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

P. D. Hermes, M. Giovannozzi, F. Van Der Veken

CERN

Acknowledgements : The LHC@home volunteers

110th WP2 Meeting

07.11.2017

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
  $\rightarrow$ Can try extrapolation to relevant timescales !
- Proven models for scaling laws of losses with DA available
  $\rightarrow$ 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)

Contents

Derivation of beam loss from DA

Ultimate Goal :

- Derivation of beam loss from SixTrack DA simulations

Derivation of beam loss from DA

Ultimate Goal :

- Derivation of beam loss from SixTrack DA simulations

Required input :

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

Derivation of beam loss from DA

Ultimate Goal :

- Derivation of beam loss from SixTrack DA simulations

Required input :

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

Result :

- Beam loss $\mathcal{L}$ given as

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

Derivation of beam loss from DA

Ultimate Goal :

- Derivation of beam loss from SixTrack DA simulations

Required input :

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

Result :

- Beam loss $\mathcal{L}$ given as

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

- 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[A)]
- Between 1.9% and 3.6% of the beam intensity beyond $4\,\sigma$
- Which distribution is compatible with this tail content ?

[A)] : F. Burkhart, *Beam Loss and Beam Shape at the LHC Collimators*, CERN-THESIS-2012-046

Possible PDFs

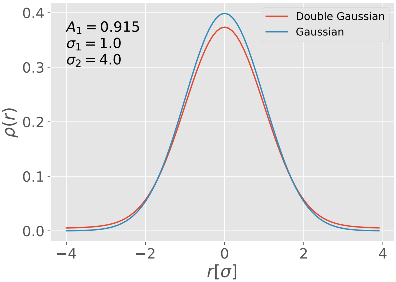
- Define a tail content function $\mathcal{T}$:

$$\boxed{\mathcal{T} = 2 \int_{4\,\sigma}^{\infty} \rho(x) dx} \quad (1)$$

- 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 $\mathcal{T}_{\mathrm{max}} = 0.6\%$
- Double Gaussian ?

Double Gaussian Distribution



- Mathematical formulation (centered at origin of the scale)

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

Double Gaussian Distribution

- Mathematical formulation (centered at origin of the scale)

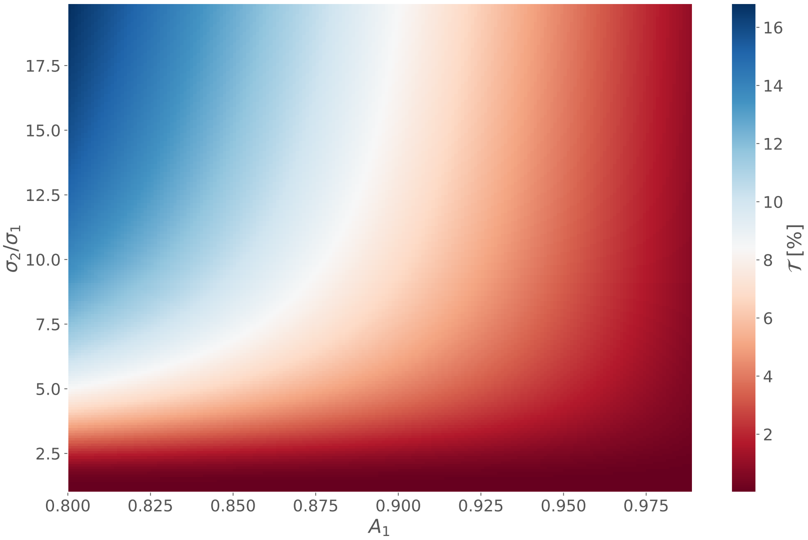
$$\rho(r) = \frac{A_1}{\sigma_1\sqrt{2\pi}} \exp\left(-\frac{1}{2}\frac{r^2}{\sigma_1^2}\right) + \frac{(1-A_1)}{\sigma_2\sqrt{2\pi}} \exp\left(-\frac{1}{2}\frac{r^2}{\sigma_2^2}\right)$$

