Studies of PACMAN effects in the HL-LHC

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Outline

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Goals

What?

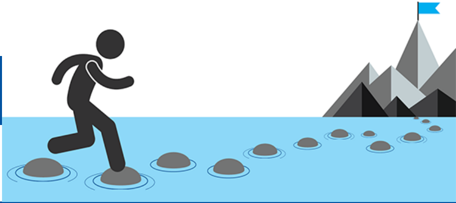
Orbit effects, tune shifts, linear coupling...

Why?

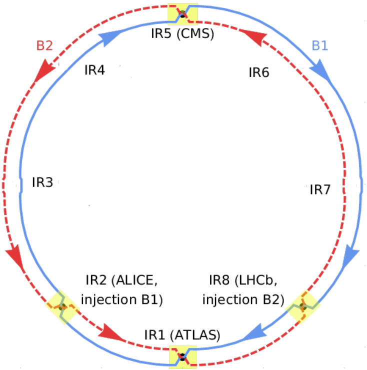
Beam-beam effects may be critical in HL-LHC

How?

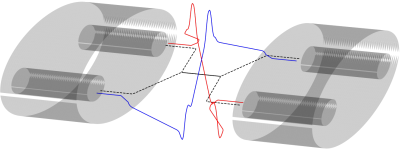
Update of TRAIN



What? Beam-Beam interactions (1/2)



- Beam 1 and beam 2 share common chambers in the **I**nteraction **R**egions
- Electromagnetic interactions
  - **Long range**
  - **Head on**



What? Beam-Beam interactions (2/2)

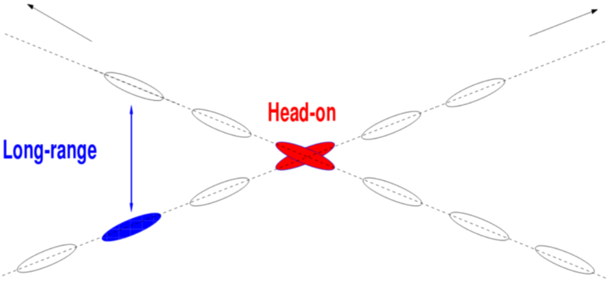
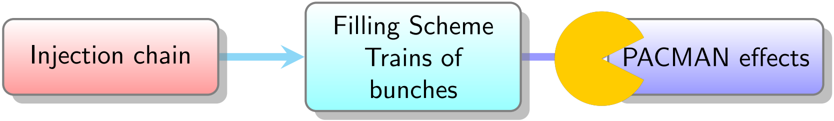


Figure 1: Extracted from [6]

What? PACMAN effects



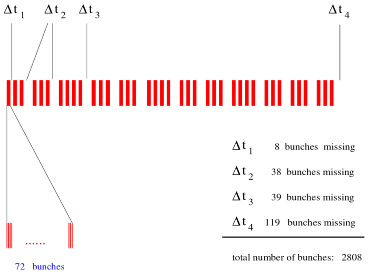


Figure 2: Extracted from [6]

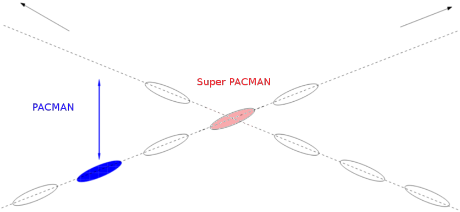


Figure 3: Extracted from [6]

What? Coherent Beam-Beam Effect (1/2)

- The coherent kick felt by a beam's centroid, exerted by a beam with Gaussian distribution of particles

$$\Delta x'_{coh}(x,y) = -\frac{2r_0 N}{\gamma_r}\frac{x}{r^2}\left(1 - e^{-r^2/4\sigma^2}\right), r = \sqrt{x^2+y^2}$$

- If we consider the two beams self-consistently

$$\delta x_1 = \Delta x'_{coh}(d + \delta x_1 + \delta x_2)\beta_1 \cot(\pi Q_1)$$

$$\delta x_2 = \Delta x'_{coh}(d + \delta x_1 + \delta x_2)\beta_2 \cot(\pi Q_2)$$

- If we add trains of bunches the distortion of each bunch have to be computed separately → **Closed orbit problem**

What? Coherent Beam-Beam Effect (2/2)

Closed orbit

First-order fixed point of a non-linear equation of the type $\bar{x}_{k+1} = M_0(\bar{x}_k)$.

