Crab Cavity Field Quality and its implication for HL-LHC

Emilia Cruz Alaniz

WP2 Meeting

July 2nd, 2019
Motivation

- Very compact design causes non-axial symmetry in the crab cavities which results in high order multipoles to be present in the crab cavities
- Higher order multipoles are expected to impact beam dynamics
- Perform dynamic aperture studies to analyze this impact
- How big are the RF multipoles? Do they affect the DA? What are the tolerances?
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- TDR, P. Baudrenghien et al: *Functional Specifications of the LHC Prototype Crab Cavity System*
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- Specifications for 4 different crab cavity models

- DA studies done for the 4RCAV, using the Lorentz method values at 10 mm:
  - $b_2 = 0.06$
  - $b_3 = 1159$
  - $b_4 = -4$

<table>
<thead>
<tr>
<th></th>
<th>Lorentz method</th>
<th>Panofsky-Wenzel</th>
<th>Helmholtz decomposition @20 mm</th>
</tr>
</thead>
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<tr>
<td></td>
<td>@10 mm</td>
<td>@20 mm</td>
<td>@10 mm @20 mm</td>
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<tr>
<td>4RCAV 2012</td>
<td>$b_2$ = -0.06</td>
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<tr>
<td></td>
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<td>$b_4$ = -4</td>
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<td>$b_3$ = 4511</td>
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<td>$b_4$ = -4</td>
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<td>QWCAV 2011</td>
<td>$b_2$ = 111.42</td>
<td>111.40</td>
<td>111.43</td>
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<tr>
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<td>$b_3$ = 1266</td>
<td>1267</td>
<td>1257</td>
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<td>$b_4$ = 1776</td>
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<td></td>
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<td>1401</td>
<td>1836</td>
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<td>QWCAV 2012</td>
<td>$b_2$ = 0.29</td>
<td>0.29</td>
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<tr>
<td></td>
<td>$b_3$ = 1074</td>
<td>1073</td>
<td>1078</td>
</tr>
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<td></td>
<td>$b_4$ = 50</td>
<td>67</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>64</td>
<td>22</td>
</tr>
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Previous Studies

- Extensive DA studies done by J. Barranco et al: *Long term dynamics of the high luminosity Large Hadron Collider with crab cavities*

  - Specifications for 4 different crab cavity models
  - DA studies done for the 4RCAV, using the Lorentz method values at 10 mm:
    - $b_2 = 0.06$
    - $b_3 = 1159$
    - $b_4 = -4$
  - Results:
    - Drop more obvious for the $b_2$, outside specification for QWcav 2011 design
    - $b_3$ slowly decreasing
    - $b_4$ very stable
Previous Studies

- TDR and P. Baudrenghien et al: *Functional Specifications of the LHCPrototype Crab Cavity System*

The quadrupolar component $b_2$ is zero in the case of perfect symmetry; due to fabrication errors and ancillary components it is non-zero – it must be smaller than 10 units leading to a tune shift in the order of $\Delta Q \approx 10^{-4}$. The first systematic multipole is the sextupolar component, $b_3$. Long-term simulations with the optical functions of the HL-LHC indicate that the $b_3$ component should be limited to approximately 1000 ±10% units, which results in an acceptable degradation of the dynamic aperture below 1 $\sigma$ for orbit offsets of 1.5 mm [13]. Both the DQW and the RFD conform are below the specified tolerance for $b_3$. No specifications are yet provided for higher order terms, but it is expected that they can be controlled to smaller values than the neighbouring D2 dipole magnet.

For $n \geq 4$, assuming a very approximate scaling of the additional kick from an orbit offset via $b_n$, the $b_n$ must be kept below $\propto O(10^n)$. Better estimates are pending; results from long-term tracking are needed to confirm the exact specifications.

<table>
<thead>
<tr>
<th></th>
<th>MBRC</th>
<th>Double Ridge</th>
<th>Quarter Wave</th>
<th>UK-4Rod</th>
</tr>
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<tbody>
<tr>
<td>$b_2$</td>
<td>55</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$b_3$</td>
<td>7510</td>
<td>4500</td>
<td>1070</td>
<td>1162</td>
</tr>
<tr>
<td>$b_4$</td>
<td>82700</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$b_5$</td>
<td>$2.9 \times 10^6$</td>
<td>$0.4 \times 10^6$</td>
<td>$-0.1 \times 10^6$</td>
<td>$2.29 \times 10^6$</td>
</tr>
<tr>
<td>$b_6$</td>
<td>$5.2 \times 10^7$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$b_7$</td>
<td>$5.6 \times 10^8$</td>
<td>$3 \times 10^8$</td>
<td>$7 \times 10^8$</td>
<td>$6.38 \times 10^8$</td>
</tr>
</tbody>
</table>