  with $\sigma_1 < \sigma_2$

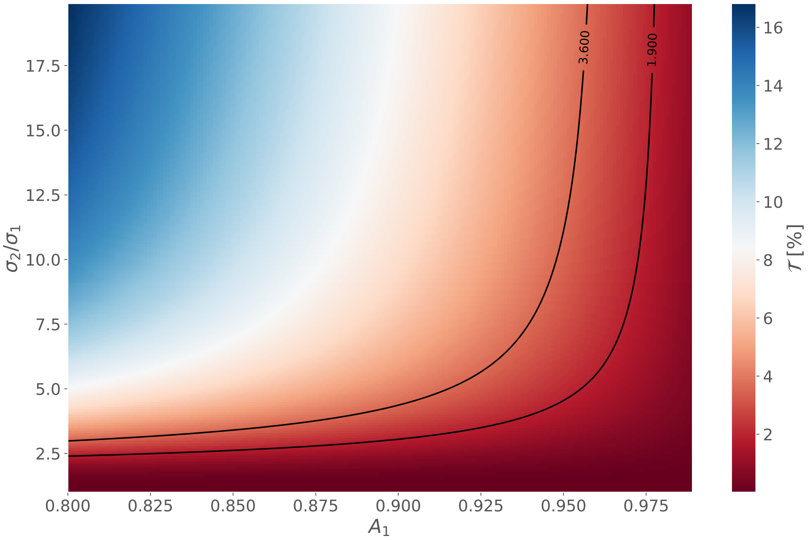
- Define the tail content as a function of the dominating Gaussian (assuming that $\sigma_1 \approx \sigma$)

$$\mathcal{T} = 2\int_{4\sigma_1}^{\infty} \rho(r)\, dr$$

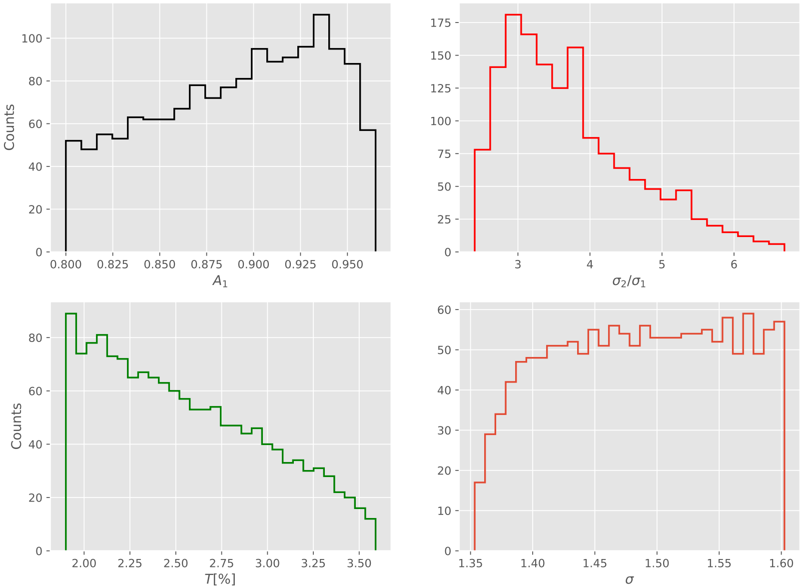
Double Gaussian Distribution



Double Gaussian Distribution



Double Gaussian Distribution



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

$$\begin{aligned}\mathcal{L}(D|\sigma_1,\sigma_2,A_1) &= \int_D^{\infty} \rho(r|\sigma_1,\sigma_2,A_1)dr \\ &= \frac{A_1}{2}\,\mathrm{Erfc}\left[\frac{D}{\sqrt{2}\,\sigma_1}\right] + \frac{1-A_1}{2}\,\mathrm{Erfc}\left[\frac{D}{\sqrt{2}\,\sigma_2}\right]\end{aligned}$$

with

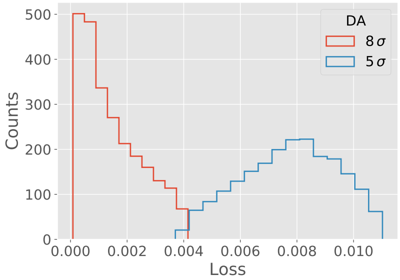
$$\mathrm{Erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-t^2}\,dt \qquad (2)$$

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

$$\mathcal{L}(D|\sigma_1,\sigma_2,A_1) = \int_D^\infty \rho(r|\sigma_1,\sigma_2,A_1)dr \qquad (3)$$

- Example : consider $D = 5\,\sigma$ and $8\,\sigma$

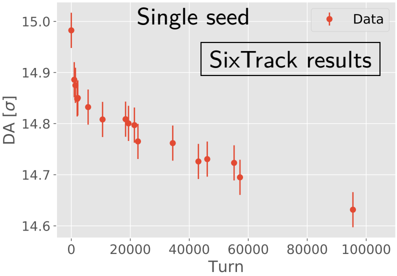


Application to dynamic aperture simulations

- 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

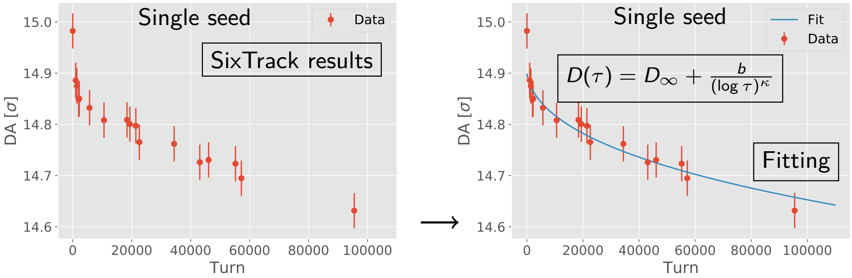
Extrapolation of the DA to macroscopic time scales