Coherent Beam-Beam effect as a closed orbit problem

- In absence of beam-beam interactions

$$\bar{x}_{i,j,k+1} = M_i(\bar{x}_{i,jk}), \quad i = 1, 2, \quad j = 1...N_b$$

- With Beam-Beam interactions $\bar{x}_{i,j,k+1} = M'_{i,j}(\bar{x}_{i,j,k})$

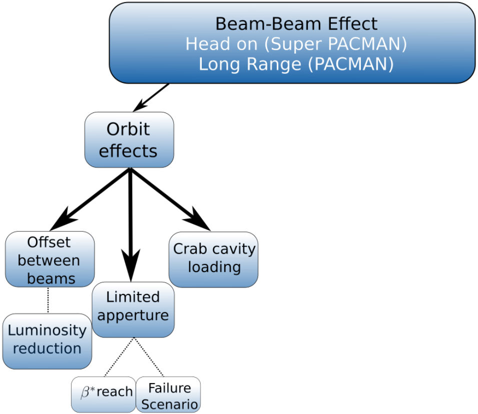
$$M'_{i,j} = \prod_{l}^{N_{BB}} M_{i,l} M^{BB}_{i,j,l}, \quad M^{BB}_{i,j,l} : x'_{i,j} \rightarrow x'_{i,j} + \Delta x'_{coh}(x_{i,j} - x_{S(i,j,l)})$$

Why do we care?

Beam-Beam Effect
Head on (Super PACMAN)
Long Range (PACMAN)

- The existence of a an irregular filling pattern generates PACMAN interactions
- PACMAN effects generate differences from bunch to bunch
- The differences from bunch to bunch cannot be globally corrected

Why do we care?



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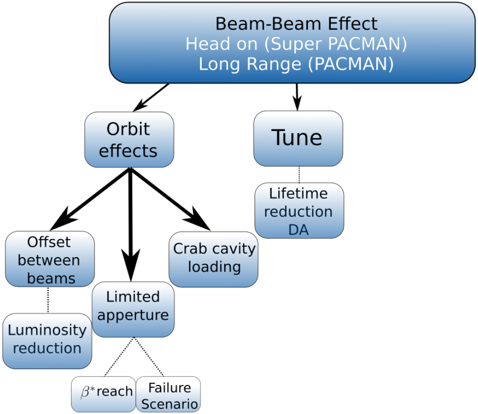

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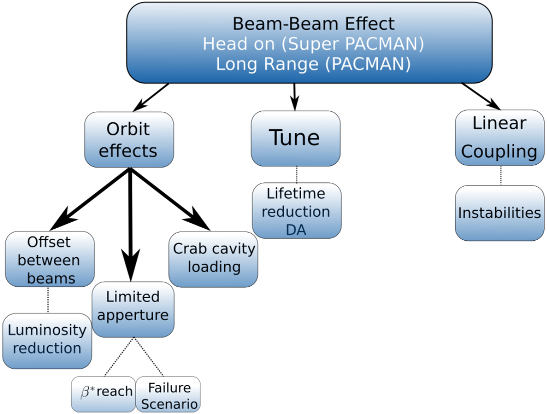

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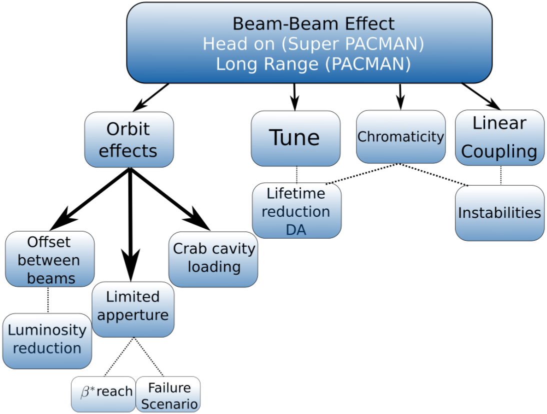


- The existence of a an irregular filling pattern generates PACMAN interactions
- PACMAN effects generate differences from bunch to bunch
- The differences from bunch to bunch cannot be globally corrected

Why don't we care now?

