Crab Cavity Field Quality and its implication for HL-LHC

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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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Previous Studies

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

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

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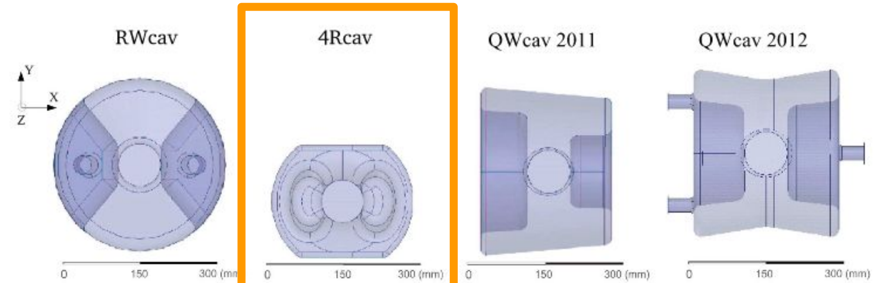

FIG. 1. Geometry of the four HL-LHC CC prototypes under design: ridged waveguide cavity (RWcav) [10]; four rod resonator cavity (4Rcav) [11]; quarter-wave resonator cavity 2011 (QWcav 2011) [12] and double quarter-wave resonator (QWcav 2012) [13].

TABLE II. Values of the multipolar rf multipoles for the crab cavity prototypes at nominal deflecting voltage: $V_{cc} = 10$ MV in units of $\mathrm{mTm/m}^{n-1}$.

		Lorentz method		Panofsky-Wenzel		Helmholtz decom-
		@10 mm	@20 mm	@10 mm	@20 mm	position @20 mm
4RCAV	b_2	−0.06	−0.05	−0.06	−0.06	−0.10
2012	b_3	1159	1159	1161	1161	1156
	b_4	−4	100	65	27	57
RWCAV	b_2	0.01	0.00	0.00	0.01	0.02
2012	b_3	4511	4511	4495	4495	4518
	b_4	−4	−7	−21	7	10
QWCAV	b_2	111.42	111.40	111.43	111.48	113.06
2011	b_3	1266	1267	1257	1260	1279
	b_4	1776	1776	1401	1836	2102
QWCAV	b_2	0.29	0.29	0.29	0.29	0.24
2012	b_3	1074	1073	1078	1078	1073
	b_4	50	67	6	64	22

- Specifications for 4 different crab cavity models
- DA studies done for the 4RCAV, using the Lorentz method values at 10 mm:
    - b2= 0.06
    - b3 = 1159
    - b4=-4

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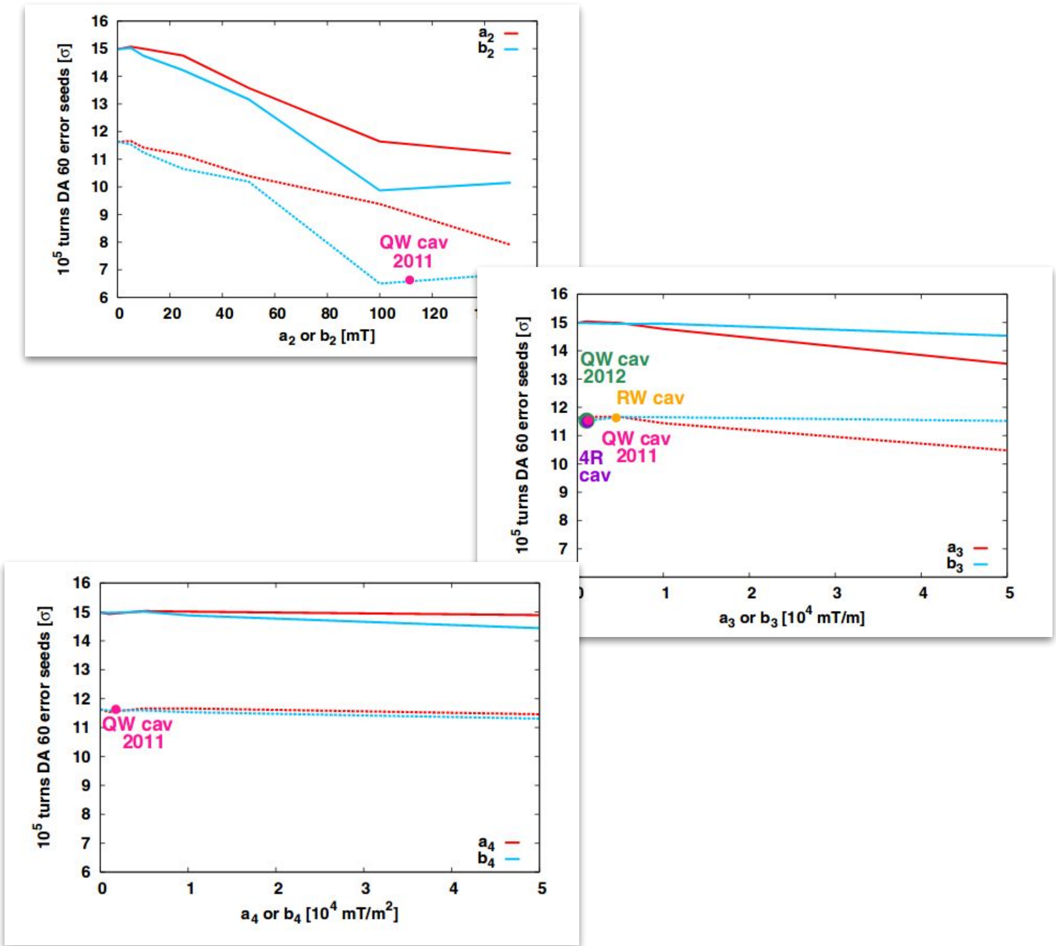

