LHC and HL-LHC DA studies with field errors at injection for proposing DA targets

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Introduction

Current Design:
- DA is used to specify field quality of magnets
- Collimation system assumes minimum beam lifetimes
- No link established between DA and beam lifetime

Obstacles:
- DA for a fixed number of turns not the whole picture
- Number of trackable turns based on available CPU-power, relevant timescales still beyond reach
- Even if CPU-power would be enough: special techniques required to keep num. errors under control (see celestial mechanics)
Introduction

- Reliable interpolation models for DA vs time available
  - Can try extrapolation to relevant timescales!
- Proven models for scaling laws of losses with DA available
  - We can try and close the loop!
- Allows to define minimum DA in terms of beam loss permitted by collimators
Introduction

Approach

- Use LHC as test bed for HL-LHC
  - Numerical simulations
  - Experimental tests
- We started with injection (see this talk) and then we will move to top energy

Parallel studies

- DA measurements in LHC injection (started in 2012 until now, in collaboration with Ewen)
- DA measurements in LHC at top energy (started in 2017, in collaboration with Ewen)
- Use scaling laws for simple analytical models of intensity change in collision burn-off and DA, only (started in 2012, in collaboration with Frederik)
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Estimating Beam Loss from DA

Extrapolating DA from an Analytical Model

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Derivation of beam loss from DA

Ultimate Goal:

- Derivation of beam loss from SixTrack DA simulations

Required input:

- Dynamic aperture $D$ at turn $\tau$ (for now, assume it was known)
- Probability density function $\rho(r)$ for modeling the transverse beam distribution

Result:

- Beam loss $L$ given as $L = \int \rho(r) dr$ ($D(\tau)$)
- What is a realistic distribution $\rho(r)$?
Derivation of beam loss from DA

Ultimate Goal :
  ▶ Derivation of beam loss from SixTrack DA simulations

Required input :
  ▶ Dynamic aperture $D$ at turn $\tau$ (for now, assume it was known)
Derivation of beam loss from DA

Ultimate Goal:

- Derivation of beam loss from SixTrack DA simulations

Required input:

- Dynamic aperture $D$ at turn $\tau$ (for now, assume it was known)
- Probability density function $\rho(r)$ for modeling the transverse beam distribution

Result:

$L(D(\tau)) = \int_{-\infty}^{\infty} D(\tau) \rho(r) dr$

What is a realistic distribution $\rho(r)$?
Derivation of beam loss from DA

Ultimate Goal:
▶ Derivation of beam loss from SixTrack DA simulations

Required input:
▶ Dynamic aperture $D$ at turn $\tau$ (for now, assume it was known)
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Result:
▶ Beam loss $\mathcal{L}$ given as

$$\mathcal{L}(D(\tau)) = \int_{D(\tau)}^{\infty} \rho(r) \, dr$$
Derivation of beam loss from DA

Ultimate Goal:
▶ Derivation of beam loss from SixTrack DA simulations

Required input:
▶ Dynamic aperture $D$ at turn $\tau$ (for now, assume it was known)
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Result:
▶ Beam loss $\mathcal{L}$ given as

$$\mathcal{L}(D(\tau)) = \int_{D(\tau)}^{\infty} \rho(r) \, dr$$

▶ What is a realistic distribution $\rho(r)$?
Selection of the PDF

In principle, many different PDFs available

- Gaussian
- Lévy-Student (Pearson type VII)
- Double Gaussian

...
Selection of the PDF

In principle, many different PDFs available

- Gaussian
- Lévy-Student (Pearson type VII)
- Double Gaussian

... 

We need information from the machine

- The tail matters for calculating $\mathcal{L}(D)$
- Measurements of the tail population carried out in 2011\textsuperscript{A)}
- Between 1.9\% and 3.6\% of the beam intensity beyond 4 $\sigma$
- Which distribution is compatible with this tail content?