LHC

- Already checked by W. Herr [6] and H.Grote [5]
- Acceptable values of orbit spread, the apertures are not compromised
- The effects on the luminosity are negligible
- Effects on tune, chromaticity and dispersion are small and the shifts can be corrected (although not the spread)

HL-LHC

- Stronger focus of the IP
- Larger beam intensity
- Expected increase of the orbit spread
- Introduction of Crab Cavities
- The dynamical aperture ($\sim 2N_0/d^4_{HL-LHC}$) for the HL-LHC must not be compromised, and since the orbit effect scales like $2N_0/d_{HL-LHC}$, we expect orbit effects 1.7 larger than for LHC.

We need to reevaluate!

How can we study the problem?

Weak-Strong Approach: Without Beam-Beam interactions

- Compute the closed orbit of Beam 1 and Beam 2 with **MAD-X**.

Strong-Strong Self-Consistent Approach: With Beam-Beam interactions

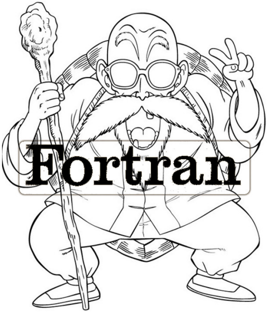
- Compute the closed orbit of Beam 1 and Beam 2 with **MAD-X** (without Beam-Beam interactions).
- Use **TRAIN** on top of **MAD-X** to account for
  - Beam 1 modifies the closed orbit of beam 2
  - Beam 2 modifies the closed orbit of beam 1

Self consistent problem → **TRAIN**

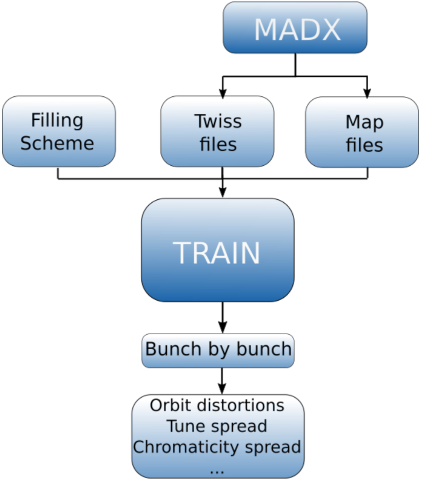
Outline

What is TRAIN? (1/2)

- Multivariate not linear problem
- Self-consistent fixed point problem
- Solves the closed orbit of all bunches with beam-beam interactions
- Set of bash scripts and a Fortran core

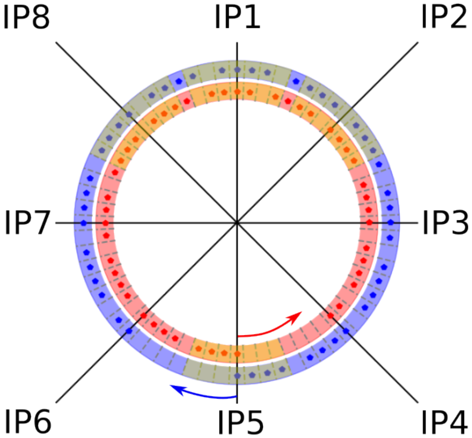


What is TRAIN? (2/2)



How does it work? (1/2)

Assembling of the optical layout and the FS:



- Beam 1
- Beam 2
- Interaction points

How does it work? (2/2)

Solve for 6 coordinates, N bunches, 2 beams and M interaction points.

1. HL-LHC lattice and optic files are prepared for TRAIN
2. The interaction points are marked
3. Identifies the position of all beam-beam encounters, i.e. simulates the collision
4. Initialization of a closed orbit without beam-beam interactions
5. Introduction of beam beam interaction. Double loop iteration:
   - **Inner loop:** Find the closed orbit with fixed beam-beam kicks.
   - **Outer loop:** Update of the bunch positions until the orbit of both beams doesn't change any more.
6. Tracking of every bunch pair with the second order maps in order to find out their tune, chromaticity and dispersion. [5]

Changes in TRAIN

Problems

- LHC
- Fixed number of parasitic encounters without taking into account the length of the common chamber
- Symplecticity issues on the maps
- Not possible to compute coupling and wrong tunes in the presence of coupling
- B2 filling scheme overwritten with B1's (bug)
- Outputs only at IR
- IP5 mandatory a beam-beam interaction point. Rigidity of the code.