- Specifications for 4 different crab cavity models
- DA studies done for the 4RCAV, using the Lorentz method values at 10 mm:
  - b2= 0.06
  - b3 = 1159
  - b4=-4
- Results:
  - Drop more obvious for the b2, outside specification for QWcav 2011 design
  - b3 slowly decreasing
  - b4 very stable

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 σ 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.

	MBRC	Double Ridge	Quarter Wave	UK-4Rod
b_2	55	0	0	0
b_3	7510	4500	1070	1162
b_4	82700	0	0	0
b_5	2.9×10^6	0.4×10^6	-0.1×10^6	2.29×10^6
b_6	5.2×10^7	0	0	0
b_7	5.6×10^8	3×10^8	7×10^6	6.38×10^8

Table 3 Multipole components of the three cavity prototypes

- Long tracking simmulations for case with b3=4500.
- A reduction of the b3 multi polar by a factor of 3 (to ~1000) is recommended to relax the orbit tolerance to >1mm
- For n>=4 values should be kept below 10^n

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Why make new studies?

Updates on RF mult

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

SPS DQW (Dressed)					
		b1	b2	b3	b4
LF	Re	33	6	1498	1026
	Im	0	-2	19	-383
LHC DQW (Dressed)					
		b1	b2	b3	b4
LF	Re	33	6	1488	1048
	Im	0	-2	21	-292
LHC RFD (Dressed)					
		b1	b2	b3	b4
LF	Re	34	0	-458	128
	Im	0	0	-74	55

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

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Calculated using the Panofsky- Wenzel method

- 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**

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

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  - Similar to magnetic kicks but these are position-dependent and have frequency

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

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

$$\Delta p_t = -\frac{\partial H}{\partial z} = \frac{q V_{\mathrm{RF}}}{p_s c} \sin\left(\vartheta_{\mathrm{RF}} - k_{\mathrm{RF}} z\right) - k_{\mathrm{RF}} \sum_{n=0}^{N} \frac{1}{(n+1)!} \Re\left[\left(K_{\mathrm{N},n} L \sin\left(\vartheta_n - k_{\mathrm{RF}} z\right) + i K_{\mathrm{S},n} L \sin\left(\varphi_n - k_{\mathrm{RF}} z\right)\right) (x+iy)^{n+1}\right]$$

J. Barranco, A. Latina, R. Tomas, R. de Maria

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Normal quadrupole

$$\Delta x' = -\frac{b_2}{B\rho} x \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,quad}}\right)$$

$$\Delta y' = \frac{b_2}{B\rho} y \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,quad}}\right)$$

$$\Delta \delta = \frac{1}{2}\frac{b_2}{B\rho}(x^2 - y^2) \sin\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,quad}}\right)\frac{\omega}{c}$$

Normal sextupole

$$\Delta x' = -\frac{b_3}{B\rho}(x^2 - y^2) \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,sext}}\right)$$

$$\Delta y' = 2\frac{b_3}{B\rho} xy \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,sext}}\right)$$

$$\Delta \delta = \frac{1}{3}\frac{b_3}{B\rho}(x^3 - 3xy^2) \sin\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,sext}}\right)\frac{\omega}{c}$$

