resonator (BNL)



# beam-beam simulation w crab cavities

M. Zobov, D. Shatilov

frequency map analysis of Lifetrac simulation



collisions with crossing angle

resona

crab crossing

resonance free!

**resonance suppression by LHC crab cavities**

*parameters:*

$\varepsilon_{x,y}$ =0.5 nm

$E$ = 7 TeV

$\beta$

cm,

$\theta_c$= 315 μrad

($\phi$ =1.5),

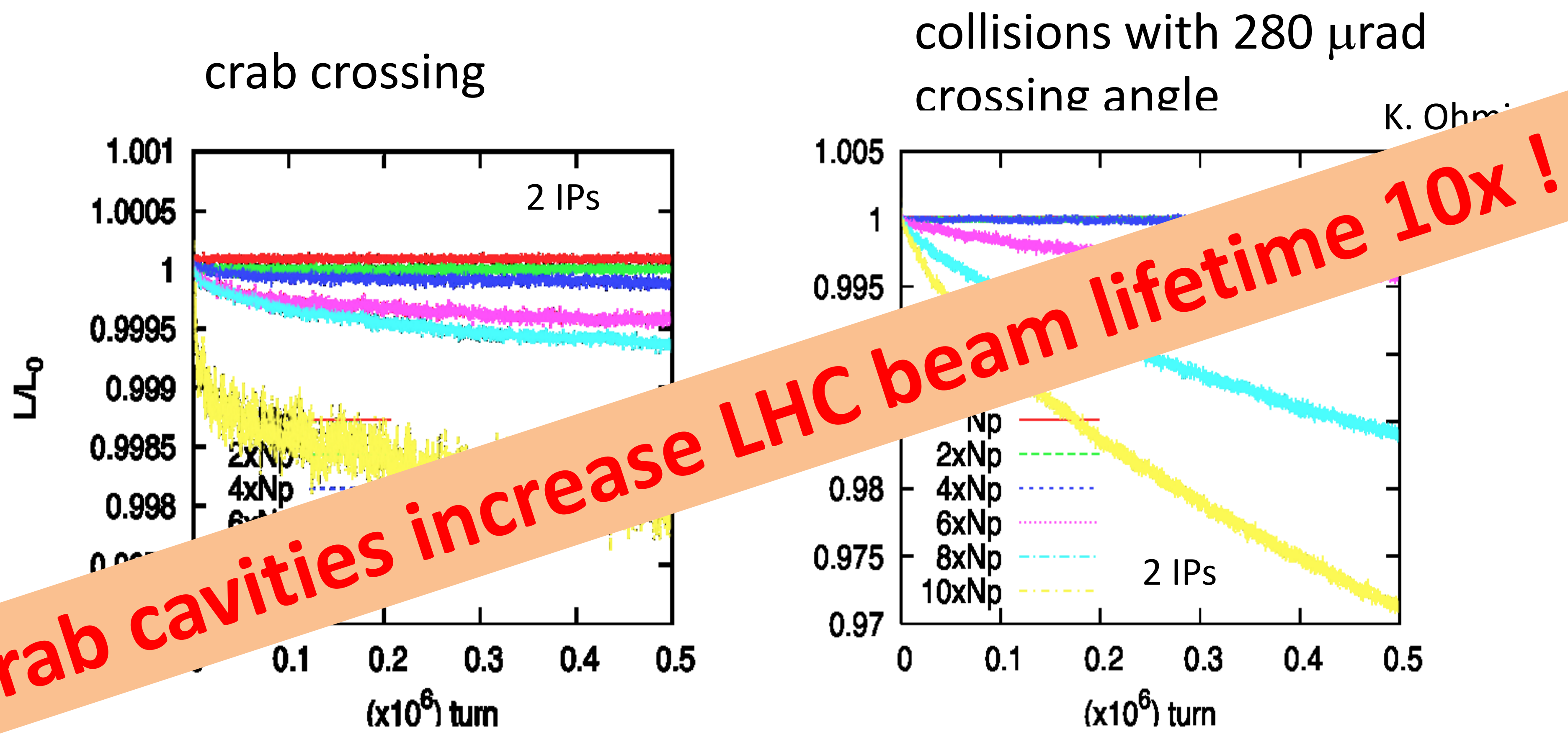
$N_b$ = 4.0x10$^{11}$,

$Q_s$ =0.002,

$\Delta Q_{x,y}$ ~ -0.0065,

single IP

# another beam-beam simulation w CC's



crab crossing

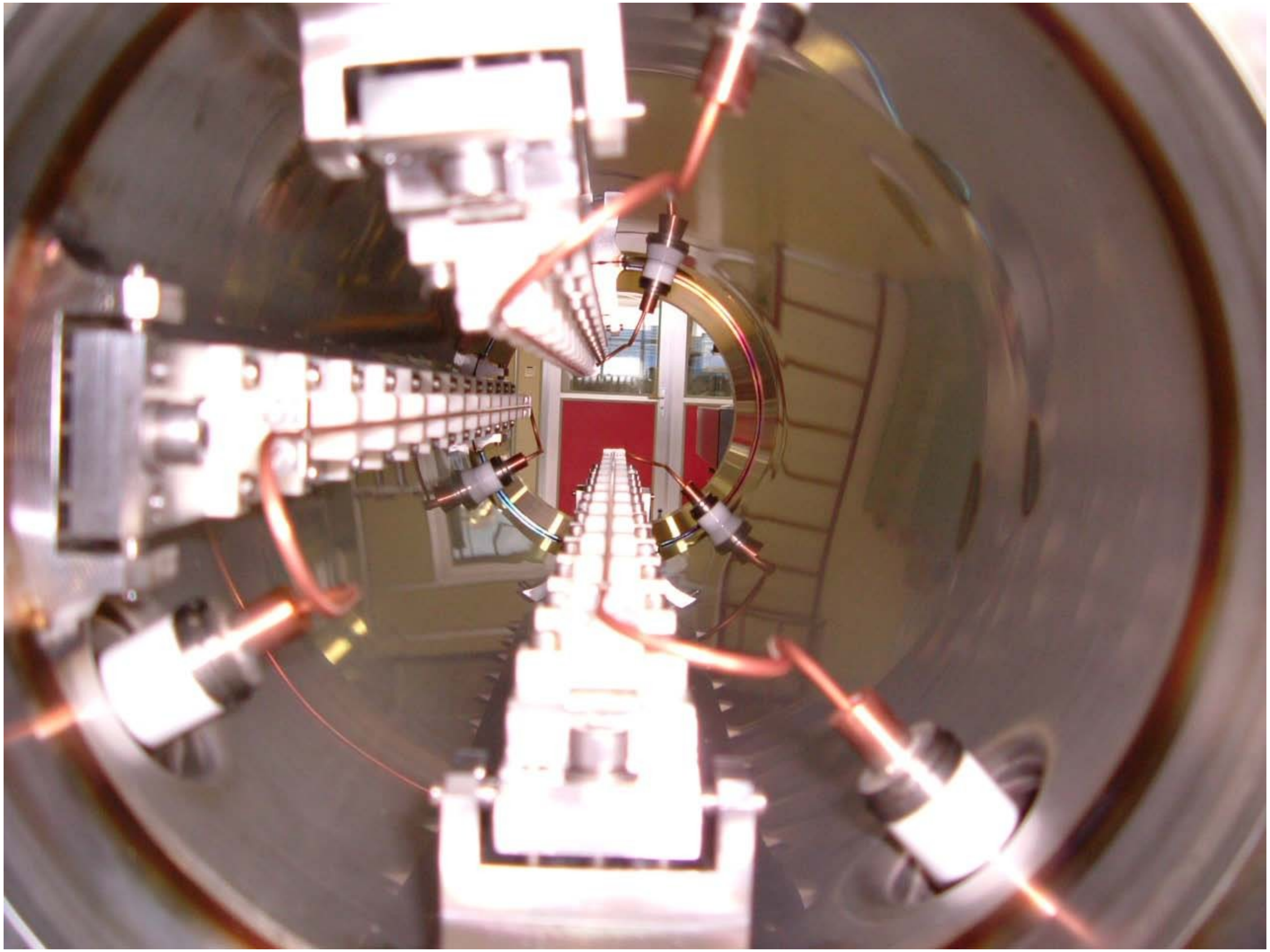
collisions with 280 μrad crossing angle

K. Ohm

crab cavities increase LHC beam lifetime 10x !

simulated luminosity lifetime with crab crossing is 10 times better than without crab crossing

# Long-Range Compensation



2x2 water-cooled units presently installed in the SPS (two with remote control)