Solutions

HL-LHC

Different number of parasitic interactions in different IR

Considering long-range interactions until D2

Check of the symplecticity of the maps

Tunes computed taking into account the linear coupling

Asymmetric Filling Schemes

Possibility of obtaining results on other non IR positions, i.e., crab cavities, triplets, collimators...

Mandatory at least one beam-beam interaction point. Allows to disentangle the effect on different IPs.

Outline

Orbit effects

Bunch-to-bunch effect

- Different effect from bunch to bunch
- There is not a global correction method

Maximum peak-to-peak

- Maximum distance between two bunches in normalized phase space
- Approximated analytical approach

$$\max_s \left(\frac{\Delta x(s)}{\sigma(s)} \right) = \frac{N_{LR} N r_p}{d\epsilon \sin(\pi Q)}$$

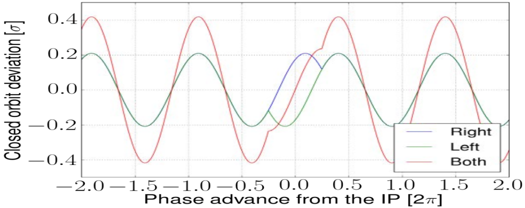


Figure 4: Extracted from [2].

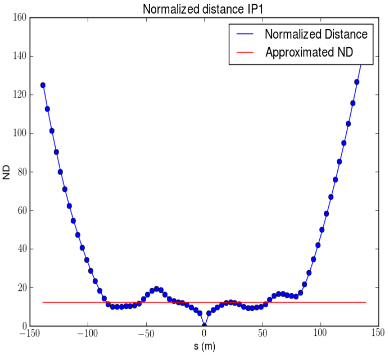
Check, check, check! (1/2)

- Comparison between analytic approach and results of TRAIN (up to D1)
- Approximated analytical approach

$$\Delta x(s) = \frac{N_{LR} N r_p}{d \sin(\pi Q)} \sqrt{\frac{\beta(s)}{\gamma \epsilon}} \sin(\phi(s))$$

with $d = \sqrt{\frac{\beta^* \gamma}{\epsilon}} \theta$.

Assumption: Optical functions are constant!



Check, check, check! (2/2)

Analytical and numerical methods agree within the expected margin. Discrepancies due to assumptions of the analytical approach and the effect of self-consistency.

Example:

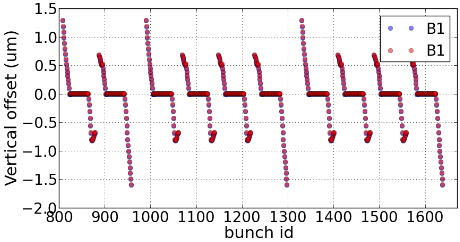


Figure 5: Vertical offset in IP5 during collision with standard Filling Scheme.

	TRAIN (μm)	Δx (μm)
B1	1.085	1.111
B2	1.084	1.110

In all cases, relative error inferior to 20%

Check, check, check! (2/2)

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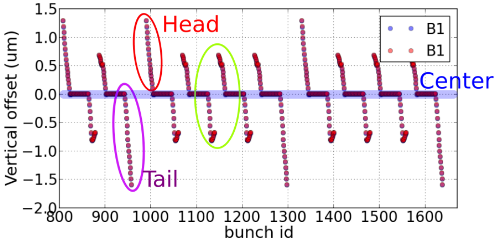

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Peak to peak vs rms

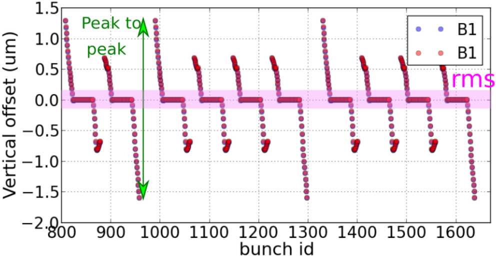


Figure 6: Vertical offset in IP5 during collision with standard Filling Scheme. In green a peak to peak offset of 0.30 μm and a rms of $7{\cdot}10^{-2}$ μm are shown.