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



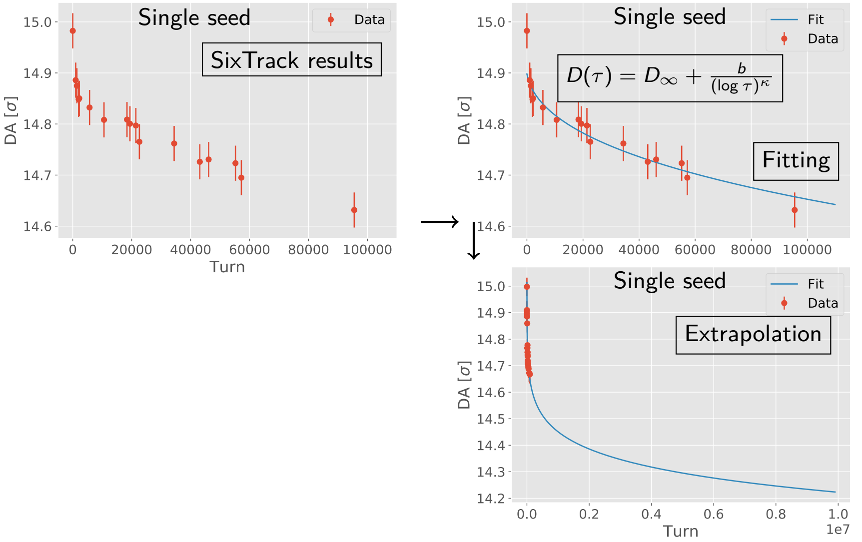
Extrapolation of the DA to macroscopic time scales

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



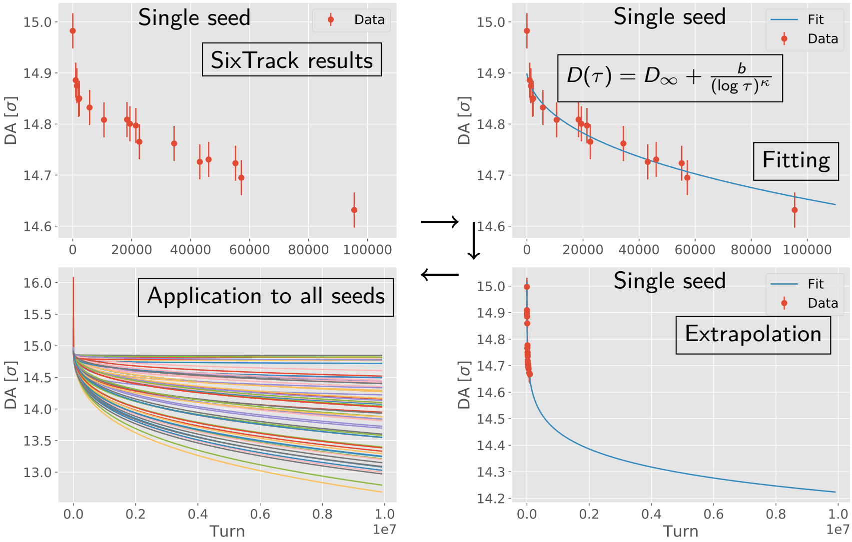
Extrapolation of the DA to macroscopic time scales

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



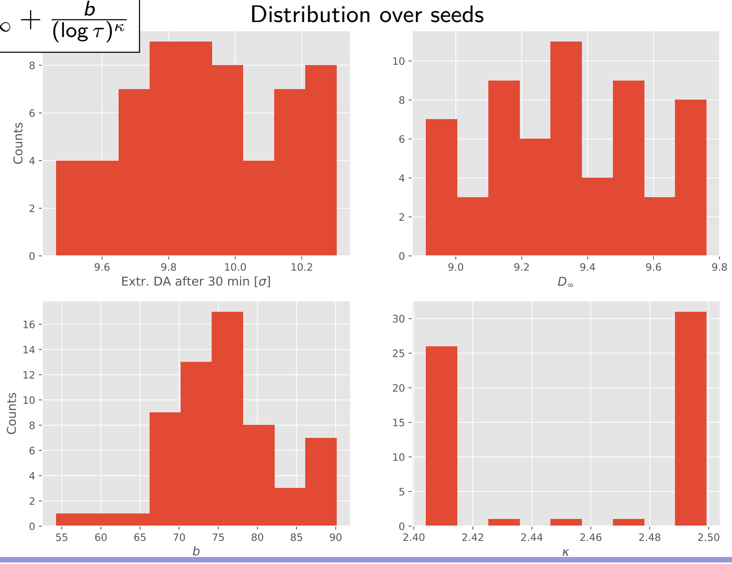
Extrapolation of the DA to macroscopic time scales