1x2 spare units ready

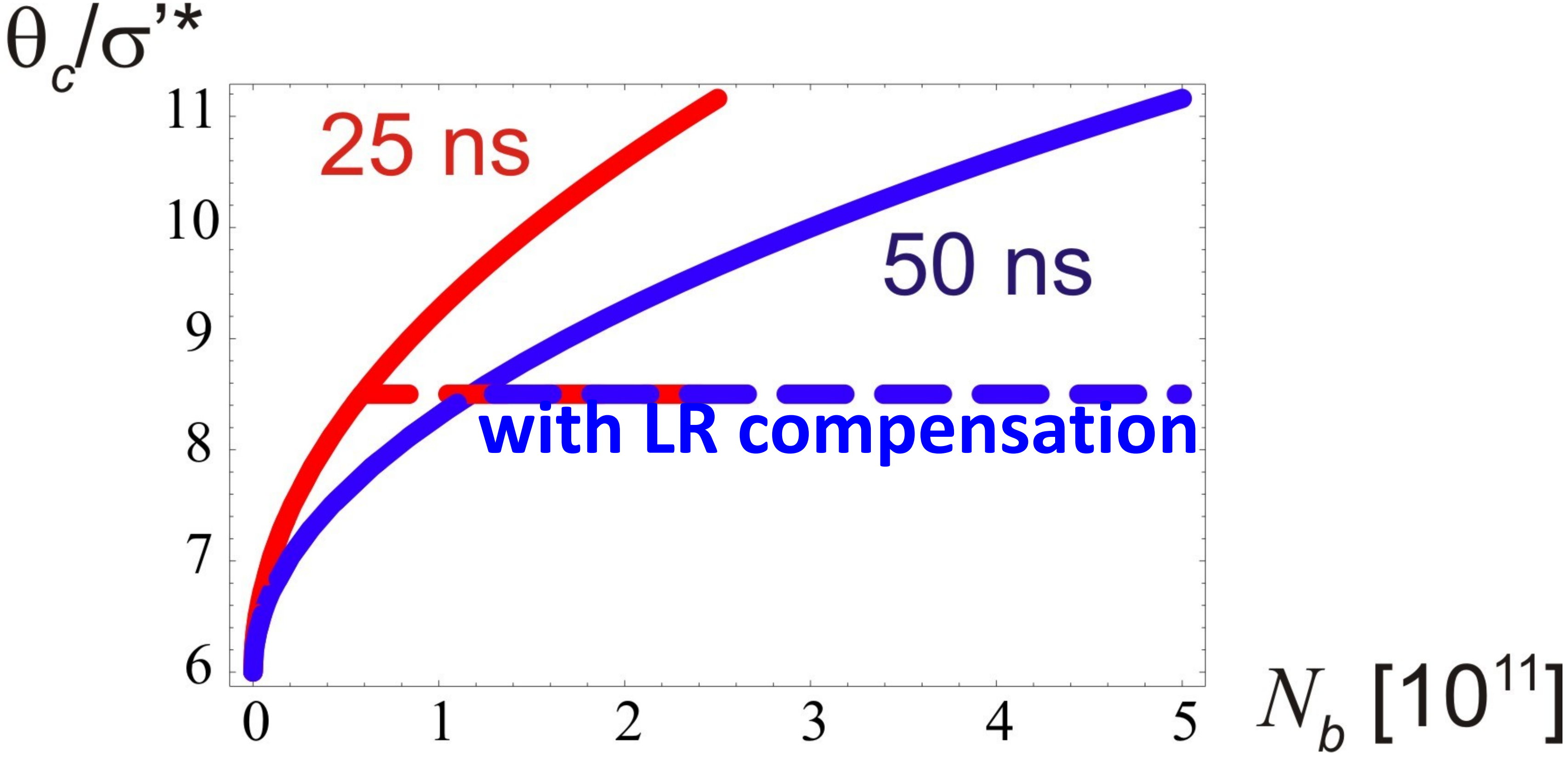
1st RHIC BBLR stored at CERN

2nd RHIC BBLR being shipped

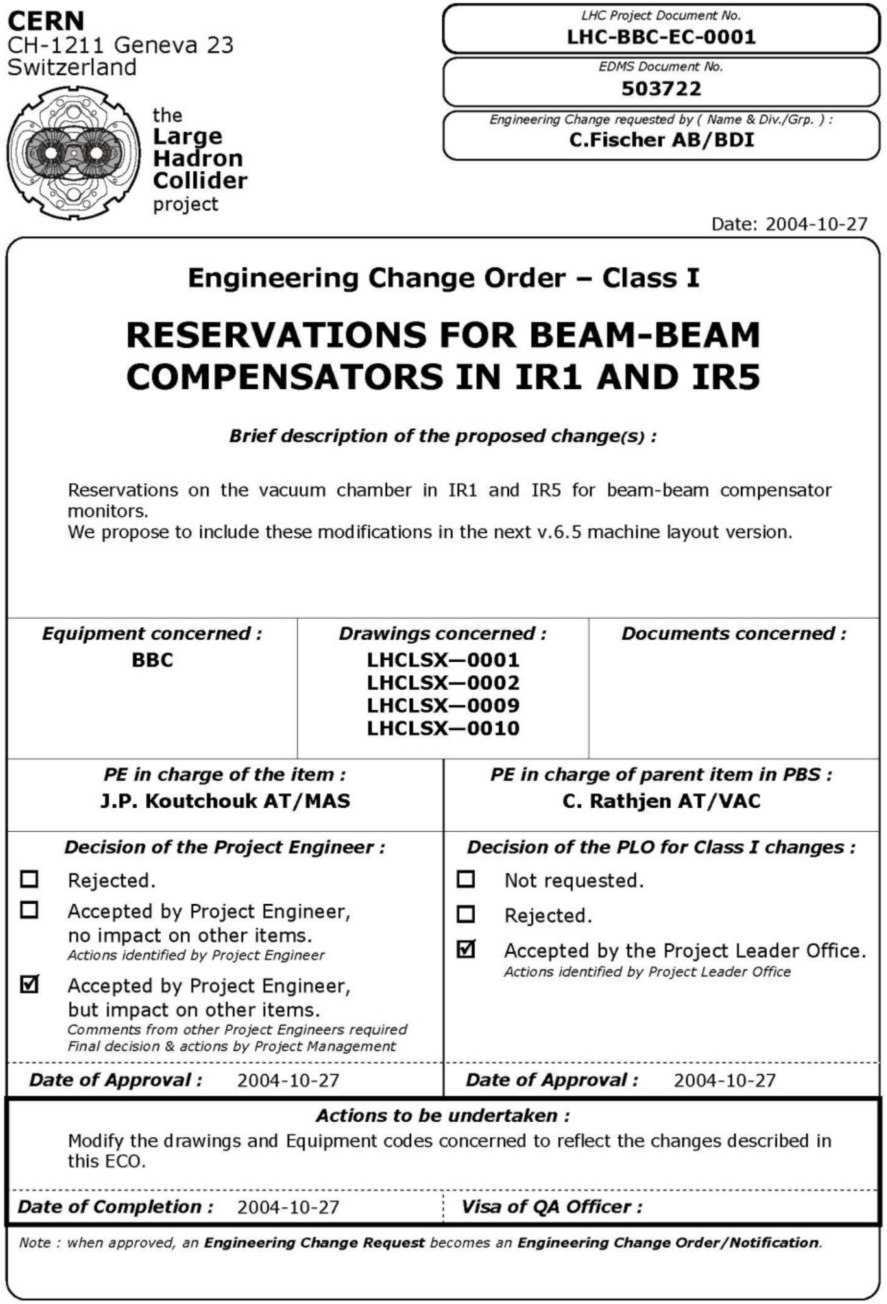
in total 5 sets available

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

# normalized crossing angle versus bunch intensity



long range compensation will reduce the crossing angle



**CERN**
CH-1211 Geneva 23
Switzerland

the
**Large**
**Hadron**
**Collider**
project

*LHC Project Document No.*
**LHC-BBC-EC-0001**

*EDMS Document No.*
**503722**

*Engineering Change requested by ( Name & Div./Grp. ) :*
**C.Fischer AB/BDI**

Date: 2004-10-27

**Engineering Change Order – Class I**

**RESERVATIONS FOR BEAM-BEAM COMPENSATORS IN IR1 AND IR5**

***Brief description of the proposed change(s) :***

Reservations on the vacuum chamber in IR1 and IR5 for beam-beam compensator monitors.
We propose to include these modifications in the next v.6.5 machine layout version.

| ***Equipment concerned :*** | ***Drawings concerned :*** | ***Documents concerned :*** |
|---|---|---|
| **BBC** | **LHCLSX—0001**<br>**LHCLSX—0002**<br>**LHCLSX—0009**<br>**LHCLSX—0010** | |

| ***PE in charge of the item :*** | ***PE in charge of parent item in PBS :*** |
|---|---|
| **J.P. Koutchouk AT/MAS** | **C. Rathjen AT/VAC** |

***Decision of the Project Engineer :***

☐ Rejected.
☐ Accepted by Project Engineer, no impact on other items.
*Actions identified by Project Engineer*
☑ Accepted by Project Engineer, but impact on other items.
*Comments from other Project Engineers required*
*Final decision & actions by Project Management*

***Date of Approval :*** 2004-10-27

***Decision of the PLO for Class I changes :***

☐ Not requested.
☐ Rejected.
☑ Accepted by the Project Leader Office.
*Actions identified by Project Leader Office*

***Date of Approval :*** 2004-10-27

***Actions to be undertaken :***

Modify the drawings and Equipment codes concerned to reflect the changes described in this ECO.