- Peak to peak account the worst possible offset between bunches
- Strongest dependence of rms on the Filling Scheme
- With both peak to peak and rms we just take into account the spread of the bunches.

Peak to peak vs rms

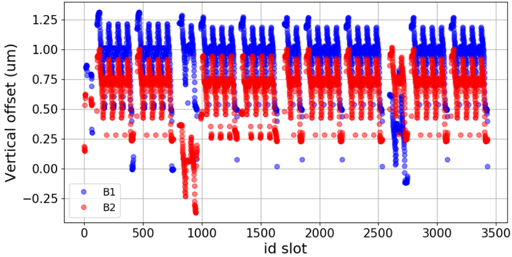


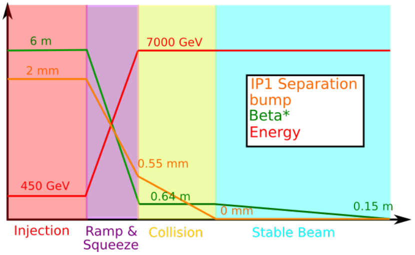
Figure 7: Vertical offset in IP5 during collision with standard Filling Scheme. There is also a collision in IP2.

- Peak to peak account the worst possible offset between bunches
- Strongest dependence of rms on the Filling Scheme
- With both peak to peak and rms we just take into account the spread of the bunches.
- There is also an offset due to the head on interactions.

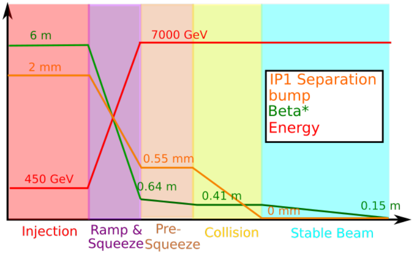
Standard HL-LHC operation cycle

Optic parameters extracted from [1]

Nominal cycle



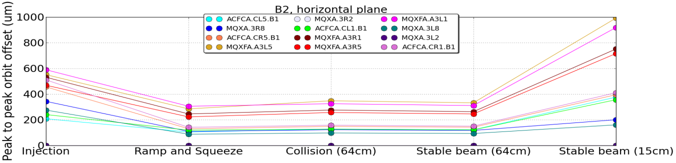
Ultimate cycle



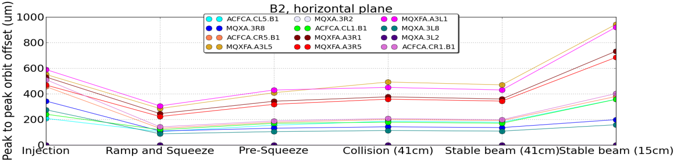
We collapse the separation bump with β^* 64 cm in the nominal scenario and β^* 41 cm in the ultimate one.

Maximum orbit distortion during the Operation Cycle

Nominal scenario



Ultimate scenario

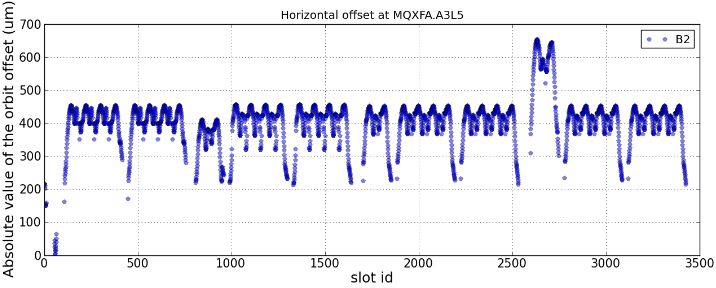


- B2
- H plane
- Standard FS
- The loss of intensity in Stable beam (15 cm) is not taken into account for showing the maximum possible orbit peak to peak shift.

Triplets

- Not possible to estimate the orbit spread in the triplets before.
- Orbit spread up to the order of mm in the worst cases on top of the orbit shift.
- Redefine tolerances for different failure scenarios?