Table 3: Multipole components of the three cavity prototypes

- Long tracking simulations for case with $b_3=4500$.
- A reduction of the $b_3$ multipolar by a factor of 3 (to $\sim 1000$) is recommended to relax the orbit tolerance to $>1$mm
- For $n \geq 4$ values should be kept below $10^n$
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<table>
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<tr>
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<tr>
<td>55</td>
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<tr>
<td>0</td>
<td>4500</td>
<td>0</td>
<td>0.4x10^6</td>
<td>3x10^8</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1070</td>
<td>0</td>
<td>-0.1x10^6</td>
<td>0</td>
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Updates on RF mult

New numbers from Rama and Jamie for the DQW measure directly from the cavity (Rama’s talk)

<table>
<thead>
<tr>
<th>SPS DQW (Dressed)</th>
<th>b1</th>
<th>b2</th>
<th>b3</th>
<th>b4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>33</td>
<td>6</td>
<td>1498</td>
<td>1026</td>
</tr>
<tr>
<td>Im</td>
<td>0</td>
<td>-2</td>
<td>19</td>
<td>-383</td>
</tr>
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<table>
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<tr>
<th>LHC DQW (Dressed)</th>
<th>b1</th>
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<tbody>
<tr>
<td>Re</td>
<td>33</td>
<td>6</td>
<td>1488</td>
<td>1048</td>
</tr>
<tr>
<td>Im</td>
<td>0</td>
<td>-2</td>
<td>21</td>
<td>-292</td>
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<table>
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<tr>
<th>LHC RFD (Dressed)</th>
<th>b1</th>
<th>b2</th>
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<th>b4</th>
</tr>
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<tbody>
<tr>
<td>Re</td>
<td>34</td>
<td>0</td>
<td>-458</td>
<td>128</td>
</tr>
<tr>
<td>Im</td>
<td>0</td>
<td>0</td>
<td>-74</td>
<td>55</td>
</tr>
</tbody>
</table>

Evaluation of \( b_n \) in units of \( mTm/m^{m-1} \). Values correspond to a transverse deflecting voltage of 10 MV and are evaluated with 64 points around the azimuth at a radius of 30 mm.

Calculated using the Panofsky-Wenzel method.
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<td>55</td>
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- Numbers from b2 and b4 are significant different from the ones used for Javier’s studies:
  - b2: 0.06 -> 6
  - b4: -4 -> 1498

- Besides b3 is over 1498, above the 1000 units specified as limit for the 1mm missalignment tolerance

- Repeat DA studies to study the impact

Evaluation of bn in units of mTm/m^{m-1}. Values correspond to a transverse deflecting voltage of 10 MV and are evaluated with 64 points around the azimuth at a radius of 30 mm

Calculated using the Panofsky-Wenzel method
RF multipoles implementation

- RF multipole available on MADX and SixTrack
- Implement RF multipoles in each crab cavity in IR1 and IR5
- Issues
RF multipoles implementation

- RF multipole available on MADX and SixTrack
  - Similar to magnetic kicks but these are position-dependent and have frequency

\[
\Delta p_x = - \frac{\partial H}{\partial x} = - \sum_{n=0}^{N} \frac{1}{n!} \Re \left[ (K_{N,n} L \cos (\varphi_n - k_{RF}z) + iK_{S,n} L \cos (\varphi_n - k_{RF}z)) (x + iy)^n \right],
\]

\[
\Delta p_y = - \frac{\partial H}{\partial y} = \sum_{n=0}^{N} \frac{1}{n!} \Im \left[ (K_{N,n} L \cos (\varphi_n - k_{RF}z) + iK_{S,n} L \cos (\varphi_n - k_{RF}z)) (x + iy)^n \right],
\]

\[
\Delta p_t = - \frac{\partial H}{\partial z} = \frac{qV_{RF}}{p_sc} \sin (\varphi_{RF} - k_{RF}z) - k_{RF} \sum_{n=0}^{N} \frac{1}{(n+1)!} \Re \left[ (K_{N,n} L \sin (\varphi_n - k_{RF}z) + iK_{S,n} L \sin (\varphi_n - k_{RF}z)) (x + iy)^{n+1} \right]
\]

