HL-LHC: parameter space, constraints & possible options

Many thanks to

Photo: courtesy R. Assmann

Chamonix 2011
LHC Performance Workshop

Frank Zimmermann
reminder - “key plot” from Chamonix ‘10

\[ <L> \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

\[ N_b = 2.3 \times 10^{11} \]

\[ N_b = 2.6 \times 10^{11} \]

\[ N_b = 4 \times 10^{11} \]

\[ T_{ta} = 5 \text{ h} \]

\[ \beta^* \text{ [cm]} \]

- 9.5σ sep.
- 10σ sep.
- reduced emittance
- crab crossing
- “LPA” at 25 ns
- “LPA” at 50 ns
- 8σ sep.
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: $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
• “ATS optics” solution for $\beta^* < 30 \text{ cm}$
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

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

\[
\tau_{\text{eff}} = \frac{N_{\text{tot}}}{n_{IP} \sigma L_{\text{lev}}}
\]

\[ L_{\text{level}} = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \]
luminosity formulae with leveling

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

\[ L_{\text{lev}} = f_{\text{lev}}(t) L_{\text{max}}(t) \]

\( f_{\text{lev}} \): time-dependent leveling factor, \( f_{\text{lev}} \leq 1 \)

define virtual “potential peak luminosity”

\[ \hat{L} \equiv L_{\text{max}}(0) = \frac{f_{\text{rev}} n_b N_b^2(0)}{4\pi \beta^*(0) \varepsilon} F(\phi_{piw,\text{min}}(0)) = \frac{L_{\text{lev}}}{f_{\text{lev}}(0)} \]
leveling schemes

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

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

• 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 $\phi_{piw}$

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

formulae above assume round beams
leveling with $\Delta x$

Example: $L_{\text{peak}} = 1.0 \ (1.5) \times 10^{35} \ \text{cm}^{-2}\text{s}^{-1}$

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

Alternating offset $\Delta x$, $\Delta y$

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

Tune shift changes sign during the store
leveling with $\theta_c$ or $V_{crab}$

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

maximum leveling time = 0.3 \ (0.42) \ $\tau_{eff}$
tune shift increases during the store
leveling with $\beta^*$

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

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

tune shift decreases during store
maximum leveling time

\[ t_{\text{level}} / \tau_{\text{eff}} \]

\[ L_{\text{level}} = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \]

\[ L_{\text{peak}} \geq 10^{35} \text{cm}^{-2}\text{s}^{-1} \]

Absolute leveling time scales linearly with total beam intensity

Universal plot
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]
integrating luminosity w leveling

\[ \text{int. } L/\text{year} \ [\text{fb}^{-1}] \]

\[ L_{\text{level}} = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \]

\[ L_{\text{peak}} = 1.10 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \]

\[ L_{\text{peak}} = 0.71 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \]

e.g. to get 300 fb\(^{-1}\) per year:
at ultimate intensity we need \( L_{\text{peak}} = 1.10 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \)
At 2x ultimate intensity \( L_{\text{peak}} = 0.71 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \)
intensity vs “peak” luminosity

\[ L_{\text{level}} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

\[ L_{\text{peak}} [10^{35} \text{ cm}^{-2}\text{s}^{-1}] \]

peak luminosity scales with (intensity)^2
how much do we need to squeeze?

\[
\frac{(\varepsilon \beta/F)/(\varepsilon \beta)}{_{\text{nom}}} = \frac{L_{_{\text{level}}}}{\text{}} = 5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}
\]

25 ns, 200 fb\(^{-1}\)/yr
50 ns, 300 fb\(^{-1}\)/yr

N\text{tot}/N_{\text{ult,tot}}

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

at \(N_b = 2 \times 10^{11}\) & 25 ns we need to reduce \((\beta \varepsilon)/F\) by \(x0.38\)

at \(N_b = 3.4 \times 10^{11}\) & 50 ns we need to reduce \((\beta \varepsilon)/F\) by \(x0.48\)
approaches to boost LHC luminosity

• low $\beta^*$ & crab cavities (80 MV)

• low $\beta^*$ & 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

parameters:
\( \varepsilon_{x,y} = 0.5 \text{ nm} \)
\( E = 7 \text{ TeV} \)
\( \beta_x = 11.8 \text{ cm} \),
\( \beta_y = 7.5 \text{ cm} \),
\( \sigma_z = 11.8 \text{ cm} \),
\( q_c = 315 \text{ m \, rad} \) \((\phi = 1.5)\),
\( N_b = 4.0 \times 10^{11} \),
\( Q_s = 0.002 \),
\( \Delta Q_{x,y} \sim -0.0065 \),
single IP

collisions with crossing angle
resonance free!

resonance suppression by LHC crab cavities
another beam-beam simulation w CC’s

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

\[ \frac{\theta_c}{\sigma^*} \]

25 ns

50 ns

with LR compensation

long range compensation will reduce the crossing angle
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

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.

<table>
<thead>
<tr>
<th>Equipment concerned</th>
<th>Drawings concerned</th>
<th>Documents concerned</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBC</td>
<td>LHCL SX–0001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LHCL SX–0002</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LHCL SX–0009</td>
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</tr>
<tr>
<td></td>
<td>LHCL SX–0010</td>
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</tr>
</tbody>
</table>

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

Decision of the Project Engineer:
- [ ] Rejected.
- [ ] Accepted by Project Engineer, no impact on other items. Actions identified by Project Engineer.
- [x] Accepted by Project Engineer, but impact on other items. Comments from other Project Engineers required. Final decision & actions by Project Management.

Decision of the PLO for Class I changes:
- [ ] Not requested.
- [ ] Rejected.
- [x] Accepted by the Project Leader Office. Actions identified by Project Leader Office.