Normal octupole

$$\Delta x' = -\frac{b_4}{B\rho}(x^3 - 3xy^2) \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,oct}}\right)$$

$$\Delta y' = \frac{b_4}{B\rho}(3x^2 y - y^3) \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,oct}}\right)$$

$$\Delta \delta = \frac{1}{4}\frac{b_4}{B\rho}(x^4 - 6x^2y^2 + y^4) \sin\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,oct}}\right)\frac{\omega}{c}$$

Skew sextupole

$$\Delta x' = -2\frac{b_3}{B\rho} xy \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,sext}}\right)$$

$$\Delta y' = \frac{b_3}{B\rho}(y^2 - x^2) \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,sext}}\right)$$

$$\Delta \delta = -\frac{1}{3}\frac{b_3}{B\rho}(y^3 - 3yx^2) \sin\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,sext}}\right)\frac{\omega}{c}$$

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  - 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};
```

T. Persson

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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 π/2. Zero transverse kick at middle of crab cavity
- Issues

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- **Issues**

  - MADX failed with phase π/2: Must be activated after turning on normal RF, otherwise MADX fails

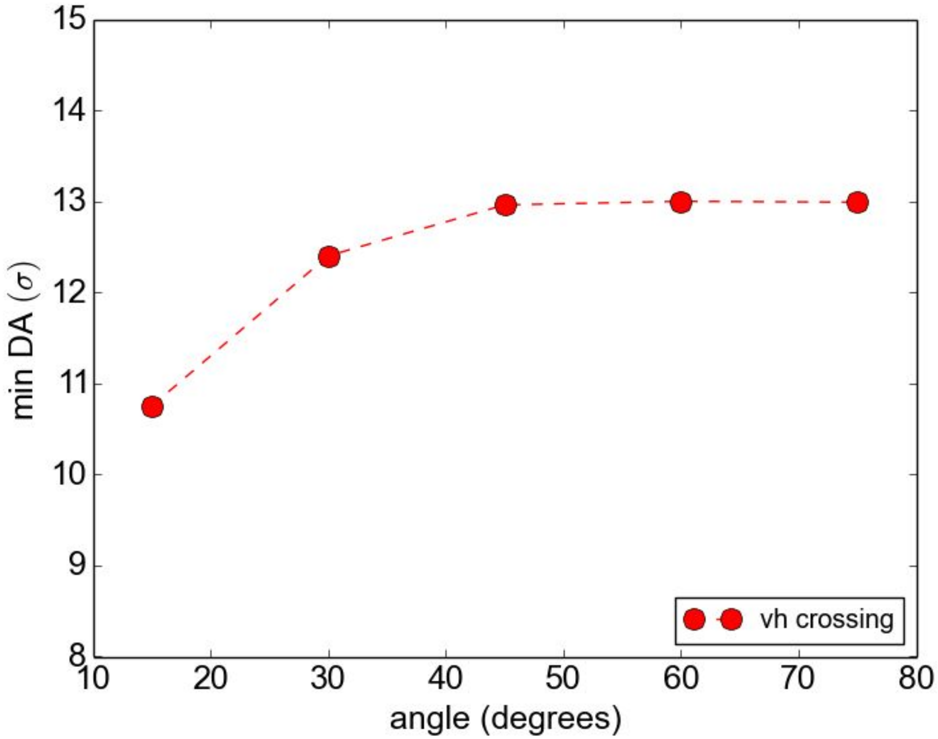
  - Problems with declaring elements with variables

  - 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