- Implement RF multipoles in each crab cavity in IR1 and IR5

- Issues
RF multipoles implementation

- RF multipole available on MADX and SixTrack
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\[
\begin{align*}
\Delta x' &= -\frac{b_2}{B \rho} x \cos \left( \frac{aoz}{c} + \phi_s + \phi_{RF,quad} \right) \\
\Delta y' &= \frac{b_2}{B \rho} y \cos \left( \frac{aoz}{c} + \phi_s + \phi_{RF,quad} \right) \\
\Delta \delta &= \frac{1}{2} \frac{b_2}{B \rho} (x^2 - y^2) \sin \left( \frac{aoz}{c} + \phi_s + \phi_{RF,quad} \right) \frac{ao}{c}
\end{align*}
\]

Normal sextupole
\[
\begin{align*}
\Delta x' &= -\frac{b_3}{B \rho} (x^2 - y^2) \cos \left( \frac{aoz}{c} + \phi_s + \phi_{RF,sext} \right) \\
\Delta y' &= \frac{b_3}{B \rho} xy \cos \left( \frac{aoz}{c} + \phi_s + \phi_{RF,sext} \right) \\
\Delta \delta &= \frac{1}{3} \frac{b_3}{B \rho} (x^3 - 3xy^2) \sin \left( \frac{aoz}{c} + \phi_s + \phi_{RF,sext} \right) \frac{ao}{c}
\end{align*}
\]

Normal octupole
\[
\begin{align*}
\Delta x' &= -\frac{b_4}{B \rho} (x^3 - 3xy^2) \cos \left( \frac{aoz}{c} + \phi_s + \phi_{RF,oct} \right) \\
\Delta y' &= \frac{b_4}{B \rho} (3x^2 y - y^3) \cos \left( \frac{aoz}{c} + \phi_s + \phi_{RF,oct} \right) \\
\Delta \delta &= \frac{1}{4} \frac{b_4}{B \rho} (x^4 - 6x^2y^2 + y^4) \sin \left( \frac{aoz}{c} + \phi_s + \phi_{RF,oct} \right) \frac{ao}{c}
\end{align*}
\]

Skew sextupole
\[
\begin{align*}
\Delta x' &= -2 \frac{b_3}{B \rho} xy \cos \left( \frac{aoz}{c} + \phi_s + \phi_{RF,sext} \right) \\
\Delta y' &= \frac{b_3}{B \rho} (y^3 - x^3) \cos \left( \frac{aoz}{c} + \phi_s + \phi_{RF,sext} \right) \\
\Delta \delta &= -\frac{1}{3} \frac{b_3}{B \rho} (y^3 - 3yxy^2) \sin \left( \frac{aoz}{c} + \phi_s + \phi_{RF,sext} \right) \frac{ao}{c}
\end{align*}
\]

- Implement RF multipoles in each crab cavity in IR1 and IR5

- Issues

J. Barranco, A. Latina, R. Tomas, R. de Maria
RF multipoles implementation

- RF multipole available on MADX and SixTrack
  - Similar to magnetic kicks but these are position-dependent and have frequency
  - In new version of MADX they can all be implemented in the same element, RFmult values now in fort.3.mad

MULT.A5 : rfmultipole, FREQ = 400, KNL:={0.0,knlb2,knlb3,knlb4}, PNL={0.0,0.25,0.25,0.25};
MULT.B5 : rfmultipole, FREQ = 400, KNL:={0.0,knlb2,knlb3,knlb4}, PNL={0.0,0.25,0.25,0.25};

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- **Implement RF multipoles in each crab cavity in IR1 and IR5**
  - \{b2, b3, b4\} in IR5 with horizontal crab cavity
  - \{-b2, a3, b4\} in IR1 with vertical crab cavity (rotation 90 degrees)
  - Phase \(\pi/2\). Zero transverse kick at middle of crab cavity

- Issues
**RF multipoles implementation**

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- Implement RF multipoles in each crab cavity in IR1 and IR5
  - \{b2, b3, b4\} in IR5 with horizontal crab cavity
  - \{-b2, a3, b4\} in IR1 with vertical crab cavity (rotation 90 degrees)
  - Phase $\pi/2$. Zero transverse kick at middle of crab cavity