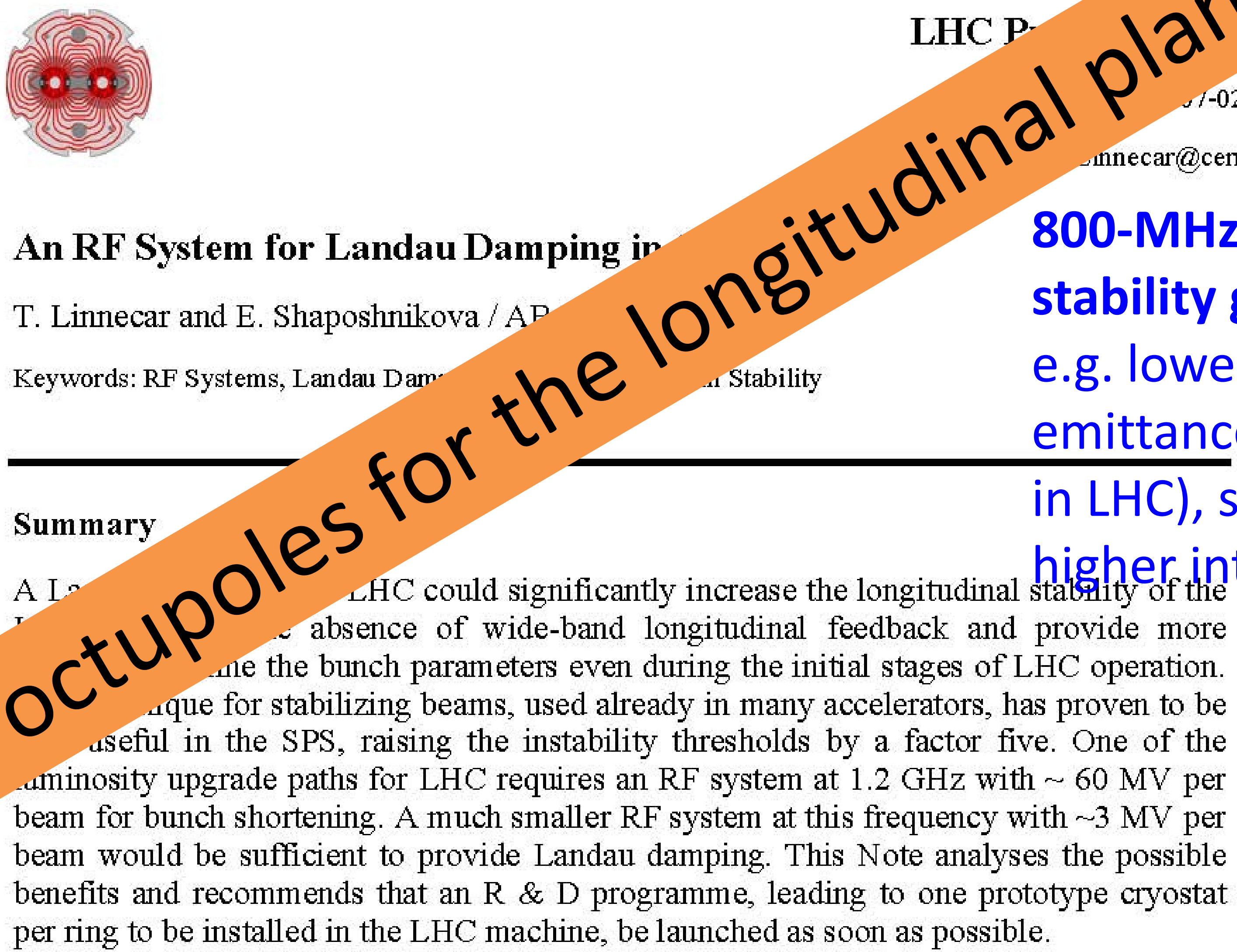
***Date of Completion :*** 2004-10-27

***Visa of QA Officer :***

*Note : when approved, an* ***Engineering Change Request*** *becomes an* ***Engineering Change Order/Notification****.*

for future wire
LR beam-beam
compensators,
3-m long sections
have been reserved
in LHC at 104.93 m
(center position)
on either side of
IP1 & IP5

# Higher-Harmonic RF Cavity



LHC P

/-02-16

innecar@cern.ch

**An RF System for Landau Damping in**

T. Linnecar and E. Shaposhnikova / AB

Keywords: RF Systems, Landau Dam… n Stability

**Summary**

A L… LHC could significantly increase the longitudinal stability of the L… absence of wide-band longitudinal feedback and provide more …ne the bunch parameters even during the initial stages of LHC operation. …ique for stabilizing beams, used already in many accelerators, has proven to be … useful in the SPS, raising the instability thresholds by a factor five. One of the …uminosity upgrade paths for LHC requires an RF system at 1.2 GHz with ~ 60 MV per beam for bunch shortening. A much smaller RF system at this frequency with ~3 MV per beam would be sufficient to provide Landau damping. This Note analyses the possible benefits and recommends that an R & D programme, leading to one prototype cryostat per ring to be installed in the LHC machine, be launched as soon as possible.

“octupoles for the longitudinal plane”

**800-MHz system;**
**stability gain > factor 3**
e.g. lower longitudinal
emittance (no blow up
in LHC), short bunches,
higher intensity