\textsuperscript{A)} : F. Burkhart, \textit{Beam Loss and Beam Shape at the LHC Collimators}, CERN-THESIS-2012-046
Possible PDFs

- Define a tail content function $\mathcal{T}$:

$$\mathcal{T} = 2 \int_{4\sigma}^{\infty} \rho(x) dx$$

- Goal: Find a distribution with $1.9\% < \mathcal{T} < 3.6\%$

- Gaussian: $\mathcal{T}$ is fixed to $5 \times 10^{-3}\%$

- Levy-Student: $\mathcal{T}$ depends on parameters but $\mathcal{T}_{\text{max}} = 0.6\%$

- Double Gaussian?
Double Gaussian Distribution

Mathematical formulation (centered at origin of the scale)

\[
\rho(r) = \frac{A_1}{\sigma_1 \sqrt{2\pi}} \exp\left(-\frac{1}{2} \frac{r^2}{\sigma_1^2}\right) + \frac{1 - A_1}{\sigma_2 \sqrt{2\pi}} \exp\left(-\frac{1}{2} \frac{r^2}{\sigma_2^2}\right)
\]

- \(A_1 = 0.915\)
- \(\sigma_1 = 1.0\)
- \(\sigma_2 = 4.0\)
Double Gaussian Distribution

- Mathematical formulation (centered at origin of the scale)

\[ \rho(r) = \frac{A_1}{\sigma_1 \sqrt{2\pi}} \exp\left(-\frac{1}{2} \frac{r^2}{\sigma_1^2}\right) + \frac{(1-A_1)}{\sigma_2 \sqrt{2\pi}} \exp\left(-\frac{1}{2} \frac{r^2}{\sigma_2^2}\right) \]

with \( \sigma_1 < \sigma_2 \)

- Define the tail content as a function of the dominating Gaussian (assuming that \( \sigma_1 \approx \sigma \))

\[ T = 2 \int_{4\sigma_1}^{\infty} \rho(r) \, dr \]
Double Gaussian Distribution

A

$\sigma_2/\sigma_1$

$A_1$

$\tau [%]$

0.8 0.825 0.85 0.875 0.9 0.925 0.95 0.975
Double Gaussian Distribution
Double Gaussian Distribution

Figure – Figure caption

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Translating DA into beam loss

- Set of double Gaussian distributions \( \{ \rho(r) \}_{\sigma_1, \sigma_2, A_1} \)
- For a given DA the set of possible losses can be calculated

\[
\mathcal{L}(D|\sigma_1, \sigma_2, A_1) = \int_D^{\infty} \rho(r|\sigma_1, \sigma_2, A_1) dr
\]

\[
= \frac{A_1}{2} \text{Erfc} \left[ \frac{D}{\sqrt{2} \sigma_1} \right] + \frac{1 - A_1}{2} \text{Erfc} \left[ \frac{D}{\sqrt{2} \sigma_2} \right]
\]

with

\[
\text{Erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt
\]  

(2)
Translating DA into beam loss

- Set of double Gaussian distributions \( \{ \rho(r) \} \sigma_1, \sigma_2, A_1 \)
- For a given DA the set of possible losses can be calculated

\[
\mathcal{L}(D|\sigma_1, \sigma_2, A_1) = \int_D \rho(r|\sigma_1, \sigma_2, A_1) dr
\]

Example: consider \( D = 5\sigma \) and \( 8\sigma \)
Application to dynamic aperture simulations

- DA is a function of turn and different for all seeds
- Simulations limited to 100000 turns, not applicable to large time scales
- Use interpolation model to derive DA after 10-50 minutes
- Result: distribution of DA values depending on seed
Extrapolation of the DA to macroscopic time scales

Example: LHC at injection with $Q' = 12$ and $I_{\text{oct}} = 0$ A

SixTrack results

Single seed

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Extrapolation of the DA to macroscopic time scales

Example: LHC at injection with $Q' = 12$ and $I_{\text{oct}} = 0 \text{ A}$
Extrapolation of the DA to macroscopic time scales

Example: LHC at injection with $Q' = 12$ and $I_{\text{oct}} = 0$ A

\[ D(\tau) = D_\infty + \frac{b}{(\log \tau)^\kappa} \]