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



Extrapolation of the DA to macroscopic time scales

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



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

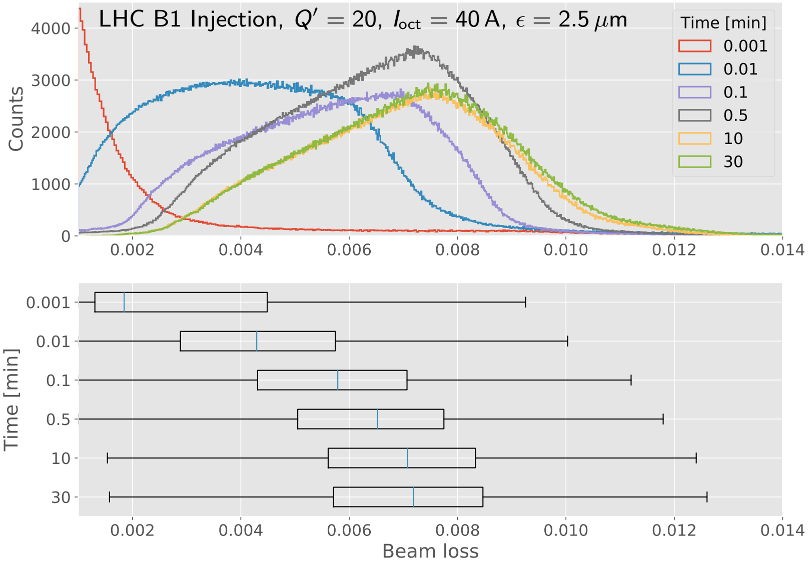
$$\mathcal{L} = \mathcal{L}(\tau | \sigma_1, \sigma_2, A_1, D_\infty, b, \kappa)$$

- Can also include uncertainty from the fitting ΔD_∞, Δb

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

- Assume Gaussian distribution of fit parameters with standard deviation ΔD_∞ etc. around the central value

Loss distribution for different times after injection



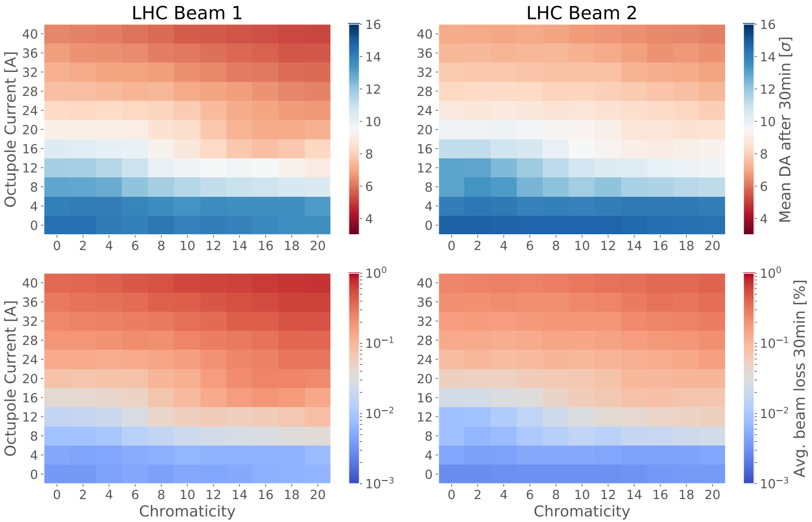
Application to LHC

- 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) :