# intensity & emittance from injectors

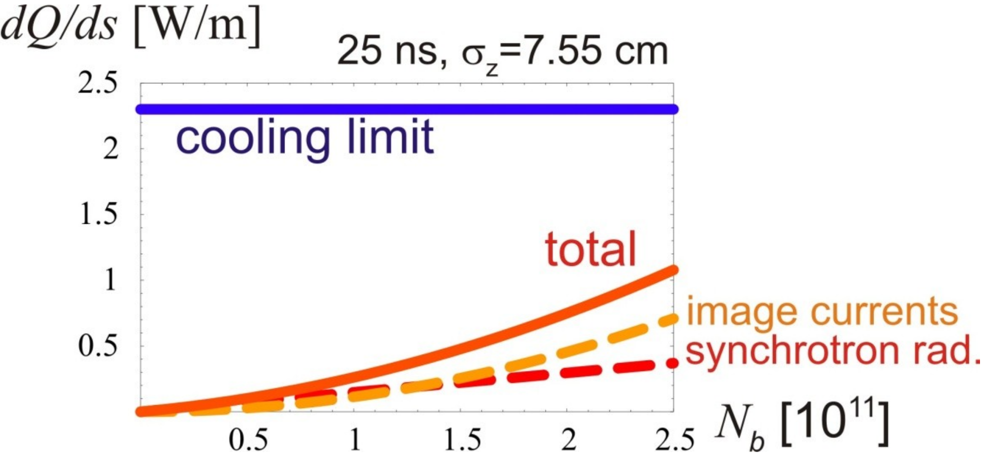
talk by O. Bruning

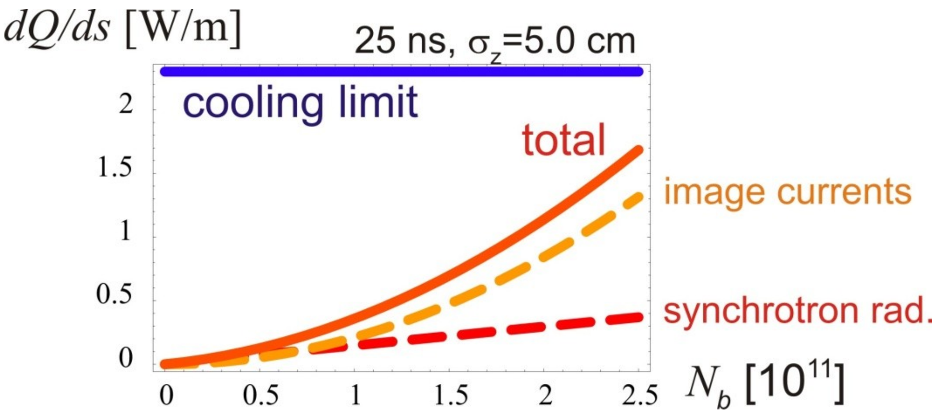
| | **spacing [ns]** | **bunch intensity $[10^{11}]$** | **transv. rms norm. emittance [μm]** |
|---|---|---|---|
| nominal | 25 | 1.15 | 3.75 |
| available “now” | **25** | **1.20** | **3.75** |
| available “now” | **50** | **1.70** | **3.75** |
| available “now” | **50** | **1.70** | **2.50** |
| w LINAC4 | **25** | **1.40** | **3.75** |
| w LINAC4 | **50** | **2.50** | **3.75** |
| w LINAC4+LIU | **25** | **2.00** | **2.50** |
| w LINAC4+LIU | **50** | **3.30** | **3.75** |