- **Issues**
  - MADX failed with phase $\pi/2$: Must be activated after turning on normal RF, otherwise MADX fails
  - Problems with declaring elements with variables
  - Misalignments: use newer version of MADX in conversion to avoid incongruence between fort.2 and fort.8
    - Check fort.2, fort.8 and fort.3.mad to check everything is set up correctly and thanks to the Sixtrack and MADX team to help me solved them!
DA at collision + CC + RF multipoles

Assumptions: $10^5$ turns, 5 angles, 60 seeds, 6D

- Min DA over 60 seeds with VH crossing and with crab cavities voltage set to 0.0
  - $\text{DA} \sim 11\,\sigma$
DA at collision + CC + RF multipoles

Assumptions: $10^5$ turns, 5 angles, 60 seeds, 6D

- Min DA over 60 seeds with VH crossing and with crab cavities voltage set to 0.0
  - $\text{DA} \sim 11\sigma$

- Added corresponding voltage in crab cavities: ~3.4 V left and right for vertical cc in IR1 and horizontal in IR5
  - No significant effect
**DA at collision + CC + RF multipoles**

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  - $DA \sim 11\sigma$
- Added corresponding voltage in crab cavities: $\sim 3.4$ V left and right for vertical cc in IR1 and horizontal in IR5
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- Added nominal RF multipoles from Jamie’s updated values
  - Changes some values but min DA stays the same
DA at collision + CC + RF multipoles

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When does it become a problem?
- Measure tolerances in multipole values and/or alignments
Limits on b2

Increasing values of b2 until it DA goes down. Original value: 6 mTm/m-1

- Increase values up to 100xb2 (600 mTm/m^(-1)) and DA stayed the same
  - DA ~ 11 σ
- Really stable
- b2 positive in IR5 but negative in IR1, is that the cause?
Limits on b2

Increasing values of b2 until it DA goes down. Original value: 6 mTm/m-1

- Increase values up to 100xb2 (600 mTm/m^-1) and DA stayed the same
  - DA ~ 11σ
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- b2 positive in IR5 but negative in IR1, is that the cause?
- Change value in IR1 to positive.
- DA goes lower much faster. Limit around 100 mTm/m-2
Limits on $b_2$

Increasing values of $b_2$ until it DA goes down. Original value: 6 mTm/m$^{-1}$

- Increase values up to 100$x b_2$ (600 mTm/m$^{-1}$) and DA stayed the same
  - $DA \sim 11 \sigma$
- Really stable
- $b_2$ positive in IR5 but negative in IR1, is that the cause?
- Change value in IR1 to positive.
- DA goes lower much faster. Limit around 100 mTm/m$^{-1}$

© seems to mainly be because of cancelling between IR1 and IR5
Careful for cases when $pos/neg$ is not the case: vv/hh crossing, different sign on other cc
Limits on $b_3$

Increasing values of $b_3$ until it DA goes down. Original value: 1488 mTm/m$^2$.

- Increase values up to 100xb3 (148,800 mTm/m$^2$).
- Big drop around 50xb3, after that more steady decrease.
- Limit found around 74,400 mTm/m$^2$.
- Very high, probably safe.
Limits on b3

Increasing values of b3 until it DA goes down. Original value: 1488 mTm/m^2

- Increase values up to 100xb3 (148,800 mTm/m^-2)
- Big drop around 50xb3, after that more steady decrease
- Limit found around 74,400 mTm/m-2
- Very high, probably safe

- Limit for case b3 was more well defined but still far away from the design
Limits on $b_4$

Increasing values of $b_4$ until it $DA$ goes down. Original value: $1048 \text{ mTm/m}^3$

- Increase values up to $200xb_4$ (209,600 mTm/m$^3$)
- Start to seeing decrease but until the very end:
  - Loss of $0.5 \sigma \sim 200,00 \text{ mTm/m}^3$
Limits on $b_4$

Increasing values of $b_4$ until it $DA$ goes down. Original value: 1048 mTm/m^3

- Increase values up to 200$x b_4$ (209,600 mTm/m-3)
- Start to seeing decrease but until the very end:
  - Loss of 0.5 $\sigma \sim 200,00$ mTm/m-3

- Found small impact of $b_4$ but only for very high values
- Probably safe increase for this case
Misalignment effects

Studies with original b2, b3, b4 values and different misalignments.