Date of Approval: 2004-10-27  
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.
Higher-Harmonic RF Cavity

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

Summary

A 800-MHz system for the LHC could significantly increase the longitudinal stability of the LHC in the absence of wide-band longitudinal feedback and provide more precise control of the bunch parameters even during the initial stages of LHC operation. This technique for stabilizing beams, used already in many accelerators, has proven to be effective in the SPS, raising the instability thresholds by a factor five. One of the possible luminosity 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.
### intensity & emittance from injectors

<table>
<thead>
<tr>
<th>spacing [ns]</th>
<th>bunch intensity ([10^{11}])</th>
<th>transv. rms norm. emittance [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>nominal</td>
<td>25</td>
<td>1.15</td>
</tr>
<tr>
<td>available &quot;now&quot;</td>
<td>25</td>
<td>1.20</td>
</tr>
<tr>
<td>available &quot;now&quot;</td>
<td>50</td>
<td>1.70</td>
</tr>
<tr>
<td>available &quot;now&quot;</td>
<td>50</td>
<td>1.70</td>
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<tr>
<td>w LINAC4</td>
<td>25</td>
<td>1.40</td>
</tr>
<tr>
<td>w LINAC4</td>
<td>50</td>
<td>2.50</td>
</tr>
<tr>
<td>w LINAC4+LIU</td>
<td>25</td>
<td>2.00</td>
</tr>
<tr>
<td>w LINAC4+LIU</td>
<td>50</td>
<td>3.30</td>
</tr>
</tbody>
</table>

**talk by O. Bruning**

Could we get 20% more?

**HL-LHC class**
intensity limit: heat load due to image currents & synchrotron radiation

also note:

**nuclear beam-gas scattering** with $\tau \sim 100$ 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

Average heat load - 25 ns of bunch spacing

Average heat load - 50ns - Scheme: ES/FCC (Gaussian bunch profile)

electron cloud contribution acceptable if $\delta_{\text{max}} \leq 1.2$
e-cloud heat load also OK for 50 ns spacing plus “LHCb satellites”

H. Maury
## example HL-LHC parameters, $\beta^*=15 \text{ cm}$

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

$L \left[ 10^{34} \text{cm}^{-2}\text{s}^{-1} \right]$

similar for all scenarios
preliminary conclusions - 1

HL-LHC parameter space well defined to achieve 300 fb\(^{-1}\) per year:

- About 1 A beam current (+/- 10%)
- Potential peak luminosity \(10^{35} \text{ cm}^{-2}\text{s}^{-1}\)
- Run time 4.3 h ~ assumed turnaround time of 5 h
- \(\beta^*\) between 15 and \(\sim 30\) cm

High(er) beam intensity helps in every regard both 50-ns and 25-ns scenarios

200 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. $r \sim 2$, $\Delta n_1 \sim 1$
  - effect of crossing plane (H-V, V-V, H-H)

• **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

<table>
<thead>
<tr>
<th></th>
<th>Without Leveling</th>
<th>$L = \text{const}$</th>
<th>$\Delta Q_{bb} = \text{const}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Luminosity Evolution</strong></td>
<td>$L(t) = \frac{\hat{L}}{(1 + t / \tau_{\text{eff}})^2}$</td>
<td>$L = L_0 \approx \text{const}$</td>
<td>$L(t) = \hat{L} \exp(-t/\tau_{\text{eff}})$</td>
</tr>
<tr>
<td><strong>Beam Current Evolution</strong></td>
<td>$N(t) = \frac{N_0}{(1 + t / \tau_{\text{eff}})}$</td>
<td>$N = N_0 - \frac{N_0}{\tau_{\text{eff}}} t$</td>
<td>$N(t) = N(0) \exp(-t/\tau_{\text{eff}})$</td>
</tr>
<tr>
<td><strong>Optimum Run Time</strong></td>
<td>$T_{\text{run}} = \sqrt{\tau_{\text{eff}} T_{ta}}$</td>
<td>$T_{\text{run}} = \frac{\Delta N_{\text{max}} \tau_{\text{eff}}}{N_0}$</td>
<td>$T_{\text{run}} = \tau_{\text{eff}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\min \left[ \ln \left( \frac{\sqrt{1 + \phi_{\text{piw}}(0)^2}}{N_0} \right) \right.$</td>
<td>$\min \left[ \ln \left( \frac{\sqrt{1 + \phi_{\text{piw}}(0)^2}}{N_0} \right) \right.$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\left. \ln \left( \frac{(T_{ta} + T_{\text{run}} + \tau_{\text{eff}})/\tau_{\text{eff}}}{\tau_{\text{eff}}} \right) \right]$</td>
<td>$\left. \ln \left( \frac{(T_{ta} + T_{\text{run}} + \tau_{\text{eff}})/\tau_{\text{eff}}}{\tau_{\text{eff}}} \right) \right]$</td>
</tr>
<tr>
<td><strong>Average Luminosity</strong></td>
<td>$L_{\text{ave}} = \frac{\tau_{\text{eff}}}{(\tau_{\text{eff}}^{1/2} + T_{ta}^{1/2})^2}$</td>
<td>$L_{\text{ave}} = \frac{L_0}{1 + \frac{L_0 \sigma_{\text{tot}} n_{IP} T_{ta}}{\Delta N_{\text{max}} n_{b}}}$</td>
<td>$L_{\text{ave}} = \frac{\tau_{\text{eff}}}{T_{ta} + T_{\text{run}}} \left( 1 - e^{-T_{\text{run}}/\tau_{\text{eff}}} \right)$</td>
</tr>
</tbody>
</table>

$\Delta Q_{bb} = \text{const} \rightarrow \text{exponential } L \text{ decay, } w \text{ decay time } \tau_{\text{eff}} \neq \tau_{\text{eff}}/2$