Prospects for the LHC Heavy-Ion Programme in the coming decade

John Jowett (CERN)

Thanks to
Abstract

The first heavy-ion run of the LHC in 2010 opened up a new energy frontier in nucleus-nucleus collisions. An immediate harvest of physics results demonstrated the potential of the collider and its three heavy-ion experiments, ALICE, ATLAS and CMS. The plan for the coming decade foresees not only increasing energy and luminosity of the primary Pb-Pb collisions but also hybrid p-Pb and Ar-Ar collisions. The programme is defined by the physics requirements, the limits from beam physics and accelerator technology in the LHC and its heavy-ion injector chain, compatibility with the p-p programme and the planning of upgrades and modifications to the CERN accelerator complex.
Outline of talk

- Generalities on LHC as nucleus-nucleus collider
- The 2010 Pb-Pb run
- The 2011 Pb-Pb run
- Possible p-Pb run in 2012
- Evolution of performance
  - Limits
  - Mitigations, how and when?
- Proposal for the years beyond 2012
LHC Ion Injector Chain

- **ECR ion source (2005)**
  - Provide highest possible intensity of Pb$^{29+}$
- **RFQ + Linac 3**
  - Adapt to LEIR injection energy
  - Strip to Pb$^{54+}$
- **LEIR (2005)**
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
- **PS (2006)**
  - Define LHC bunch structure
  - Strip to Pb$^{82+}$
- **SPS (2007)**
  - Define filling scheme of LHC

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I-LHC construction and commissioning project (2003-2010) successfully concluded.

Vital role in creating the high brightness nuclear beams needed by LHC (vs. fixed target).

Already delivered “Early” beam with parameters significantly beyond design in 2010.

Mostly commissioned for more complex “Nominal” beam.
Reference: Luminosity of a hadron collider

\[ L = \frac{N^2 k_c f}{4\pi \sigma_x \sigma_y} F = \frac{N^2 k_c f_0 \gamma}{4\pi \varepsilon_n \beta^*} F(\theta_c) \]

**Parameters in luminosity**
- No. of particles per bunch \( N \)
- No. of bunches per beam \( k_b \)
- No. of bunches colliding at IP \( k_c \)
- \( k_c < k_b \)
- Relativistic factor \( \gamma \)
- Normalised emittance \( \varepsilon_n \)
- Beta function at the IP \( \beta^* \)
- Crossing angle factor
  - Full crossing angle \( \theta_c \)
  - Bunch length \( \sigma_z \)
  - Transverse beam size at the IP \( \sigma^* \)

Hour glass factor: \( F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2} \)

**Equal amplitude functions:**
- \( \beta^*_x = \beta^*_y = \beta^*_z \)
- Geometric and normalised emittance:
  \[ \varepsilon^*_x = \varepsilon^*_y = \varepsilon^* = \frac{\varepsilon_n}{\sqrt{\gamma^2 - 1}} \]

\( \Rightarrow \) Round beams at IP:
- \( \sigma^*_x = \sigma^*_y = \sigma^* = \sqrt{\beta^* \varepsilon_n / \gamma} \)

(N.B. LHC uses RMS emittances.)
Three large and highly capable heavy-ion physics experiments:

ALICE
ATLAS
CMS
Design Parameters for Pb-Pb (~2001)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Early Beam</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per nucleon</td>
<td>TeV</td>
<td>2.76</td>
<td>2.76</td>
</tr>
<tr>
<td>Initial ion-ion Luminosity $L_0$</td>
<td>cm$^{-2}$ s$^{-1}$</td>
<td>$\sim 5 \times 10^{25}$</td>
<td>$1 \times 10^{27}$</td>
</tr>
<tr>
<td>No. bunches, $k_b$</td>
<td></td>
<td>62</td>
<td>592</td>
</tr>
<tr>
<td>Minimum bunch spacing</td>
<td>ns</td>
<td>1350</td>
<td>99.8</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>m</td>
<td>1.0</td>
<td>0.5 /0.55</td>
</tr>
<tr>
<td>Number of Pb ions/bunch</td>
<td></td>
<td>$7 \times 10^7$</td>
<td>$7 \times 10^7$</td>
</tr>
<tr>
<td>Transv. norm. RMS emittance</td>
<td>$\mu$m</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Longitudinal emittance</td>
<td>eV s/charge</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Luminosity half-life (1,2,3 expts.)</td>
<td>h</td>
<td>14, 7.5, 5.5</td>
<td>8, 4.5, 3</td>
</tr>
</tbody>
</table>

