Long-Range Beam-beam effects: dynamic aperture versus intensity lifetime


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Overview

- Recap of LHC long-range beam-beam study results from machine development last September
  - Impact of the number and strength of LR interaction on lifetimes
  - Impact of chromaticity and octupole strength on lifetimes.

- Introduction to the dynamic aperture model and how the model relates to intensity loss.

- Procedure for fitting the model to the data.

- Comparison to simulation and discussion of possible discrepancies.

- Preliminary investigation of the impact of Proton burn off on the dynamic aperture.
Two trains of 48 bunches collided at IP1 and IP5 with bunches having a varying number of long range beam-beam interactions depending on the bunch position in the train.

Nominal bunches had 68 LR and 2 HO per turn.

The strength of the long range beam-beam interaction is dependent on the normalised beam separation, which in turn is related to the crossing angle.

We reduced the crossing angle in steps and observed the lifetimes for 10-15 minutes at each step.

At the smallest crossing angle the impact of chromaticity and octupole strength was investigated once again observing the impact on the lifetimes.

See MD note and IPAC paper for more details [1,2,3] and previous studies [4,5,6]
Decay rate calculated from the LR MD

- The decay rates are obtained by fitting a simple exponential decay model to the bunch by bunch intensity data [7]

  \[ I = I_0 e^{-\lambda t} + c \]

- From this one can calculate the decay rate (\( \lambda \)), taking the inverse of \( \lambda \) gives the lifetime, \( \tau \).

- The decay rate is then plotted against crossing angle, showing a strong dependence with crossing angle, with beam 2 worse than beam 1.

- The decay rate \( \lambda \), has a strong dependence on the strength and number of the long-range beam-beam interactions.

- Seen in both the intensity and luminosity data [1, 2, 3].

![Graph showing decay rate against crossing angle for Beam 1 and Beam 2.](image)
Crossing angle dependency for different bunch families in beam 1

- Non linear dependency versus $\alpha$ in presence of octupoles and chromaticity
- Depends on # of LR
Beam 1 Dependency on #LR: Nominal versus Pacman bunches

Intensity Decay Constant [Hrs$^{-1}$]

- $\alpha = 212 \, \mu \text{rad}$
- $\alpha = 192 \, \mu \text{rad}$
- $\alpha = 174 \, \mu \text{rad}$
- $\alpha = 158 \, \mu \text{rad}$
- $\alpha = 118 \, \mu \text{rad}$
Nominal bunches LR BB pattern in beam 1.
At the smallest crossing angle of 118 $\mu$ rad corresponding to a beam-beam separation of 5.5 to 7.6 $\sigma$, the chromaticity was reduced from 15 units to 2 units and the lifetimes were observed.

At the same crossing angle and chromaticity, the Landau octupole current was reduced from 476 [A] to 0 [A] and after optimisation of the tunes, the lifetimes were observed.

Lifetimes improve from below 10 hours to above 30 hours, recuperating lifetimes obtained at a crossing angle of 290 $\mu$ rad.

Both beam lifetimes improve [1,2,3].
The relationship between lifetimes and the dynamic aperture

- Lifetime model does not provide any “physics” with regard to the stability of the beam.
- The idea is to compare the intensity lifetimes with the dynamic aperture model as done by M. Giovannozzi [8]
- To be able to explain the decay rate increase in terms of separation, the dynamic aperture model for different BB encounters, Q’ & Landau octupole strengths.
- In the case when $D_\infty > 0, b_0 > 0, \kappa > 0$, we can separate the bunch into two regions.

\[
\begin{align*}
\lambda N &= \frac{1}{2} D^2(N) \\
D(N) &= D_\infty + \frac{b}{\log(N)^\kappa} \\
D(N) &= D_\infty + \frac{b_0}{(\log(N e^{-b_1}))^\kappa}
\end{align*}
\]
Dynamic aperture from Intensity decay

- Partitioning of phase space.
  - When \( r < D_\infty \) defines the motion of the particles to a KAM surface
  - When \( r > D_\infty \) where chaotic motion occurs and the escape rate to infinity is determined by a Nekhoroshev like estimate

- Assuming a Gaussian charge density distribution

\[
\frac{I}{I_0} = 1 - \int_{D(N)}^\infty re^{-\frac{r^2}{2}} \, dr
\]

- The losses are given by the particles in the bunch outside of the dynamic aperture at turn \( N \).