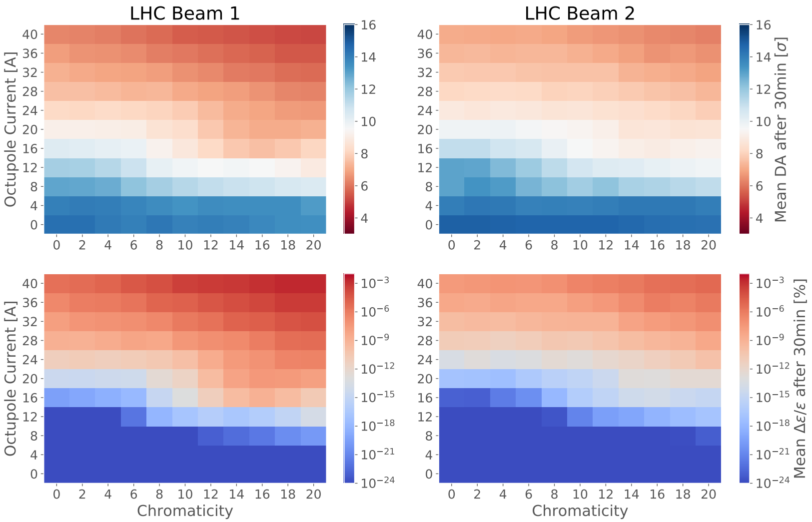
$$\frac{\Delta\epsilon}{\epsilon}(D) = \frac{D^2 \exp\left(-D^2/2\right)}{2\left(1 - \exp\left(-D^2/2\right)\right)} \tag{4}$$

- LHC 2016 optics assuming $\epsilon = 2.5\,\mu$m

Simulation Results

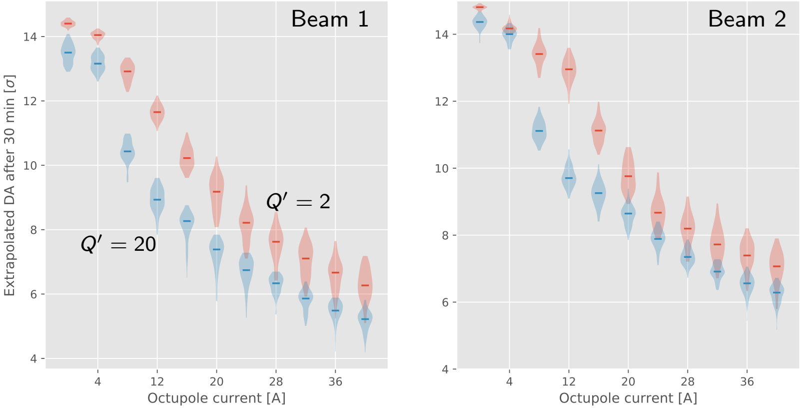


Simulation Results



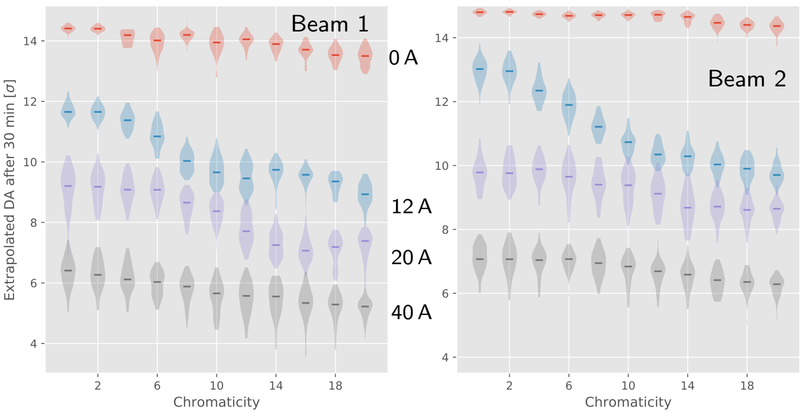
Extrapolated DA from SixTrack simulations

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

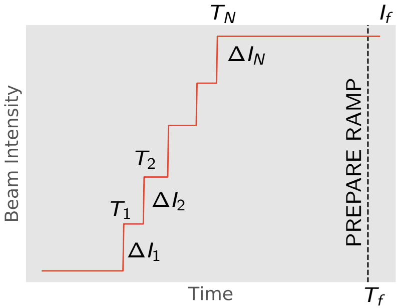


Extrapolated DA from SixTrack simulations

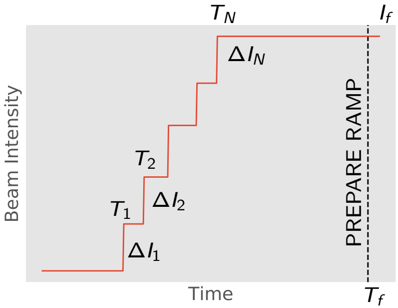
Injection, $\epsilon = 2.5\,\mu$m, distribution over seeds



Calculation of the expected beam loss



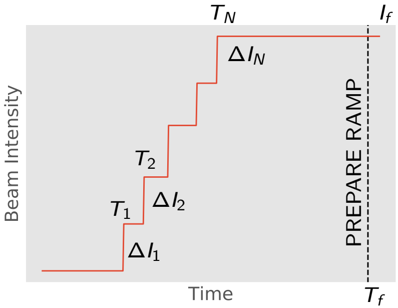
Calculation of the expected beam loss



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

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

Calculation of the expected beam loss



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

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

- 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 $I_{\mathrm{oct}} = 40\,\mathrm{A}$ 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 $I_{\mathrm{oct}} = 40\,\mathrm{A}$ and $16 \leq Q' \leq 20$
- Consider ten realizations of each set (D_{∞}, b, κ) from fit errors $\rightarrow$ 600 extrapolated DA values (with 60 seeds)