At full energy, luminosity lifetime is determined mainly by collisions ("burn-off" from ultraperipheral electromagnetic interactions) $\sigma \approx 520$ barn

Something like this at reduced energy, higher $\beta^*$, in 2010

Probably unattainable without DS collimators (see later)
THE 2010 LEAD-LEAD RUN
Commissioning in 2010

- The LHC really worked with Pb beams!
  - No rapidly decaying, invisible beams
  - No quenches, so far

- Expanded the energy frontier for laboratory nuclear collisions by a factor 13.7 (later up to 28) beyond RHIC
  - Historically: biggest energy factor ever made by any collider over its predecessor

- Rich and novel beam physics,
  - Some similarities with protons:
    - Orbits, optics, aperture
  - Many differences from protons (and RHIC heavy ions), much as predicted:
    - Nuclear processes, ultraperipheral physics in collimation and luminosity, strong IBS effects (more later)
  - Some surprises nevertheless:
    - Emittances sometimes blown-up by unexpected effects
    - Some new loss locations and radiation problems
Rapid commissioning plan exploited established proton cycle to speed through initial phase of magnetic setup (injection, ramp, squeeze).

Collision crossing angles and collimation conditions different.
Monday morning: First Stable Beams for Pb-Pb

Later same day, 5 bunches/beam, then increased on each fill: 17, 69, 121
Factor 100 in peak luminosity within 6 days.
Many interesting new RF manipulations in LHC in first 2 weeks.
Ion injectors exceeded design intensity/bunch by 70%.
Collision conditions for p-p in 2010.

How sizes of beam bunches are squeezed by focusing magnets.

Crossing angle: $\pm 110 \mu$rad

(7$\sigma_x$, 7$\sigma_y$, 5$\sigma_z$) envelope for $\epsilon_x = 1.00529 \times 10^{-9}$ m, $\epsilon_y = 1.00529 \times 10^{-9}$ m, $\sigma_z = 0.000306$

Beam pipe is about twice transverse size of box.

Yellow planes indicate where bunches have long-range beam-beam interactions on their way in and out of the collision point (75 ns bunch spacing).
Collision conditions for Pb-Pb in 2010.

How sizes of beam bunches are squeezed by focusing magnets.

Zero crossing angle at IP (external crossing angle compensates ALICE spectrometer magnet bump).

Beam pipe is about twice transverse size of box.

J.M. Jowett, Europhysics Conference on High-Energy Physics, Grenoble, 23/7/2011
Interrupted twice by source refills (+ few days “parasitic” proton MD), some time to recover source performance (improvements for 2011).

Last few days: bunch number increased again to 137 with 8-bunches/batch from SPS.
Good fill: after detailed analysis of data from ATLAS and machine instrumentation, there is good agreement with simulation model (non-gaussian IBS, emittance growth, debunching from RF bucket, luminosity burn-off, etc.). Parameters of two beams evolve separately.

Simulations by T. Mertens, based on earlier work by R. Bruce, JMJ, M. Blaskiewicz, W. Fischer.

