Luminosity modeling for the LHC

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Introduction: Luminosity

\[ L = \frac{n_b f_{rev}}{2 \pi} \frac{N_{B1}(t)N_{B2}(t)}{\sigma_x(t)\sigma_y(t)} H \left( \frac{\sigma_s(t)}{\beta^*} \right) F_{geom}(\sigma_s(t), \beta^*) \]

\[ \frac{1}{\tau_L} = \frac{1}{L \, dt} = \frac{1}{\tau_{N1}} + \frac{1}{\tau_{N2}} + \frac{1}{\tau_{\sigma_x}} + \frac{1}{\tau_{\sigma_y}} + \frac{1}{\tau_F} \]

- Model components:
  - Beam current decay with time
  - Beam size (or emittance) evolution with time

- Geometric Factor
  \[ F_{geom} = \left( 1 + \sqrt{\frac{\sigma_s(\varphi/2)}{\sqrt{\epsilon_t \beta^*}}} \right)^{-1} \]

- Hourglass effect
  - Very small for LHC params
  - Should be considered for HL-LHC params
Luminosity decay

- During stable beams the interplay between different effects affects the bunch characteristics evolution:
  - Intra-beam scattering, Burn-off, Synchrotron Radiation, Beam-beam, noise, other unknown mechanisms, ...
- Many of the effects depend on the initial bunch brightness
- Big spread in the bunch by bunch behavior is observed

⇒ We need a model that takes the bunch-by-bunch variations into account
Model components (1)

- **Emittance and bunch length evolution at Flat Top energy:**
  - **Intrabeam scattering (IBS):**
    - Multiple Coulomb scattering effect leading to the redistribution of phase space and finally to emittance blow up in all three planes
    
    \[
    \frac{d\varepsilon_i}{dt} = f(En, N_{b0}, \varepsilon_{x0}, \varepsilon_{y0}, \sigma_{l0}) \rightarrow \text{Analytical integrals}
    \]
  - Iteration in time as the beam characteristics are evolving
  - **Synchrotron Radiation (SR):**
    - At high energies becomes important for proton beams as well, leading to emittance damping in all three planes
    
    \[
    \varepsilon_i = \varepsilon_{i0} \exp\left(-\frac{t}{\tau_i}\right), \tau_i: \text{emittance damping time}
    \]

- **The emittance evolution** due to IBS and SR has been **fully parameterized**
  - The parameterization is based on MADX computations using the IBS module
  - Their effect in any plane can be calculated through a function:
    \[
    [\varepsilon_x(t_i), \varepsilon_y(t_i), \sigma_l(t_i)] = \text{ComputeIBSEmitEvoll}(En, N_{b0}, \varepsilon_x(t_0), \varepsilon_y(t_0), \sigma_l(t_0), \text{timestep})
    \]
Model components (2)

- Bunch intensity degradation
  - **Luminosity burn-off**: Luminosity decay due to the collisions themselves:

\[
\tau_{\text{nuclear}} = \frac{N_{\text{tot},0}}{L_0 \sigma_{\text{tot}} k}
\]

\[
N_{\text{tot}}(t) = \frac{N_{\text{tot},0}}{1 + t/\tau_{\text{nuclear}}}
\]

- \(N_{\text{tot},0}\): the initial beam intensity
- \(L_0\): the initial Luminosity
- \(\sigma_{\text{tot}}\): the total cross section
- \(k\) the number of interaction points

It can be easily folded into the emittance evolution function in order to have a self consistent evolution
Luminosity model summary

• The **basic model** includes the three main mechanisms of the transverse emittance, bunch length, bunch intensity and luminosity evolution due to **IBS**, **SR** and **Burn-off**

• It can be easily applied and compared with the data for **bunch by bunch** and averaged quantities studies
  - On going effort to find correlations from the data from average and bunch by bunch behavior (brightness, long ranges, losses, blow-up,...)

• Other sources need to be considered
  • Non-linearities of the machine
  • Noise effects
  • Scattering on residual gas
  • ...