- The dynamic aperture is related to intensity loss through

\[
D(N) = \sqrt{-2 \times \log \left( \frac{\Delta I}{I_0} \right)}
\]

\( D_\infty \): Is the asymptotic value of the amplitude of the stability domain.
Different intensity decay regimes

However one could also consider the scenario when the fitting parameters can be negative. In this case there are two different scenarios:

\[
\begin{align*}
D_\infty & > 0, \quad \kappa < 0, \quad b < 0, \\
D_\infty & \leq 0, \quad \kappa > 0, \quad b > 0,
\end{align*}
\]

In the first regime, a positive \(D_\infty\) and negative \(\kappa\) and \(b_0\) corresponds to global chaoticity. When the KAM surface shrinks to zero and particles escape to infinity following the Nekhoroshev like behavior.

Although there is no KAM surface, the time taken for the particles to escape to infinity may be significantly larger than any fill length.

The second regime goes beyond the model of phase space partitioning into KAM and Nekhoroshev regions.
Definition of the fitting parameters.

- \( D_\infty \) is the asymptotic value of the amplitude of the stability domain (KAM surface) if all fitting parameters are positive (otherwise it has no real physical meaning).

- The fitting parameter \( \kappa \) varies the rate of the diffusion mechanism.

- The parameter \( b_0 \) corresponds to the width of the amplitude interval in which the diffusive behavior occurs.

- The fitting parameter \( b_1 \) was introduced to stabilise the fitting parameters \( b_0 \) and \( \kappa \) (see ref [9]).
Fitting method

Firstly intensity decay is converted into dynamic aperture by turn.

First 2.5M turns removed from fitting.

The dynamic aperture model is linearised, where

\[ Z = \frac{1}{\log(N e^{-b1})^\kappa} \]

This is then fitted for different variables of \( \kappa \) and \( b1 \), where the final fitting parameters are given using the values of \( \kappa \) and \( b1 \) that give the smallest residual.

As done for single beam analysis.

\[
D(N) = D_\infty + \frac{b_0}{(\log(N e^{-b_1}))^\kappa}
\]

Data Fit \([D_\infty=7.834, b_0=\ -0.0862, b_1=\ -1.30, \kappa=\ -1.0] \)

Diagram showing the fitting of data to the model equation.
We scan over a range of $\kappa$ and $b_1$ and compare the residue.

The fitting parameters $\kappa$ and $b_1$ that provide the minimum residue are used.

Scanned from $\kappa = -2 : 0.1 : 2$  
$b_1 = -2 : 0.1 : -0.5$

Resolution of scan fairly sparse.
Dynamic aperture per turn variation with crossing angle from measurement.

Variation of DA with turn number and crossing angle for nominal bunch.

Behaves as expected with smaller crossing angles resulting in a smaller dynamic aperture due to larger losses.

This bunch experiences a combination of HO and LR collisions.

Per turn HO: 2, LR: 68
Comparison of DA to lifetime

\[ D(N) \propto \sqrt{\tau^{-1}} \]

- All colliding bunches for crossing angles 212 \( \mu \) rad \( \Rightarrow 118 \mu \) rad.
- Follows a distinct square root relation for 3.5 Mturns.
- Trend behaves as expected and can be shown by directly comparing the lifetime and dynamic aperture model.
Dynamic aperture variation with crossing angle compared to bunch lifetime

The lifetimes and dynamic aperture move down the curve to smaller lifetimes and dynamic aperture as the crossing angle is reduced.
Emittance correction to simulation

Emittances are not constant throughout the crossing angle steps with emittance reducing towards smaller crossing angles (still to be understood and analysis is on going)

- Normalise the DA to the emittance of 2.5 μm to allow a direct comparison to simulations

- Normalised to the mean of the emittance at each crossing angle step.
The dynamic aperture from the experiment is calculated by taking the value of the D(N) for N=1×10^6.