“Hump-influenced” fill: similar analysis and simulation show the influence of an unknown intermittent excitation, mainly Beam 2 vertical
Injectors for last LHC ion fill of the year

- 8 bunches $\times 17 \times 2$ from SPS to LHC
- Despite shorted source intermediate electrode
- Thanks to LEIR double injection
- $1.15 \times 10^8$ ions/bunch (64% above design)
- $\varepsilon_H = 0.5\mu m$ (<design/2); $\varepsilon_V = 1.1\mu m$ (<design)
Integrated nucleon–nucleon luminosity for LHC beam species in 2010

Source and p-p break

Pb–Pb (ATLAS)
Pb–Pb (ALICE)
Pb–Pb (CMS)
p–p (ATLAS)
p–p (CMS)
p–p (LHCb)
p–p (ALICE)
• Most important conference series for ultra-relativistic AA collisions
• First edition after start of LHC
  – > 800 participants
→ First, rich LHC harvest, a few examples…
• Quarkonium suppression
  – e.g.: Y family
  – measurement of detailed suppression pattern will give information on QGP temperature, evolution
  – Long-range $\eta$ correlations
  – Explanations invoking response of QGP medium to propagating partons were proposed at RHIC ("ridge", "Mach cone")
  – Fourier analysis of new data suggests very natural alternative explanation in terms of almost ideal hydrodynamic response of QGP to initial state fluctuations
• Suppression of di-jet production

  – recoiling high energy jets strongly quenched in QGP
  (but no visible angular decorrelation in azimuth!)

• Heavy flavour energy loss

  – suppression with respect to scaled pp

  – D almost as strongly suppressed as π

  → information on dependence of energy loss in QGP on mass and colour charge of propagating parton

→ Start of new hard probes era for ultra-relativistic A-A collisions
Much more about physics in plenary talks at this conference:

- 17:30 Monday, Experiment, F. Antinori,
- 18:00 Monday, Theory, C. Salgado
General assumptions for future years

- In a typical running year of LHC, a heavy-ion run will take place in the last few weeks before the end-of-year stop/shutdown.
  - Radiological cool-down benefit
  - No time cost to restore p-p conditions

- The beam conditions chosen for this run will not affect the preceding p-p run
  - Essentially free choice according to HI physics needs and feasibility
  - Nevertheless choose them (e.g., same beam rigidity) to exploit established operational conditions for rapid, efficient commissioning, c.f., 2010
THE 2011 LEAD-LEAD RUN
Physics conditions

- **Number of bunches affects bunch intensity**
  - Injectors, Early or Nominal operation

- **Optics and orbits**
  - Take over ATLAS and CMS $\beta^*$ from pp
    - Possibly reduce crossing angles? Quick in 2010.
  - Squeeze ALICE to same value $\beta^*= 1.5$ m
    - 2 days setup
    - Crossing angles in ALICE
    - Zero-degree calorimeter (ZDC) preferences

- **TCTVs (tertiary collimators in IR) open in IR2**
  - Pending replacement for 2012 run
Nominal Filling scheme

- Nominal beam has been prepared in injectors up to PS
  - Intensity/bunch $N_b$ close to design (but: we had better with the Early scheme in 2010)

- In LHC, 592 bunches of Nominal described in LHC Design Report reduced to 540 by present “abort gap keeper” requirement

- Some concerns about behaviour of beams (IBS, space-charge, ...) on long (~40 s) injection plateau in SPS
  - No clear data with recent definitive RF configuration
Intermediate filling scheme

- Based on “Early” mode of operation of injectors
- Two bunches at 200 ns in PS but no splitting
- Inject up to 15 times into SPS
  - Work on SPS injection kicker should give gap of 200 ns (E. Carlier)
  - Batches of up to 30 bunches to LHC – can optimise the length, 200 ns spacing, ~300 bunches
- Potential to retain higher bunch intensity (70% beyond design) already realised with Early scheme
- Decide between schemes in late Aug/early Sept
Predictions for Pb-Pb at 3.5 Z TeV/beam

- Luminosity factors w.r.t. 2010
  - 1.5/3.5 from $\beta^*$
  - 2-2.5 from bunch number and intensity

\[ L = 1 - 1.5 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1} \]

Integrated luminosity 30-50 $\mu$b$^{-1}$

- Very sensitive to lost time in short run
- Some prospects for doing better eg, $\beta^* = 1$ m?
Single bunch intensity

Debunching from IBS

Luminosity burn-off

Realistic choice between blue (Nominal) and brown (Intermediate) filling cases. Blow-up may be worse than this.
THE (POSSIBLE)
2012 PROTON-LEAD RUN
EITHER physics with Pb-Pb, maximum luminosity, OR physics with p-Pb (and Pb-p) Nominal beam

- For ALICE, choice depends on sufficient integrated luminosity with Pb-Pb in 2011
- Also depends on success of feasibility test.