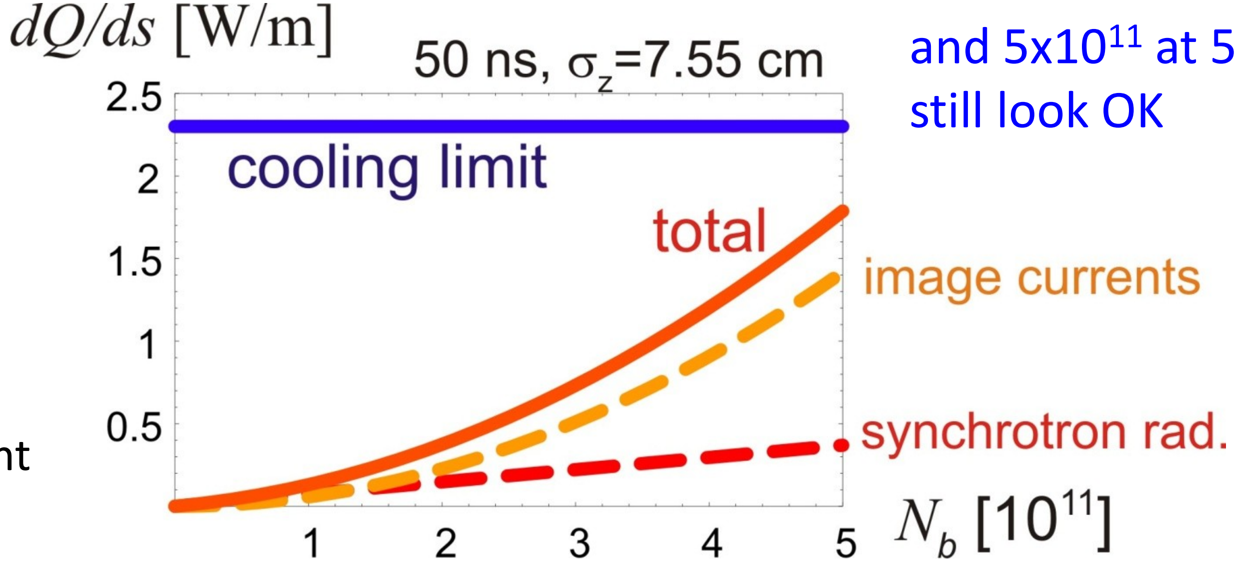
***HL-LHC class***

*could we get 20% more?*

# intensity limit: heat load due to image currents & synchrotron radiation





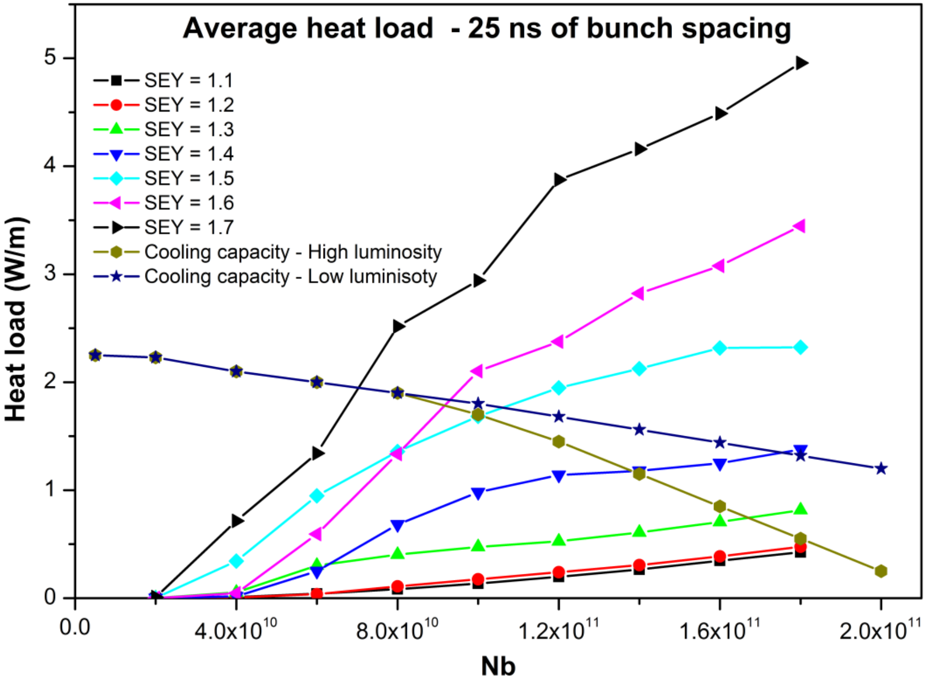


$2.5 \times 10^{11}$ at 25 ns and $5 \times 10^{11}$ at 50 ns still look OK

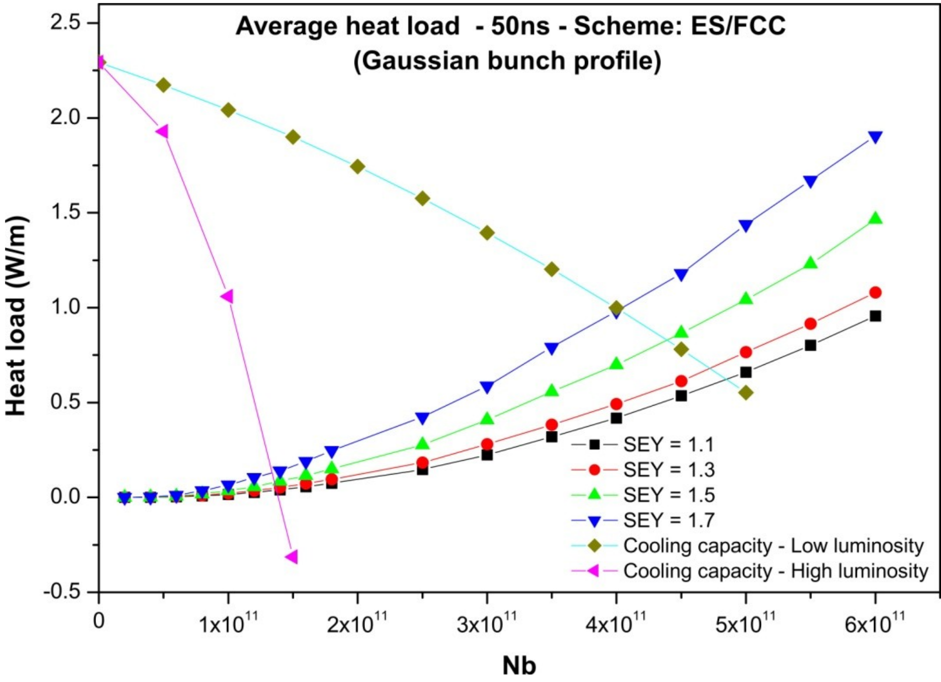
also note: **nuclear beam-gas scattering** with $\tau$~100 h (32 ntorr RT hydrogen) contributes an equivalent 0.15 W/m at nominal current [e.g. HHH-2004]