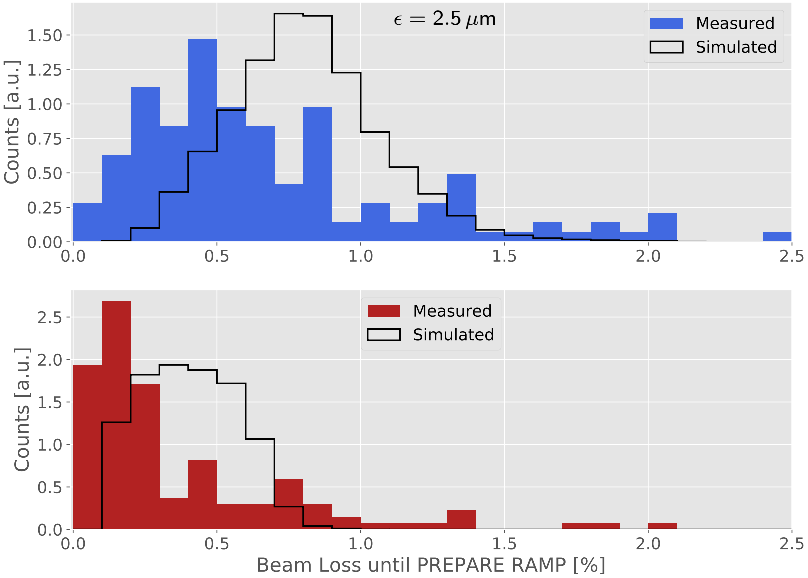
Measured and Simulated Beam Loss

- Analyze all proton fills for physics in 2016
- Compare beam intensity at beginning of PREPARE RAMP with sum of injected bunch intensity
- Baseline : All simulations with $I_{\text{oct}} = 40\,\text{A}$ and $16 \leq Q' \leq 20$
- Consider ten realizations of each set (D_∞, b, κ) from fit errors $\rightarrow$ 600 extrapolated DA values (with 60 seeds)
- Take into account all Double Gaussians from our model (around 4700)

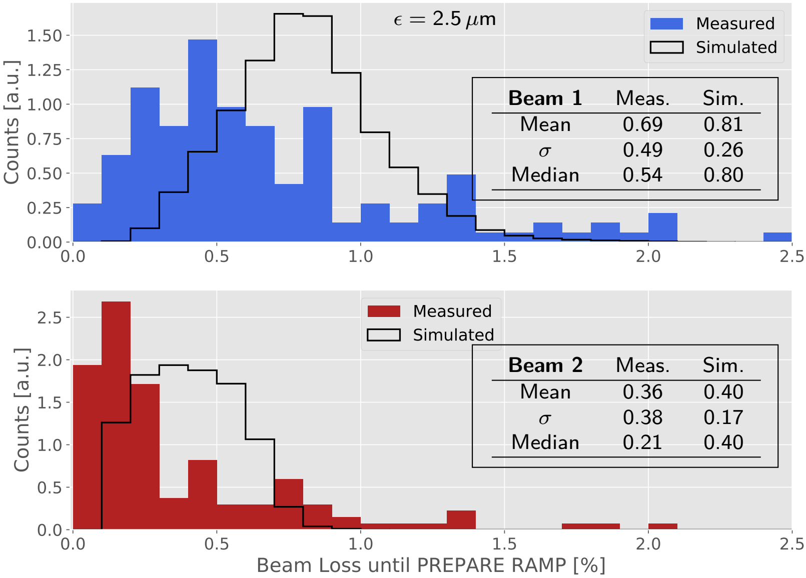
Measured and Simulated Beam Loss

- Analyze all proton fills for physics in 2016
- Compare beam intensity at beginning of PREPARE RAMP with sum of injected bunch intensity
- Baseline : All simulations with $I_{\mathrm{oct}} = 40\,\mathrm{A}$ and $16 \leq Q' \leq 20$
- Consider ten realizations of each set (D_∞, b, κ) from fit errors $\rightarrow$ 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