HI run should be at end of run

- Avoids interrupting high luminosity p-p
- Benefit from radiological cool-down
- Start source, Linac3, LEIR, PS, SPS in good time
RF Frequency for p and Pb

RF frequency

\[ f_{RF} = \frac{h_{RF}}{T(p, m, Q)} \]

where the harmonic number \( h_{RF} \in \mathbb{Z} \), \( h_{RF} = 35640 \) in LHC

RF frequencies needed to keep p or Pb on stable central orbit of constant length \( C \) are different at low energy.

No problem in terms of hardware as LHC has independent RF systems in each ring.
Distorting the Closed Orbit

- Additional degree of freedom: adjust length of closed orbits to compensate different speeds of species.

- Done by adjusting RF frequency

\[ T(p_p, m, Q) = \frac{C}{c} \sqrt{1 + \left(\frac{mc}{Qp_p}\right)^2} (1 + \eta \delta) \]

where \( \delta = \frac{(p - Qp_p)}{Qp_p} \) is a fractional momentum deviation and

the phase-slip factor \( \eta = \frac{1}{\gamma_T^2} - \frac{1}{\gamma^2}, \quad \gamma = \sqrt{1 + \left(\frac{Qp_p}{mc}\right)^2}, \quad \gamma_T = 55.8 \) for LHC optics.

Moves beam on to off-momentum orbit, longer for \( \delta > 0 \).

Horizontal offset given by dispersion: \( \Delta x = D_x(s) \delta \).
Momentum offset required through ramp

Minimise aperture needed by
\[ \delta_p = -\delta_{Pb} = \frac{c^2 \gamma_T^2}{4p_p^2} \left( \frac{m_{Pb}^2}{Z_{Pb}^2} - m_p^2 \right). \]

Revolution frequencies must be equal for collisions at top energy

Lower limit on energy of p-Pb collisions, \( E = 2.7 \ Z \ TeV \)

Below this energy, RF frequencies must be unequal for injection, ramp.

Moving long-range beam-beam encounters may be a problem (cf RHIC).
Preparation and Feasibility test in 2011

- Review of all LHC systems done - basically OK
- **Tests in August**
  - Injection into ring with wrong RF frequency (Machine Protection)
  - Ramp with independent radial loops
  - RF rephasing to move collision point
- **Tests in October MD**
  - Injection of 100 ns p beam (to match Pb)
  - Commission Pb injection
  - Inject Pb against p
- **During 1st week of physics (Pb ramp available)**
  - Ramp p and Pb together
- **If successful, can do p-Pb in 2012!**

J.M. Jowett, Europhysics Conference on High-Energy Physics, Grenoble, 23/7/2011
Possible range of collision energies
Minimum p-Pb energy for equal revolution frequency.

Relations between these numbers are a simple consequence of the two-in-one magnet design

Charges $Z_1, Z_2$ in rings with magnetic field set for protons of momentum $p_p$

\[
\sqrt{s_{NN}} \approx 2c \ p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}},
\]

\[
y_{NN} = \frac{1}{2} \ \log \frac{Z_1 A_2}{A_1 Z_2}
\]
Assume Pb ion bunch with nominal intensity \( N_{\text{Pb}} = 7 \times 10^7 \), proton bunch with 10% nominal intensity \( N_p = 1.15 \times 10^{10} \), nominal emittances (equal geometric beam sizes).

With Pb ion nominal bunch structure in both beams, \( \beta^* = 0.5 \text{ m} \), peak \( L = 1.5 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1} \), in p+Pb collisions at 7 Z TeV.