# electron-cloud heat load

## 25-ns bunch spacing



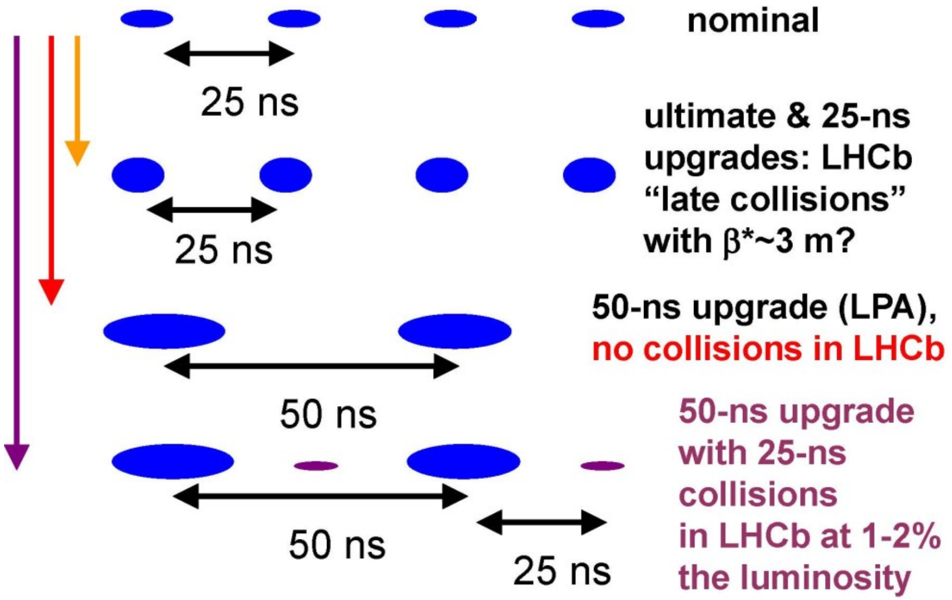
## 50-ns bunch spacing



H. Maury

electron cloud contribution acceptable if $\delta_{max} \leq 1.2$

# e-cloud heat load also OK for 50 ns spacing plus “LHCb satellites”



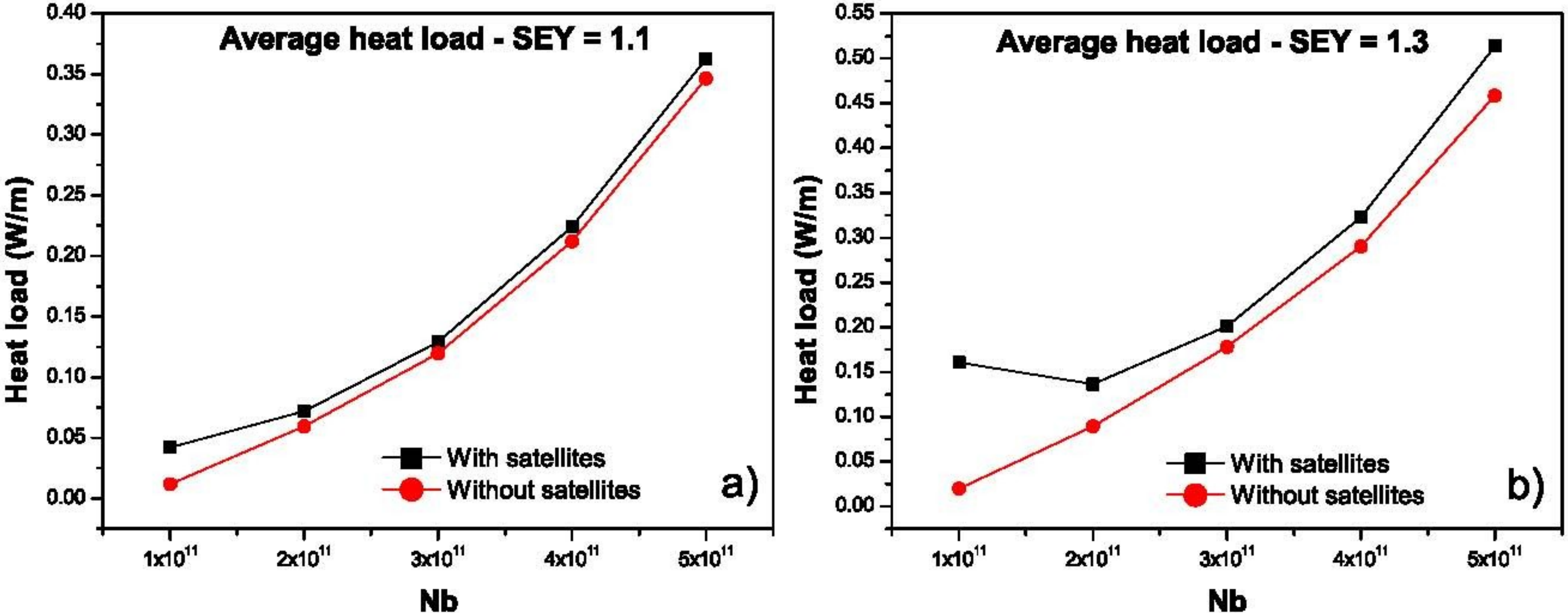
nominal

ultimate & 25-ns upgrades: LHCb “late collisions” with β*~3 m?