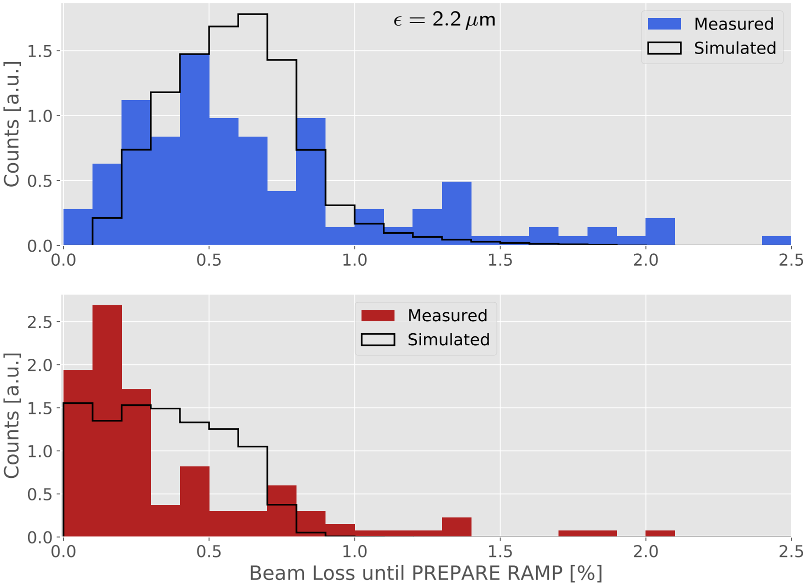
Beam 1	Meas.	Sim.
Mean	0.69	0.81
σ	0.49	0.26
Median	0.54	0.80

Beam 2	Meas.	Sim.
Mean	0.36	0.40
σ	0.38	0.17
Median	0.21	0.40

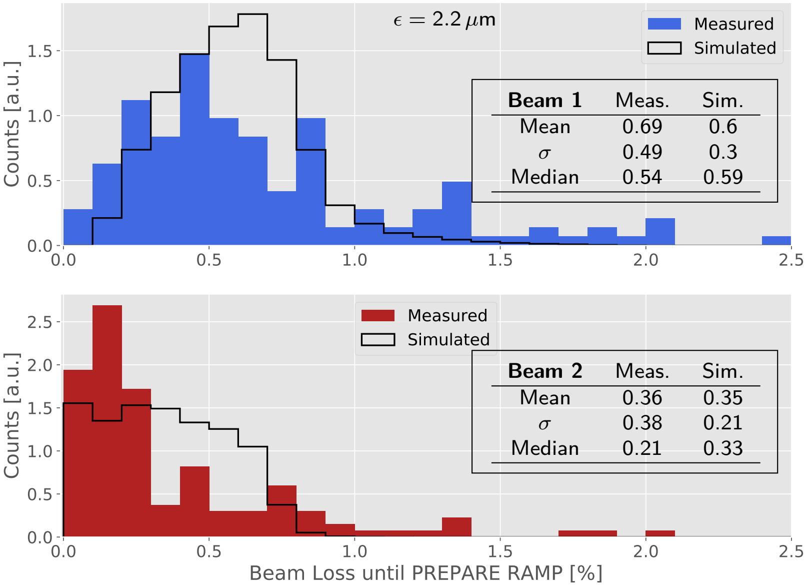
Measured and Simulated Beam Loss

- Simulations made with emittance 2.5 μm, in reality 2.2 μm
- Can we improve the agreement by applying the correct emittance ?