  - **DA ~ 11 σ**

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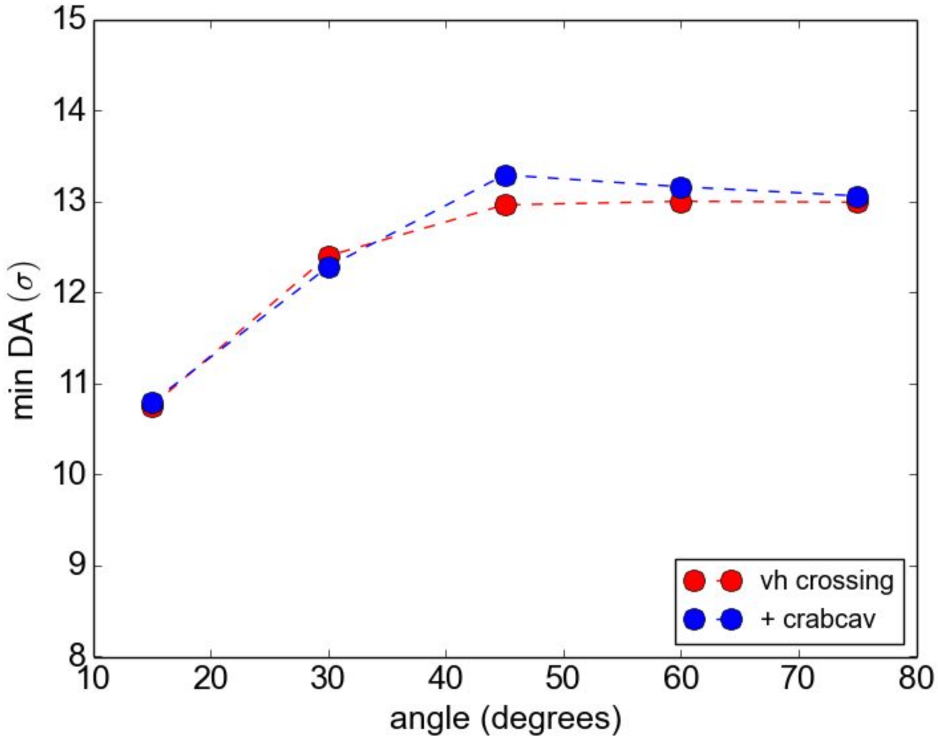

- Min DA over 60 seeds with VH crossing and with crab cavities voltage set to 0.0
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- Added corresponding voltage in crab cavities: ~3.4 V left and right for vertical cc in IR1 and horizontal in IR5
  - **No significant effect**

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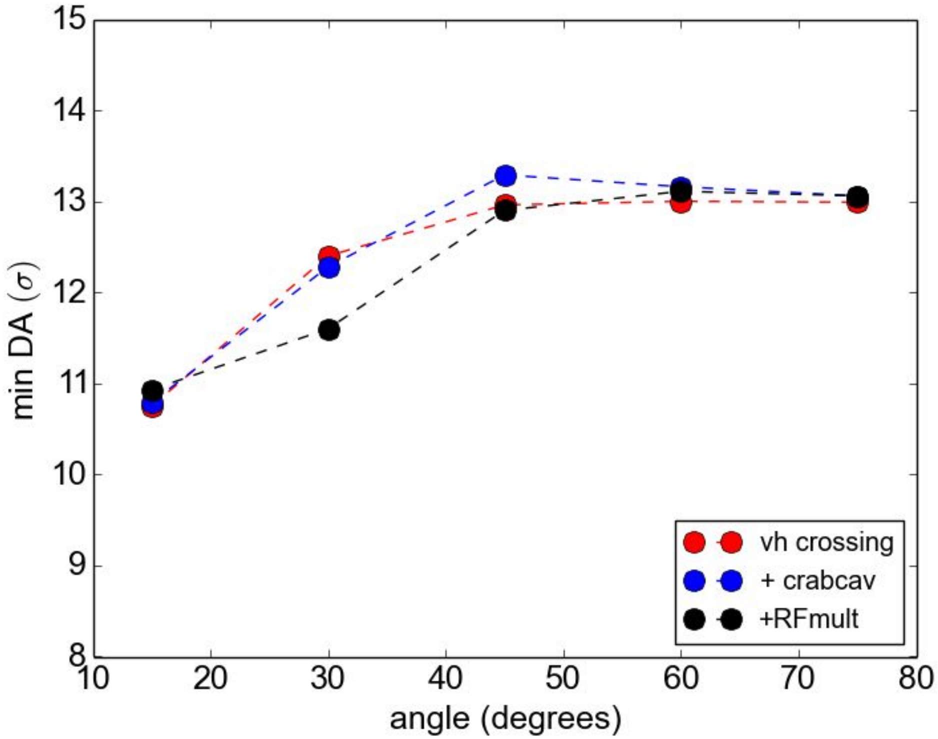

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  - **Changes some values but min DA stays the same**

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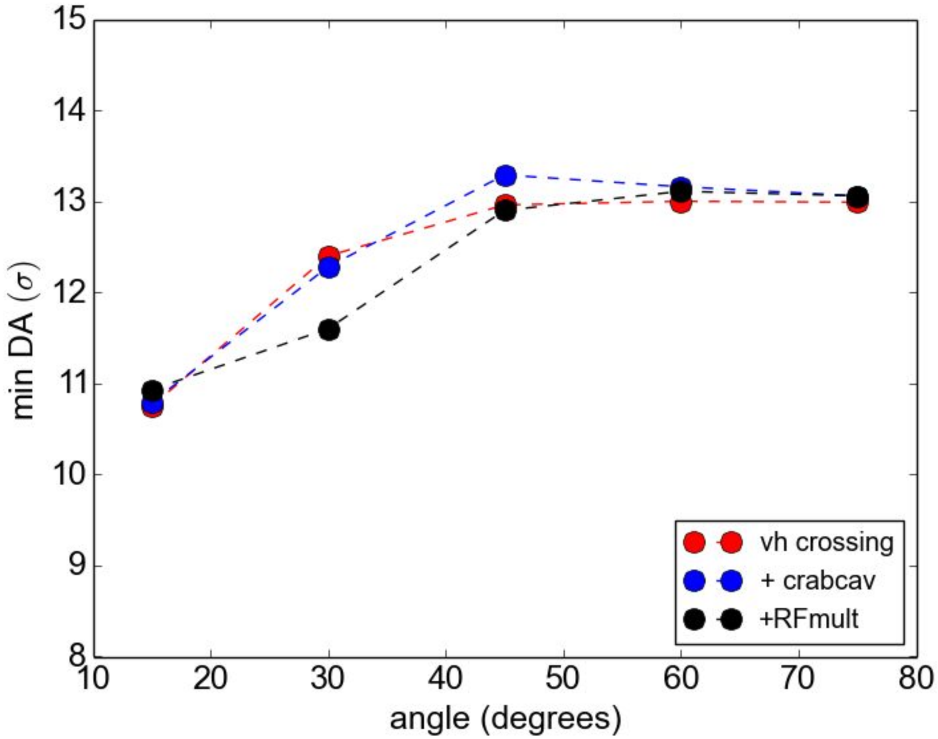