Ultimate scenario



- B2
- H plane
- Standard FS
- Triplet 3 at the left of IP5
- Collision

Triplets

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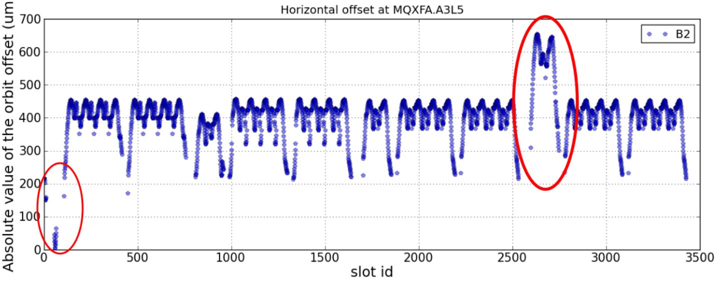
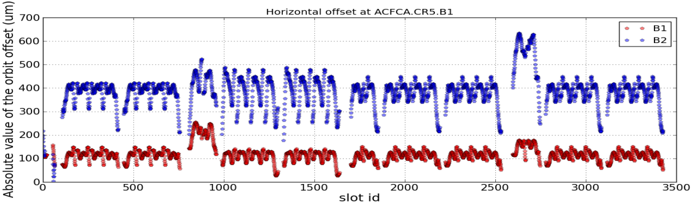
Ultimate scenario



- B2
- H plane
- Standard FS
- Triplet 3 at the left of IP5
- Collision

Crab cavities

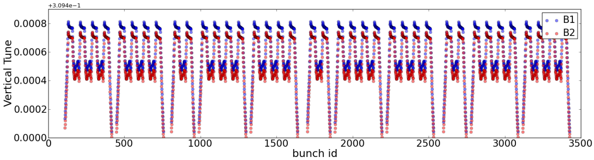
- More precise update with respect to the estimations that were provided to BE-RF for the HL-LHC collaboration meeting in Madrid (at the time it was not possible to estimate the orbit effects in the crab cavities).
- The results obtained match the first estimation. Now we have a more precise tool to estimate the orbit effects, although the order of magnitude of the effect should not have an impact on the Crab cavities.



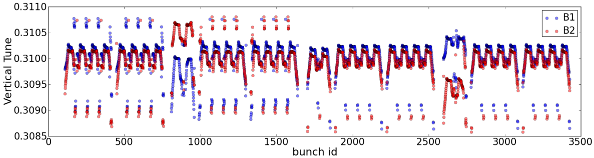
Outline

Tune shift

IP1 and IP5



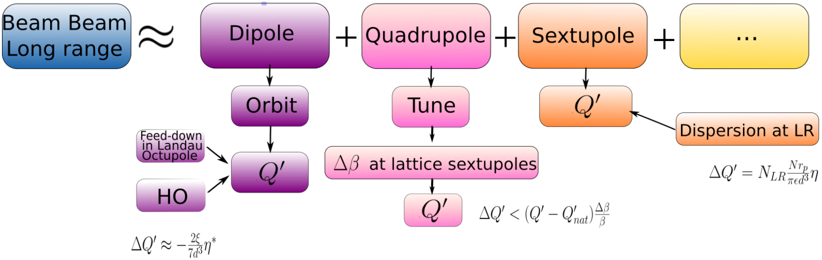
IP1, IP2, IP5 and IP8



- This effect must be taken into account.
- We can provide an estimation of the order of magnitude of Beam-Beam effects on the tune shift
- Other codes exist for evaluating the DA → SixTrack

Chromaticity shifts (1/3)

The Chromaticity shift and offset have several contributions due to the non-linearity of the beam-beam force, that can be decomposed in a dipolar component, quadrupolar component...



Observing the Chromaticity shifts before and during collision we will identify the dominant cause generating the offset and the shift.

Chromaicity shifts (2/3)

Before collision

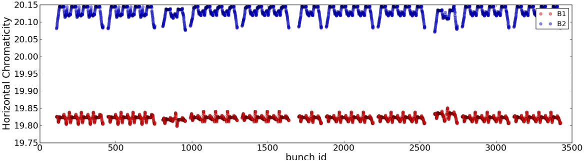


Figure 8: Standard FS, end of ramp and squeeze.

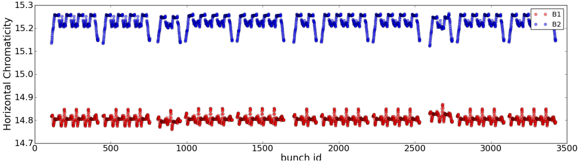


Figure 9: Standard FS, presqueeze (41 cm).