At 3.5 Z TeV, \( \beta^* = 1.5 \text{ m} \), peak \( L \approx 3 \times 10^{28} \text{ cm}^{-2}\text{s}^{-1} \).

Luminosity burn-off much less than Pb-Pb:

BFPP flux of \(^{208}\text{Pb}\,^{81+}\) from IP reduced to 1.5% of Pb-Pb value
(BFPP flux of neutral H atoms to ZDC is tiny!)
EMD also less
BEYOND 2012 ...
Main performance limits

- **IBS**
  - Slow blow-up of emittances, debunching from RF bucket
  - Countered by radiation damping at 7 Z TeV

- **Collision products from IP**
  - Ultraperipheral EM processes, BFPP, EMD
  - Quench magnets

- **Collimation inefficiency**
  - Nuclear interactions with collimator material
  - Very different from protons
  - *Much* less efficient collimation
  - Losses can quench magnets, cause radiation problems
Main and secondary Pb beams from ALICE IP

Losses can quench superconducting magnets

Large EM cross sections. Similar in ATLAS, CMS
Variations of operating conditions affect luminosity limit, see paper for details.

Elaborate chain of calculations with several uncertainties from IP to liquid He flow.
Example of $^{206}$Pb created by 2-neutron EMD

- Green rays are ions that almost reach collimator
- Blue rays are $^{206}$Pb rays with rigidity change

Beam pipe in IR7 of LHC
Global view of losses, Pb-Pb stable beams

- Momentum collimation:
  - $^{208}\text{Pb}^{81+}$ (BFPP at ATLAS)
  - $^{207}\text{Pb}^{82+}$ (EMD1)

- Betatron collimation:
  - $^{206}\text{Pb}^{82+}$ (EMD2 in TCP)
  - + many other nuclides from hadronic fragmentation and EMD in TCPs

Possibly:
- $^{206}\text{Pb}^{82+}$ (EMD2 at IPs), other nuclides from collimation ??

Generally according to predictions, detailed analysis under way as time allows …

Record luminosity, the last fill of 2010
<table>
<thead>
<tr>
<th>Combination</th>
<th>DS</th>
<th>COLD</th>
<th>TCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1h</td>
<td>0.02</td>
<td>0.006</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>B1v</td>
<td>0.027</td>
<td>0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>B2h</td>
<td>0.03</td>
<td>0.011</td>
<td>$8 \times 10^{-5}$</td>
</tr>
<tr>
<td>B2v</td>
<td>0.025</td>
<td>0.006</td>
<td>$1.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>B1+B2 pos. off momentum</td>
<td>0.045</td>
<td>8e-4</td>
<td>0.06</td>
</tr>
<tr>
<td>B1+B2 neg. off momentum</td>
<td>0.007</td>
<td>2e-4</td>
<td>0.005</td>
</tr>
</tbody>
</table>

3.5TeV eq. Physics conditions

D Wollmann, Evian Dec 2010

J.M. Jowett, Europhysics Conference on High-Energy Physics, Grenoble, 23/7/2011
IR3 combined cleaning without TCRYOs

<table>
<thead>
<tr>
<th>Sector</th>
<th>Family</th>
<th>Half gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSS7</td>
<td>TCP IR7</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>TCSG IR7</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>TCLA IR7</td>
<td>open</td>
</tr>
<tr>
<td>LSS3</td>
<td>TCP IR3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>TCSG IR3</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>TCLA IR3</td>
<td>10</td>
</tr>
<tr>
<td>LSS1/2/5/8</td>
<td>TCTH</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>TCTV</td>
<td>8.3</td>
</tr>
</tbody>
</table>

τ=12 min lifetime
\[7 \times 10^7 \times 592 = 4.14 \times 10^{10} \text{ ions}\]
\[E=7 \text{ Z TeV eq.}\]