50-ns upgrade (LPA), no collisions in LHCb

50-ns upgrade with 25-ns collisions in LHCb at 1-2% the luminosity

H. Maury



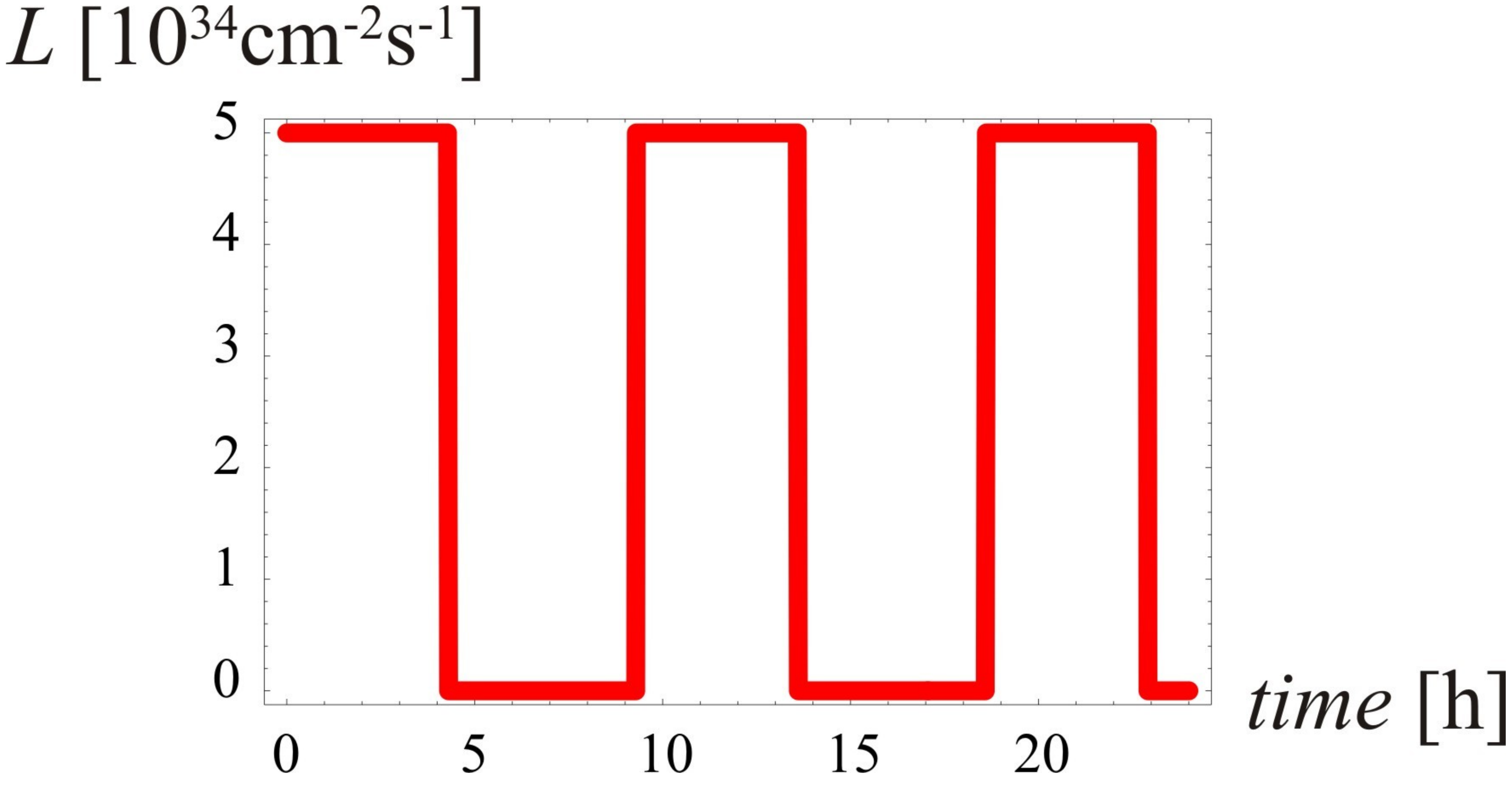
# example HL-LHC parameters, $\beta^*=15$ cm

| parameter | symbol | **nom.** | nom.* | **HL crab** | **HL sb + lrc** | **HL 50+lrc** |
|---|---|---:|---:|---:|---:|---:|
| protons per bunch | $N_b$ [$10^{11}$] | **1.15** | 1.7 | **1.78** | **2.16** | **3.77** |
| bunch spacing | $\Delta t$ [ns] | **25** | 50 | **25** | **25** | **50** |
| beam current | I [A] | **0.58** | 0.43 | **0.91** | **1.09** | **0.95** |
| longitudinal profile |  | **Gauss** | Gauss | **Gauss** | **Gauss** | **Gauss** |
| rms bunch length | $\sigma_z$ [cm] | **7.55** | 7.55 | **7.55** | **5.0** | **7.55** |
| beta* at IP1&5 | $\beta^*$ [m] | **0.55** | 0.55 | **0.15** | **0.15** | **0.15** |
| full crossing angle | $\theta_c$ [µrad] | **285** | 285 | **(508-622)** | **508** | **508** |
| Piwinski parameter | $\phi=\theta_c\sigma_z/(2^*\sigma_x^*)$ | **0.65** | 0.65 | **0.0** | **1.42** | **2.14** |
| tune shift | $\Delta Q_{tot}$ | **0.009** | 0.0136 | **0.011** | **0.008** | **0.010** |
| potential pk luminosity | $L$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | **1** | 1.1 | **10.6** | **9.0** | **10.1** |
| events per #ing |  | **19** | 40 | **95** | **95** | **189** |
| effective lifetime | $\tau_{eff}$ [h] | **44.9** | 30 | **13.9** | **16.8** | **14.7** |
| run or level time | $t_{run,level}$ [h] | **15.2** | 12.2 | **4.35** | **4.29** | **4.34** |
| e-c heat SEY=1.2 | P [W/m] | **0.2** | 0.1 | **0.4** | **0.6** | **0.3** |
| SR+IC heat 4.6-20 K | $P_{SR+IC}$ [W/m] | **0.32** | 0.30 | **0.62** | **1.30** | **1.08** |
| IBS $\varepsilon$ rise time ($z$, $x$) | $\tau_{IBS,z/x}$ [h] | **59, 102** | 40, 69 | **38, 66** | **8, 33** | **18, 31** |
| annual luminosity | $L_{int}$[fb$^{-1}$] | **57** | 58 | **300** | **300** | **300** |