- Nominal chromaticity for end of ramp and squeeze $Q'_n = 20$.
- Nominal chromaticity for end of presqueeze $Q'_n = 15$.
- Comes from the dispersion at the location of the long range.
- The shifts are consistent with the contribution of beta beating at the sextupoles.
- Critical for beam stability due to the small tune spread.
- In order to control instabilities we need a control of 1-2 units of chromaticity.
- Acceptable values of the spread (less than 2 units).

Chromaicity shifts (3/3)

In collision

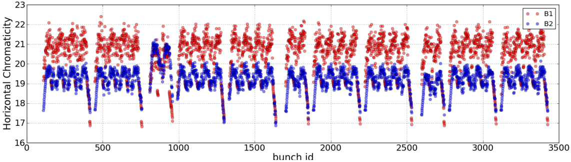


Figure 10: Standard FS, nominal collision.

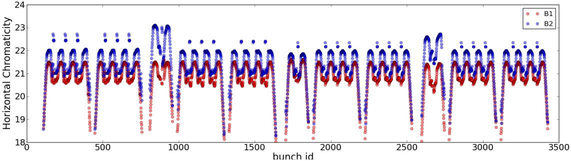


Figure 11: Standard FS, ultimate collision (41 cm).

- Nominal chromaticity for nominal collision (64 cm) $Q'_n = 15$.
- Nominal chromaticity for ultimate collision (41 cm) $Q'_n = 15$.
- Both the offset and the shift in chromaticity come from the head-on interaction of both beams plus the offset existing in the interaction point.
- Big Landau damping.
- The chromaticity spread is less problematic for instabilities but may compromise the beam lifetime.
- In collision we can have a chromaticity shift of several units.
- We can recorrect the offset.
- The spread is left.

Octupole PACMAN feed-down

- We can quantify the effect of the existence of an offset in the octupoles in the chromaticity due to the feed-down effect.
- We evaluate the absolute difference of the maximum chromaticity spread with respect to the chromaticity without the effect of the offset in the octupoles.
- The effect of the PACMAN feed-down is negligible.
- Some discrepancies between configurations.

	Ramp and squeeze 10^{-5}		Collision (41 cm) 10^{-5}	
	H	V	H	V
B1	1.77	1.40	0.37	5.93
B2	0.54	0.88	2.57	13.25

Table 1: Chromaticity shift increase in the presence of octupoles during the end of ramp and squeeze and ultimate collision with the standard filling scheme.

Outline

Minimum tune approach

Minimum tune approach

The minimum tune approach, defined as

$$\Delta Q_{min} = |Q_x - Q_y|_{min}$$

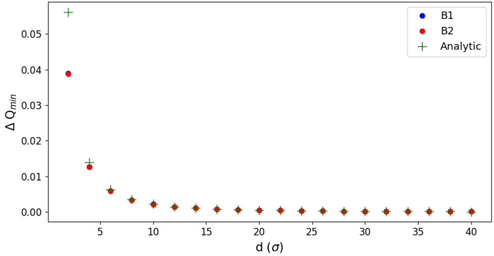
is used for estimating the global linear coupling.

- $\Delta Q_{min} = 0$ indicates that there is no linear coupling.
- Linear coupling is generated by beam-beam interaction with a transverse offset in both transverse planes.
- May be originated by the presence of skew quadrupoles in the lattice.
- Coupling was identified as a cause for loss of Landau damping → major concern before collision!

Linear coupling: Benchmark

Minimum tune approach in TRAIN vs linear coupling strength

- Single skew quadrupole at IP5.
- The analytic approach is expected to break at small separation (long-range approximation).
- $N = 4.6 \cdot 10^{12}$



The approximated analytical linear coupling strength can be derived following [3]

$$k = 2\frac{r_0 N}{\pi \epsilon} \sum_{i}^{N_{LR}} \frac{\sin(\alpha_i)\cos(\alpha_i)}{d_i^2}$$

Outline

Conclusions

- The modifications made in TRAIN allow now to estimate the orbit spread in different points of the accelerator.
- We can confirm the first estimates that were provided for the Crab Cavities.
- The orbit spread in the Triplets is significant and comparable to the order of magnitude of their tolerance when added to the orbit offset.
  - How does it affect the failure scenario?
- The spread in chromaticity before collision has been checked to be acceptable.
- The PACMAN Octupole feed-down effect seems to be negligible.
- We have implemented the linear coupling in TRAIN and benchmarked it against the analytical formula. We will study the effect of linear coupling due to misalignments in the IR. We will compare these results in an MD at the beginning of August. Linear coupling have been observed but never measured.