SixTrack results

Extrapolation
Extrapolation of the DA to macroscopic time scales

Example: LHC at injection with $Q' = 12$ and $I_{\text{oct}} = 0$ A

\[
D(\tau) = D_\infty + \frac{b}{(\log \tau)^k}
\]
Extrapolation of the DA to macroscopic time scales

\[ D(\tau) = D_\infty + \frac{b}{(\log \tau)^\kappa} \]

Distribution over seeds

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Extrapolation of the DA to macroscopic time scales

- Distr. and DA model can be combined to derive beam loss
- Loss function becomes parametric in Double Gaussian and fitting parameters

\[ \mathcal{L} = \mathcal{L}(\tau|\sigma_1, \sigma_2, A_1, D_\infty, b, \kappa) \]

- Can also include uncertainty from the fitting \( \Delta D_\infty, \Delta b \)

\[ \mathcal{L} = \mathcal{L}(\tau|\sigma_1, \sigma_2, A_1, D_\infty, b, \kappa, \Delta D_\infty, \Delta b) \]

- Assume Gaussian distribution of fit parameters with standard deviation \( \Delta D_\infty \) etc. around the central value
Loss distribution for different times after injection

LHC B1 Injection, $Q' = 20$, $I_{oct} = 40$ A, $\epsilon = 2.5$ $\mu$m
Application to LHC

- Study case: LHC at injection energy with 11 different chromaticities and octupole currents
- Calculate extrapolated DA, loss distribution
- Calculate emittance growth from DA (assuming Gaussian):

\[
\frac{\Delta \epsilon}{\epsilon}(D) = \frac{D^2 \exp(-D^2/2)}{2 \left(1 - \exp(-D^2/2)\right)}
\]

- LHC 2016 optics assuming \( \epsilon = 2.5 \, \mu m \)
Simulation Results

LHC Beam 1

Octupole Current [A] vs Chromaticity

Mean DA after 30min [\%]

Avg. beam loss 30min [\%]

LHC Beam 2

Octupole Current [A] vs Chromaticity

Mean DA after 30min [\%]

Avg. beam loss 30min [\%]
Simulation Results

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Extrapolated DA from SixTrack simulations

Injection, $\epsilon = 2.5 \mu m$, distribution over seeds

\[Q' = 2\]

\[Q' = 20\]
Extrapolated DA from SixTrack simulations

Injection, $\epsilon = 2.5 \mu m$, distribution over seeds
Calculation of the expected beam loss

\[
I_f = \sum_{i=1}^{N} \Delta I_i \cdot (1 - L(T_f - T_i))
\]

Our model predicts \(L(T_f - T_i)\) based on a DA simulation!

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Calculation of the expected beam loss

Final intensity $I_f$ given by injected bunch intensity $\Delta_i$ and the time difference $T_f - T_i$:

$$I_f = \sum_{i=1}^{N} \Delta_i (1 - \mathcal{L}(T_f - T_i))$$
Final intensity $I_f$ given by injected bunch intensity $\Delta_i$ and the time difference $T_f - T_i$:

$$I_f = \sum_{i=1}^{N} \Delta I_i (1 - \mathcal{L}(T_f - T_i))$$

Our model predicts $\mathcal{L}(T_f - T_i)$ based on a DA simulation!
Measured and Simulated Beam Loss

- Analyze all proton fills for physics in 2016
Measured and Simulated Beam Loss

- Analyze all proton fills for physics in 2016
- Compare beam intensity at beginning of PREPARE RAMP with sum of injected bunch intensity
Measured and Simulated Beam Loss

- Analyze all proton fills for physics in 2016
- Compare beam intensity at beginning of PREPARE RAMP with sum of injected bunch intensity
- Baseline : All simulations with $I_{\text{oct}} = 40 \text{ A}$ and $16 \leq Q' \leq 20$
Measured and Simulated Beam Loss

- Analyze all proton fills for physics in 2016
- Compare beam intensity at beginning of PREPARE RAMP with sum of injected bunch intensity
- Baseline: All simulations with $I_{oct} = 40$A and $16 \leq Q' \leq 20$
- Consider ten realizations of each set $(D_\infty, b, \kappa)$ from fit errors → 600 extrapolated DA values (with 60 seeds)
Measured and Simulated Beam Loss