Studies presented in HL meeting by M. Sosin “Accuracy of absolute position of Crab-cavities inside cryomodule : +/- 50 μm”

I assumed crab cavity with respect to the tunnel between 0.5mm-2mm
Misalignment effects

Studies with original b2, b3, b4 values and different misalignments

- For original values there's an effect on misalignment but min DA stays around 11σ
Misalignment effects

Studies with original b2, b3, b4 values and different misalignments. Misalignments in crab cavities but not in RF multipoles (fixed problem now and running)

- For original values there's an effect on misalignment but min DA stays around $11\sigma$
- From 10-50x for all bn DA drops $2\sigma$ but stays around the same value ($\sim 9\sigma$)
Misalignment effects

Studies with original b2, b3, b4 values and different misalignments

- For original values there’s an effect on misalignment but min DA stays around $11\sigma$
- From 10-50x for all bn DA drops $2\sigma$ but stays around the same value ($\sim 9\sigma$)
Misalignment effects

Studies with original b2, b3, b4 values and different misalignments

- For original values there’s an effect on misalignment but min DA stays around 11σ
- From 10-50x for all bn DA drops 2σ but stays around the same value (~9σ)
- When misalignment meets (0 misalignment) limit drops accordingly (7σ->5σ)
Misalignment effects

Studies with original b2, b3, b4 values and different misalignments

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- Perhaps more interestingly is the zone when the two initial sigma drops for each bn
Misalignment effects

Studies with original b2, b3, b4 values and different misalignments

- For original values there’s an effect on misalignment but min DA stays around $11\sigma$
- From 10-50x for all bn DA drops $2\sigma$ but stays around the same value ($\sim 9\sigma$)
- When misalignment meets (0 misalignment) limit drops accordingly ($7\sigma \rightarrow 5\sigma$)
- Perhaps more interestingly is the zone when the two initial sigma drops for each bn

- Not obvious reduction of DA for different misalignments and default values
- But lost of $2\sigma$ for 1 mm misalignment for $<10x$ for all bn. When?
Input from RF Dipole design

- So far using values from DQW on both cavities
- Since values between designs/geometries vary so much estimate studies with RF dipole values, even when they are still only from simulations.
- Input from Suba De Silva/JLAB, values from IPAC2015 paper: “some modifications since then but multipoles should be around <5% change”. Will let me know updated values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>From RF Cavity</th>
<th>From Magnets</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_2$</td>
<td>0.0017</td>
<td>18.4</td>
<td>mT/m</td>
</tr>
<tr>
<td>$b_3$</td>
<td>2871</td>
<td>$5.0 \times 10^5$</td>
<td>mT/m$^2$</td>
</tr>
<tr>
<td>$b_4$</td>
<td>14.9</td>
<td>$4.0 \times 10^6$</td>
<td>mT/m$^3$</td>
</tr>
<tr>
<td>$b_5$</td>
<td>$2.0 \times 10^6$</td>
<td>$7.3 \times 10^8$</td>
<td>mT/m$^4$</td>
</tr>
</tbody>
</table>

Values at 3.3 mV

- $b_2$ and $b_4$ lower
- But $b_3$ value (‘biggest’ limit’) is 6x higher
Input from RF Dipole design

- Implement new values in IR5 for VH crossing
- Implement values in IR1 for HV crossing

- Same crossing HV has the same DA $11\sigma$
Input from RF Dipole design

- Implement new values in IR5 for VH crossing
- Implement values in IR1 for HV crossing

- Same crossing VH has the same DA
  Min DA = 11σ

- VH is (surprisingly low) with:
  Min DA=9 σ
Input from RF Dipole design

- Implement new values in IR5 for VH crossing
- Implement values in IR1 for HV crossing

- Same crossing VH has the same DA
  \[ \text{Min DA} = 11\sigma \]

- HV is (surprisingly low) with:
  \[ \text{Min DA}=9 \sigma \]

- Case with VH with RF dipole values is very similar, as expected
- Check HV with more cases to check consistency
Conclusions

- DA studies have been performed to analyze the impact of the updated RF multipoles obtained for the DWQ design.
- Studies show very impact with the nominal values but limits on different orders was explored:
  - Cases for $b_2$ were very stable, mainly due to pos/neg in the VH configuration.
  - For $b_3$ a (comfortable) limit was found around 50 times the original value.
  - For $b_4$ cases remained very stable until very high values.
- More urgent impact might come from the misalignments. 1 mm misalignments show impact of $2\sigma$ for less than 10 times for all orders. Investigations of where exactly.
- More studies to be done with RF dipole values and study the impact on HV and VH crossing.