# example HL-LHC parameters, $\beta^*=30$ cm

| parameter | symbol | **nom.** | nom.* | **HL crab** | **HL sb + lrc** | **HL 50+lrc** |
|---|---|---|---|---|---|---|
| protons per bunch | $N_b$ [$10^{11}$] | **1.15** | 1.7 | **2.28** | **2.47** | **4.06** |
| bunch spacing | $\Delta t$ [ns] | **25** | 50 | **25** | **25** | **50** |
| beam current | I [A] | **0.58** | 0.43 | **1.15** | **1.25** | **1.03** |
| longitudinal profile | | **Gauss** | Gauss | **Gauss** | **Gauss** | **Gauss** |
| rms bunch length | $\sigma_z$ [cm] | **7.55** | 7.55 | **7.55** | **5.0** | **7.55** |
| beta* at IP1&5 | $\beta*$ [m] | **0.55** | 0.55 | **0.30** | **0.30** | **0.30** |
| full crossing angle | $\theta_c$ [μrad] | **285** | 285 | **(359-462)** | **359** | **359** |
| Piwinski parameter | $\phi=\theta_c\sigma_z/(2*\sigma_x*)$ | **0.65** | 0.65 | **0.0** | **0.71** | **1.07** |
| tune shift | $\Delta Q_{tot}$ | **0.009** | 0.0136 | **0.0145** | **0.0128** | **0.0176** |
| potential pk luminosity | $L$ [$10^{34}$ cm$^{-2}$s$^{-1}$] | **1** | 1.1 | **8.69** | **8.32** | **9.41** |
| events per #ing | | **19** | 40 | **95** | **95** | **189** |
| effective lifetime | $\tau_{eff}$ [h] | **44.9** | 30 | **17.8** | **19.3** | **15.8** |
| run or level time | $t_{run,level}$ [h] | **15.2** | 12.2 | **4.29** | **4.33** | **4.29** |
| e-c heat SEY=1.2 | P [W/m] | **0.2** | 0.1 | **0.6** | **0.7** | **0.3** |
| SR+IC heat 4.6-20 K | $P_{SR+IC}$ [W/m] | **0.32** | 0.30 | **0.93** | **1.65** | **1.23** |
| IBS ε rise time (*z*, *x*) | $\tau_{IBS,z/x}$ [h] | **59, 102** | 40, 69 | **30, 52** | **7, 29** | **17, 29** |
| annual luminosity | $L_{int}$[fb$^{-1}$] | **57** | 58 | **300** | **300** | **300** |

# *typical day at the HL-LHC…*



similar for all scenarios

# preliminary conclusions - 1

HL-LHC parameter space well defined

to achieve 300 $\mathrm{fb}^{-1}$ per year:

- about 1 A beam current (+/- 10%)
- potential peak luminosity $10^{35}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- run time 4.3 h ~ assumed turnaround time of 5 h
- $\beta^*$ between 15 and ~30 cm

high(er) beam intensity helps in every regard

both 50-ns and 25-ns scenarios

200 $\mathrm{fb}^{-1}$ per year would relax intensity demand

# preliminary conclusions - 2

beam-beam limit (at 0.02) no longer a constraint

three alternative scenarios for 300 $fb^{-1}$ / year:

- crab cavities
- higher harmonic RF (shorter bunches) + LR compensation
- 50 ns bunch spacing, large Piwinski angle, + LR compensation

decreasing $\beta^*$ from 30 to 15 cm is equivalent to 10-20% beam current increase (scenario -dependent)

effect of smaller $\varepsilon$ similar to (better) than smaller $\beta^*$

# proposed roadmap & branching points

- ***LHC MDs*** for HL-LHC – starting in **2011**
  - ATS optics ingredients (beta wave, phase changes)
  - LR beam-beam limits
  - effect of crossing angle on HO b-b limit
  - electron cloud limits
  - “flat beam” optics [S. Fartoukh, LHCMAC19, e.g. r~2, $\Delta n_1$~1
  - effect of crossing plane (H-V, V-V, H-H)

several MDs may be done regardless of HL-LHC and also benefit nominal LHC performance

- ***install LR-BB compensators in LHC*** (**2013**)
- develop & prototype ***compact crab cavity (2011-16) for beam test in (SPS+) LHC (2017)***
- develop&install ***LHC 800-MHz system*** (**2016**?)

# thank you for your attention!

# useful leveling formulae

| | w/o leveling | *L*=const | $\Delta Q_{bb}$=const |
|---|---|---|---|
| luminosity evolution | $L(t) = \frac{\hat{L}}{\left(1+t/\tau_{eff}\right)^2}$ | $L = L_0 \approx const$ | $L(t) = \hat{L}\exp\left(-t/\tau_{eff}\right)$ |
| beam current evolution | $N(t) = \frac{N_0}{\left(1+t/\tau_{eff}\right)}$ | $N = N_0 - \frac{N_0}{\tau_{eff}}t$ | $N(t) =$<br>$N(0)\exp\left(-t/\tau_{eff}\right)$ |
| optimum run time | $T_{run} = \sqrt{\tau_{eff}T_{ta}}$ | $T_{run} = \frac{\Delta N_{\max}\tau_{eff}}{N_0}$ | $T_{run} = \tau_{eff}$<br>$\min\left[\ln\left(\sqrt{1+\phi_{piw}(0)^2}\right),\right.$<br>$\left.\ln\left(\left(T_{ta}+T_{run}+\tau_{eff}\right)/\tau_{eff}\right)\right]$ |
| average luminosity | $L_{ave} = \hat{L}\frac{\tau_{eff}}{\left(\tau_{eff}^{1/2}+T_{ta}^{1/2}\right)^2}$ | $L_{ave} = \frac{L_0}{1+\frac{L_0\sigma_{tot}n_{IP}}{\Delta N_{\max}n_b}T_{ta}}$ | $L_{ave} = \frac{\tau_{eff}}{T_{ta}+T_{run}}\left(1-e^{-T_{run}/\tau_{eff}}\right)$ |

$\Delta Q_{bb}$=const→ exponential *L* decay, w decay time $\tau_{eff}$ ($\neq \tau_{eff}/2$)