- Analyze all proton fills for physics in 2016
- Compare beam intensity at beginning of PREPARE RAMP with sum of injected bunch intensity
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- Take into account all Double Gaussians from our model (around 4700)
Measured and Simulated Beam Loss

- Analyze all proton fills for physics in 2016
- Compare beam intensity at beginning of PREPARE RAMP with sum of injected bunch intensity
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- Consider ten realizations of each set $(D_\infty, b, \kappa)$ from fit errors → 600 extrapolated DA values (with 60 seeds)
- Take into account all Double Gaussians from our model (around 4700)
- Ignore fills with more than 5% loss (mostly dumps)
Measured and Simulated Beam Loss
Measured and Simulated Beam Loss

![Graph showing measured and simulated beam loss]

<table>
<thead>
<tr>
<th>Beam 1</th>
<th>Meas.</th>
<th>Sim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.69</td>
<td>0.81</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.49</td>
<td>0.26</td>
</tr>
<tr>
<td>Median</td>
<td>0.54</td>
<td>0.80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam 2</th>
<th>Meas.</th>
<th>Sim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.36</td>
<td>0.40</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.38</td>
<td>0.17</td>
</tr>
<tr>
<td>Median</td>
<td>0.21</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Measured and Simulated Beam Loss

- Simulations made with emittance 2.5 $\mu$m, in reality 2.2 $\mu$m
- Can we improve the agreement by applying the correct emittance?
Measured and Simulated Beam Loss

$\epsilon = 2.2 \mu m$

Counts [a.u.]

Measured
Simulated

Counts [a.u.]

Measured
Simulated

Beam Loss until PREPARE RAMP [%]
Measured and Simulated Beam Loss

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.pdf}
\end{figure}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
\textbf{Beam 1} & \textbf{Meas.} & \textbf{Sim.} \\
\hline
Mean & 0.69 & 0.6 \\
\hline
\textit{\sigma} & 0.49 & 0.3 \\
\hline
Median & 0.54 & 0.59 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
\textbf{Beam 2} & \textbf{Meas.} & \textbf{Sim.} \\
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Mean & 0.36 & 0.35 \\
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\hline
Median & 0.21 & 0.33 \\
\hline
\end{tabular}
\end{table}

\(\epsilon = 2.2 \mu m\)
Application to HL-LHC

- HL-LHC at injection energy assuming $\epsilon = 2.5 \, \mu m$
- Scan over chromaticity and octupole current, nominal tune
- Tune scans
  - With $Q' = 20$ and $I_{\text{oct}} = 40$ A
  - With $Q' = 3$ and $I_{\text{oct}} = 0$ A
  - With $Q' = 20$ and $I_{\text{oct}} = -40$ A
HL-LHC Estimated DA and beam loss after 30 minutes

Scan over chromaticity and octupole current
HL-LHC Estimated DA and emittance growth
Scan over chromaticity and octupole current
HL-LHC Estimated DA and beam loss after 30 minutes

Tune scan with $Q' = 20$ and $I_{\text{oct}} = 40$ A
HL-LHC Estimated DA and emittance growth

Tune scan with $Q' = 20$ and $I_{oct} = 40$ A
Outlook

- Comparison to measurement: calculate beam loss using the individual (measured) bunch emittance
- Simulations: Extension of parameter space
- HL-LHC tune scan with
  - \( Q' = 3 \) and \( I_{\text{oct}} = 0 \) A
  - \( Q' = 20 \) and \( I_{\text{oct}} = -40 \) A
- LHC: new simulation set with ATS optics and validation
- HL-LHC: use simulations to derive beam loss rates and compare to DR specifications
- Possibly re-measure the transverse beam distribution and re-calibrate model
Summary

- Model for beam loss from DA based on double Gaussian
- Model for extrapolating DA vs. turn to macroscopic timescales
- Allow deriving beam loss from DA from simulations
- Application to LHC and comparison with measured beam loss
- Good agreement when using the correct emittance
- Application to HL-LHC parameter scans: prediction of beam loss to be compared with design specifications