Evian 2015
Luminosity performance: RunI Vs RunII

- 2015 configuration with **low bunch intensity**, low brightness and relaxed $\beta^*$ results in:
  - Low peak luminosity
  - Long luminosity lifetime

- **Integrated luminosity** over a “typical” fill is very similar to what we used to get in 2012

**2012 (4 TeV)**
- 50 ns, 1380 b.
- $1.7\times10^{11}$ ppb, 1.6 um (inj.)
- $\beta^* = 60$ cm

**2015 (6.5 TeV)**
- 25 ns, 1825 b.
- $1.1\times10^{11}$ ppb, 2.5 um (inj.)
- $\beta^* = 80$ cm

**Peak luminosity**
- 2012 (4 TeV)
  - 7200 (ub.s)$^{-1}$
- 2015 (6.5 TeV)
  - 4500 (ub.s)$^{-1}$

**Integrated luminosity (12h)**
- 2012 (4 TeV, 50 ns) - Fill 3249
  - 0.18 fb$^{-1}$
- 2015 (6.5 TeV 25 ns) – Fill 4485
  - 0.17 fb$^{-1}$

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G. Iadarola
Analyzing RunII data

- In Run II we have **emittance measurements both at Flat Bottom and Flat Top**
  - **BSRT** data for both beams and both planes
  - Convoluted emittance from luminosity from the **experiments**
  - Convoluted horizontal and vertical emittance from **OP scans**
- Comparison between the **different methods not always in good agreement**
  - Work in progress to understand the data
- The data were compared with the model predictions for all Fills that arrived at Stable Beams
Luminosity model Vs RunII data: Emittance @ SB

- Fill 4538 is used as an example here
- Emittance evolution (averaged) during SB from BSRT, Lumi ATLAS and Lumi CMS
  - Different evolution
- **Blow up** observed, with respect to the model
- We need to understand the data and include other sources of emittance blow-up
Luminosity model Vs RunII data: Bunch current & bunch length @ SB

- Smoother current decay and more bunch length damping is observed with respect to the model prediction.
Luminosity model Vs RunII data: Bunch current & bunch length @ SB

- Smoother current decay and more bunch length damping is observed with respect to the model prediction.

- Using the **emittance evolution from the data (mean)** → **Very good prediction** for the current and bunch length evolution.

- Identify and add other sources of emittance evolution to the model is very important!

- The emittance blow up results in an **integrated luminosity reduction of the order of 20%**.
Optimal Fill times for 2016

- 2016 proposed parameters:
  - $\beta^*=40$ cm in IP1/5
  - 410 $\mu$rad (11 $\sigma$) or 370 $\mu$rad (10 $\sigma$) in IR1 and 5
  - Similar bunch brightness and bunch length as in 2015 ($1.2\times10^{11}$, 3$\mu$m, 1.3ns)

- Most probable turnaround time (based on 2015) of 6-8h (see M. Solfaroli)

- Using different emittance evolution scenarios (based on 2015 observations)
  - Long Fills are favorable
  - For 6h prep. Time: 18-20h
  - For 8h prep. Time: 22-24h
  - For 4h prep. Time: 13-15h
Summary and Outlook

- A model including IBS, SR and Burn-off at Flat Top (4TeV, 6.5TeV and 7TeV) and Flat Bottom energy is ready
  - Can be easily applied bunch-by-bunch

- The model is based on analytical formulas which assume Gaussian distributions
  - This is not always the case for the LHC (especially in the longitudinal plane)
  - Work in progress to understand the effect of the beam distribution on the IBS evolution of the bunch characteristics (S. Papadopoulou)
Summary and Outlook

- Observations from RunII data:
  - Differences have been observed on the emittance evolution from the different methods of measurement → Need to be understood
  - Using the emittance from the data, good prediction for the bunch length and bunch current evolution
  - Modeling the emittance evolution is a very important component of the model
- Based on the model and the observations, in 2016 long Fills should still be favorable
- Bunch-by-bunch analysis is in progress
  - Aims to identify correlations between the observed emittance blow-up and the bunch “lifestyle” (brightness, long-ranges, etc..)
THANK YOU FOR YOUR ATTENTION!