Max TCP load ~ 4500W
Peak loss in DS3 ~ 20W/m

\[\eta (\text{local}) = 0.0044\]
and with TCRYOs in

50 sigma half gap
  –
  DS already significantly cleaner

20 sigma half gap,
No losses visible!
It had been proposed to add collimators in dispersion suppressors of collimation insertions to intercept losses
- Shown to be extremely effective in simulations for p, Pb
- Similar devices around experiments for BFPP losses
- To make space, required moving dipole magnets, changing geometry, difficult engineering problems
- Could be facilitated later by higher field magnets and other developments
Long shutdown LS1: desirable work for heavy-ion programme

- Splices for heavy ion energy limit ...
- Following recent Collimation Review, there will be NO installation of dispersion suppressor collimators in LHC IR3

Consequences

- Risk for Pb beam intensity
  - Plan to measure limit this year
- Luminosity may still be limited by BFPP losses around each experiment
  - Hope for DS collimators around experiments to fix that in next long shutdown.
Physics with Pb-Pb at end of each year

- Nominal (or maybe even higher) intensity at top energy but peak luminosity may be limited
  - Luminosity levelling in all experiments, new regime with strong luminosity burn-off, significant radiation damping (see previous talks)

\[ L \sim 5 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1} \]

- This is the core period of the LHC Heavy Ion programme, devoted to maximum Pb-Pb luminosity integration
EITHER:

Physics with p-Pb (which energy?) to enhance 2015-16 data

OR:

Pb-Pb collisions at top energy
- Maximum possible luminosity
- Scheduled at the end of the year.
Long shutdown LS2: desirable work for heavy-ion programme

- Installation of dispersion suppressor collimators in IR2 (previously requested), to increase Pb-Pb luminosity limit.
  - N.B. collimator locations are different from IR3, IR7 (see diagram in Chamonix talk) with performance and integration schemes still to be studied

- Installation of dispersion suppressor collimators in IR3 (collimation inefficiency)

- Installation of dispersion suppressor collimators in IR7 may help Pb and Ar intensity limit (unless IR3 already sufficient)
2019: Pb-Pb collisions at top energy
- Maximum possible luminosity should now be higher
- Scheduled at the end of the year.

2020: Physics with p-Pb

2021: Physics with Ar-Ar collisions.
- Already commissioned in the injectors, Ar ion beam will be ready
- Intensity, luminosity to be seen
- Preliminary study indicates demanding collimation requirements
General shutdown LS3

- DS collimators for p-p luminosity debris in IR1, IR5?
  - Similar requirement for BFPP, so could also help with Pb-Pb luminosity limit for ATLAS, CMS.
  - To be checked whether required locations are the same.

Other upgrades for heavy ions?
Longer term

- Future for LHC heavy ions beyond 2021
  - See S. Bertolucci at Chamonix workshop 2011
- Would certainly require enhanced performance
- Need motivated and *timely* R&D to develop, eg:
  - DS collimator options
  - Hollow electron beam collimators? (Fermilab)
  - Beam cooling – cf: major success of stochastic cooling at RHIC
  - Crystal collimation?
  - Other species and sources?
  - HE-LHC (~2×energy) would be a very favourable beam dynamics regime for heavy ion beams
    - Natural cooling from rapid radiation damping
Conclusions

- LHC heavy-ion collisions have already produced a remarkable harvest of physics
- The coming decade will see the exploration of a vastly extended energy frontier in nucleus-nucleus collisions
- p-Pb collision mode will be tested soon and, we hope, implemented in 2012
- Luminosity limits may be encountered in 2015
  - Tests in 2011 should clarify
  - No DS collimators before 2018
    - Review priorities: IR2 for ALICE luminosity, IR3/7 for intensity, IR1/5 for ATLAS/CMS luminosity
- Longer term operation requires some R&D on new concepts for higher performance
Alternative to p-Pb, not currently requested
- Smaller central rapidity shift in collisions
- Smaller frequency differences between beams

Interest for e-D in LHeC, possibly also medical

Implementation
- Second source to produce deuterons, a second RFQ, a LEBT and a switchyard (to be decided more than 5 years earlier if needed).
- Some alternatives mooted recently (D. Kuchler)
- Commissioning of the new source would have to be done during a long shutdown.