Thank you very much for your attention!

Minimum tune approach (1/2)

Minimum tune approach from the one-turn map

- In the presence of coupling the 2×2 off-diagonal block matrices are different from 0 and the one-turn map can be written

$$M = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

- The minimum tune approach is derived from the N-turn map in [4] as

$$\Delta Q_{min} = \frac{\sqrt{det|C + \bar{B}|}}{\pi(\sin\mu_A + \sin\mu_D)}$$

$$\bar{R} = -SR^T S, \quad S = \begin{pmatrix} S_2 & & \\ & S_2 & \\ & & \ddots \end{pmatrix}, \quad S_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Minimum tune approach (2/2)

- The computation of the linear coupling in stable motion, that includes finding the eigentunes $\mu_{A,D} = 2\pi Q_{A,D}$, consists of finding some similarity R_M that transforms the one-turn map into its normal form $M_\perp$, defined as

$$M_\perp = g^2 \bar{R}_M M R_M = \begin{pmatrix} E & 0 \\ 0 & F \end{pmatrix} \quad R_M = \begin{pmatrix} \mathbb{I} & \bar{R} \\ -R & \mathbb{I} \end{pmatrix}$$

$$R = -(\frac{1}{2}(\mathrm{Tr}A - \mathrm{Tr}D) + \frac{1}{2} sign(\mathrm{Tr}A - \mathrm{Tr}D)\sqrt{\Delta})^{-1}(C + \bar{B})$$

$$\Delta = (\mathrm{Tr}A + \mathrm{Tr}D)^2 + 4|C + \bar{B}|, \quad g = (1 + |R|)^{-\frac{1}{2}}$$

- Compute the Twiss parameters from the normal form of the one-turn map

$$E = \begin{pmatrix} E_{1,1} & E_{1,2} \\ E_{2,1} & E_{2,2} \end{pmatrix} = \begin{pmatrix} \cos\mu_A + \alpha_A \sin\mu_A & \beta_A \sin\mu_A \\ -\gamma_A \sin\mu_A & \cos\mu_A - \alpha_A \sin\mu_A \end{pmatrix}$$

Linear coupling

From the expression of the beam-beam kick for round beams $\Delta x'_{coh}$

$$\frac{\partial \Delta x'}{\partial y}(x = d\cos(\alpha), y = d\sin(\alpha)) \approx 4\frac{r_0 N}{\gamma}\frac{\sin(\alpha)\cos(\alpha)}{d^2}$$

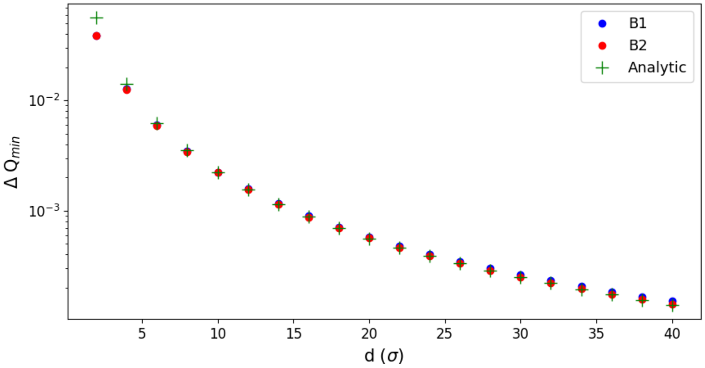
the linear coupling strength can be derived following [3]

$$k = 2\frac{r_0 N}{\pi\epsilon}\sum_{i}^{N_{LR}}\frac{\sin(\alpha_i)\cos(\alpha_i)}{d_i^2}$$

This approximate prediction of the linear coupling can be used in order to evaluate the goodness of the minimum tune approach implemented in TRAIN.

Linear coupling: Benchmark

In logarithmic scale



Outline

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