Qualitatively shows the same trend with dynamic aperture saturating towards larger crossing angles and reducing with smaller crossing angles.

The dynamic aperture for bunches measured in the experiment have some variation from one another possibly depending on train position (electron cloud effects, closed orbit effects from the long-range etc.)
Comparison of simulation and experiment

![Graph comparing simulation and experiment](image-url)
Comparison of simulation and experiment

- Fairly close agreement of the experimental result and the sixtrack simulations for the last 5 crossing angles (within ~5%)
- However there are no errors included which could have a large impact.
- Crossing angle had a 10-20% error at the time of MD
- Unlike the simulations the experimental data includes proton burn off.
- One needs to remove the effect of proton burn off from the experimental data.
Calculating proton burn off

- The protons lost to burn off can be calculated by finding the number of events per crossing and multiplying by the cross section
  \[ \epsilon = L \times \sigma_{inelastic} \]

- So the total number of events at each crossing angle step will be
  \[ N_{burnoff} = \epsilon \times n_c \times t \]

- Calculated the total losses from proton burn off and include it in the calculation of the dynamic aperture.

- Burn off accounts for approximately \(10^5\) events per turn for a bunch luminosity \(L \sim 2 \text{ [Hz/\(\mu\)b]}\) and an inelastic cross section \(\sigma_{inelastic} = 60 \text{ mb}\) (inelastic cross section to be confirmed)

- The luminosity data was obtained directly from ATLAS measurements.

- But initially only the value of the luminosity at the beginning of the crossing angle step was used.
Simplistic proton burn off model

- For a simple (non-realistic case) and to gain some initial qualitative understanding the total particles lost through burn off are considered.

- This shifts the dynamic aperture up by approximately 0.75 $\sigma$.

- Burn off will not remain linear over time and will reduce proportionally with the luminosity.

- We have essentially changed $D_\infty$, but not $b_0, b_1$ and $\kappa$. 

Graph showing $D(N)[\sigma]$ vs. N Turn with two curves indicating Proton Burn off excluded and Proton Burn off included.
How does including burn off compare to simulation?

- The simplistic model of burn off shifts the dynamic aperture up.
- Over estimation of the effect of proton burn off.
- Proton burn off should decay exponentially and this is not taken into account.
The relative losses for nominal bunches (left) and for all colliding bunches with long-range interactions (right).

- The burn off losses should decay exponentially with the luminosity.
- Assuming that there are no offsets etc.
- On going analysis with more realistic model.
Bunch by bunch intensity lifetimes have been analysed for the LR MD as a function of crossing angle ($\alpha$), # of LR, $Q'$ and octupole strength.

Scaling laws show a non linear dependence of $\alpha$ and the # of LR.

Analysis indicates that reducing the chromaticity and octupole strength allows the LHC to operate at a smaller crossing angle without effecting beam stability (with only the non colliding bunch going unstable) and hence obtaining a gain in luminosity.

A model for the intensity loss relation to dynamic aperture from ref [8] has been applied to the data and directly compared to dynamic aperture simulations.

A preliminary (simplistic) model of burn off was excluded from the data and once again compared to simulation to show an improvement in dynamic aperture.

Still more work to be done...
Outlook

- Detailed more sophisticated model of burn off to be applied to the data. *(ongoing).*

- Simulations of the dynamic aperture and time evolution of dynamic aperture for varying parameters (ε, Np, etc) are ongoing.

- Plan to repeat experiment in next MD block, with the aim of obtaining cleaner data.

- Simulations of possible sources of losses to be addressed based on results from experiment (e.g., noise).
Thank you for listening
Further reading


[10] M. Crouch et al., “MD 385: Long-range beam-beam interaction and the effect on the beam and luminosity lifetimes”. Talk at the Luminosity and beam-beam meeting. 01/02/2016
SPARE SLIDES
Correcting for emittance variation over the crossing angle step.