Measured and Simulated Beam Loss



Measured and Simulated Beam Loss

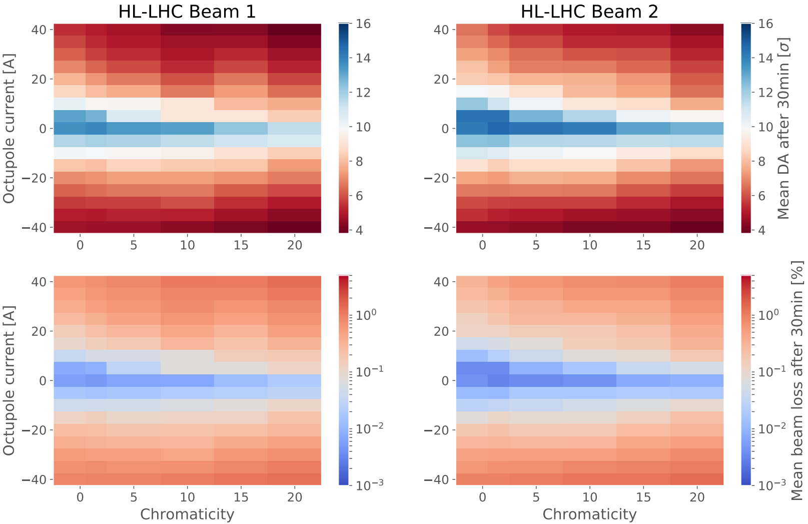


Application to HL-LHC

- 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

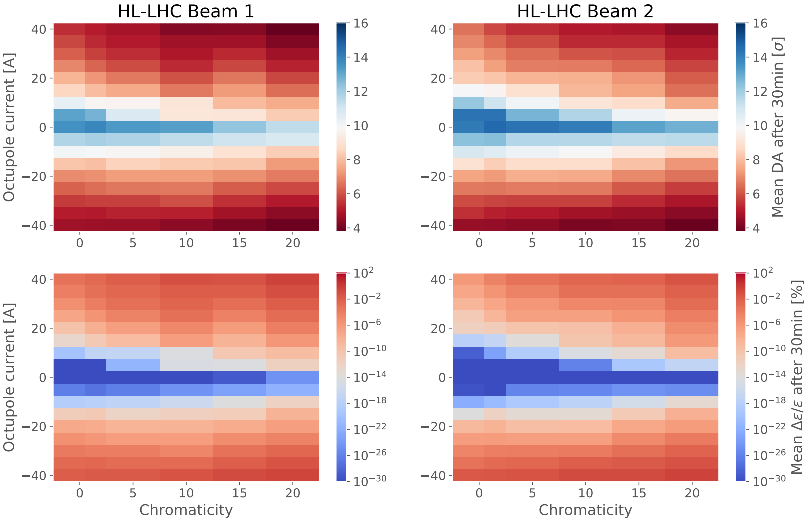
HL-LHC Estimated DA and beam loss after 30 minutes

Scan over chromaticity and octupole current



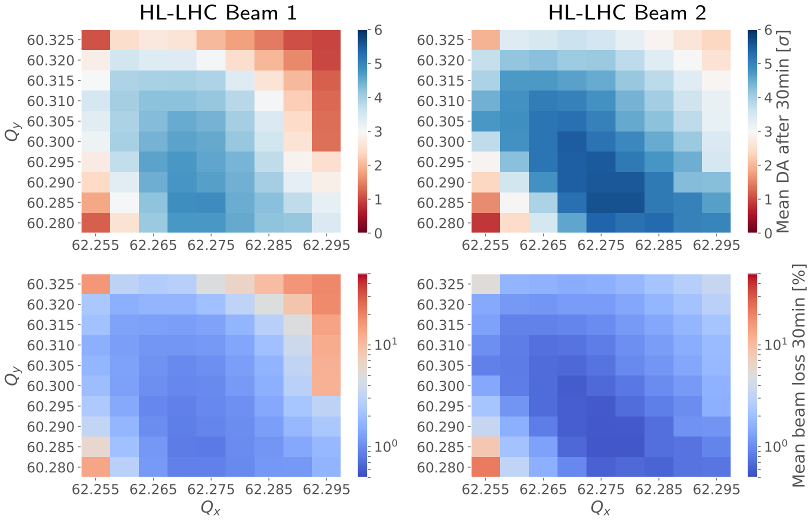
HL-LHC Estimated DA and emittance growth

Scan over chromaticity and octupole current



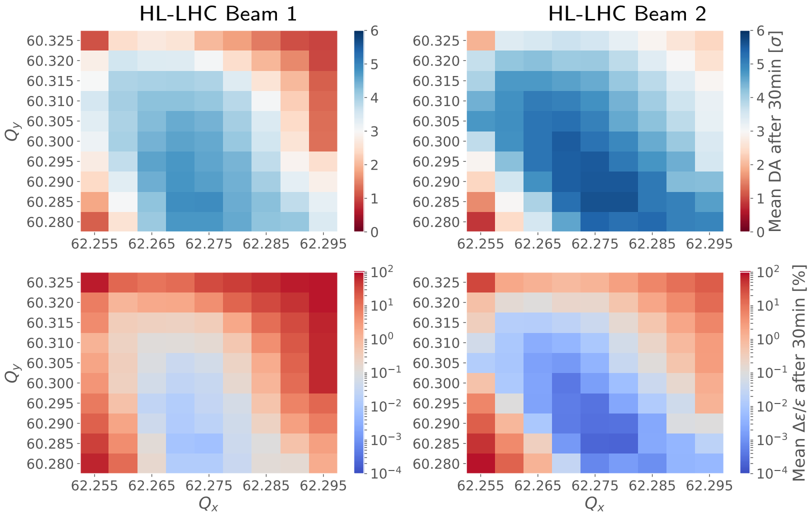
HL-LHC Estimated DA and beam loss after 30 minutes

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



HL-LHC Estimated DA and emittance growth

Tune scan with $Q' = 20$ and $I_{oct} = 40\,\mathrm{A}$



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 $I_{\text{oct}} = 0\,\text{A}$
  - $Q' = 20$ and $I_{\text{oct}} = -40\,\text{A}$
- 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