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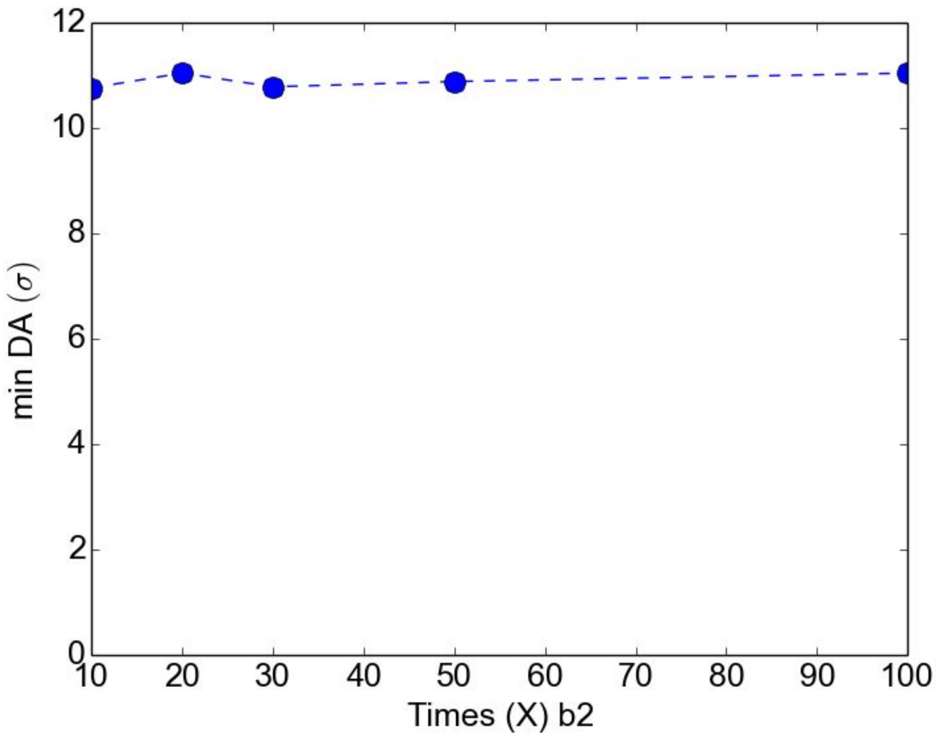
- When does it become a problem?
- Measure tolerances in multipole values and/or alignments

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?

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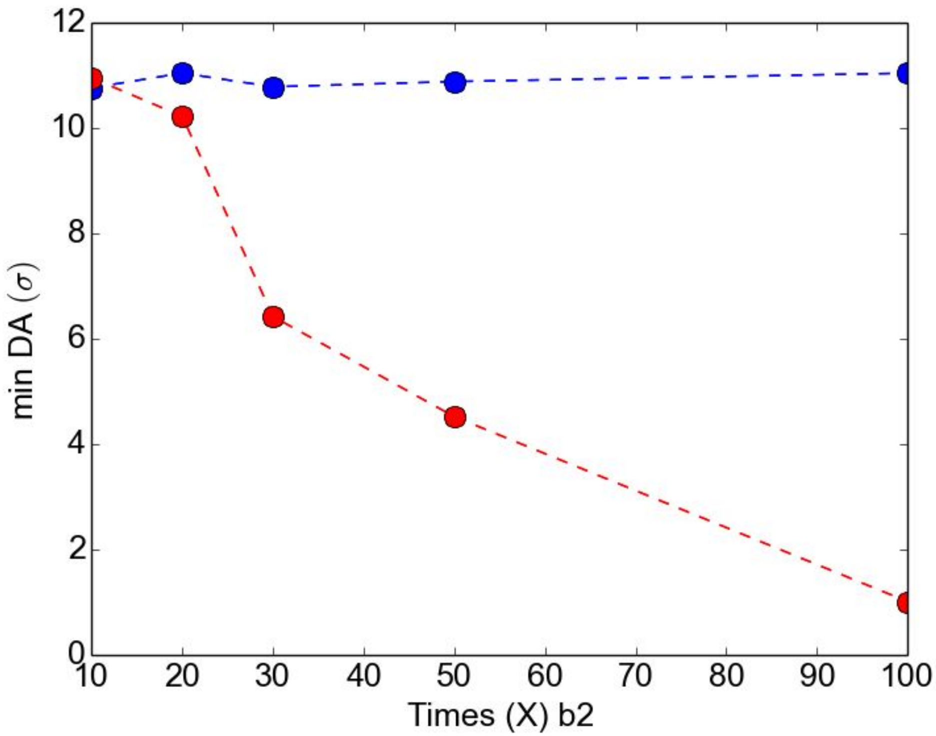

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- Change value in IR1 to positive.
- DA goes lower much faster. Limit around 100 mTm/m-2

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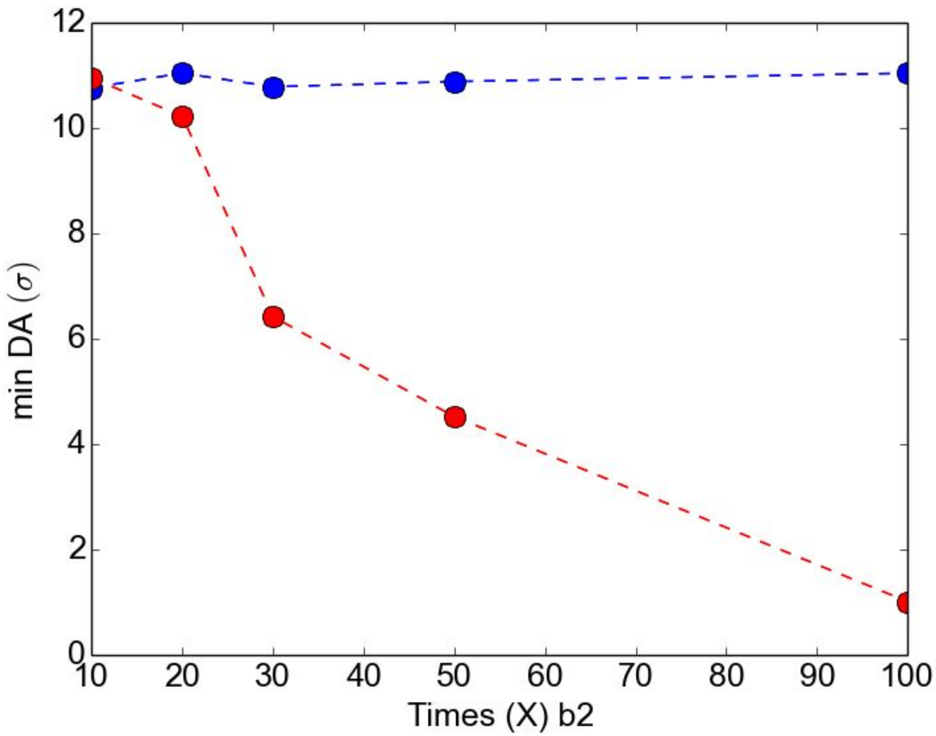

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- Change value in IR1 to positive.
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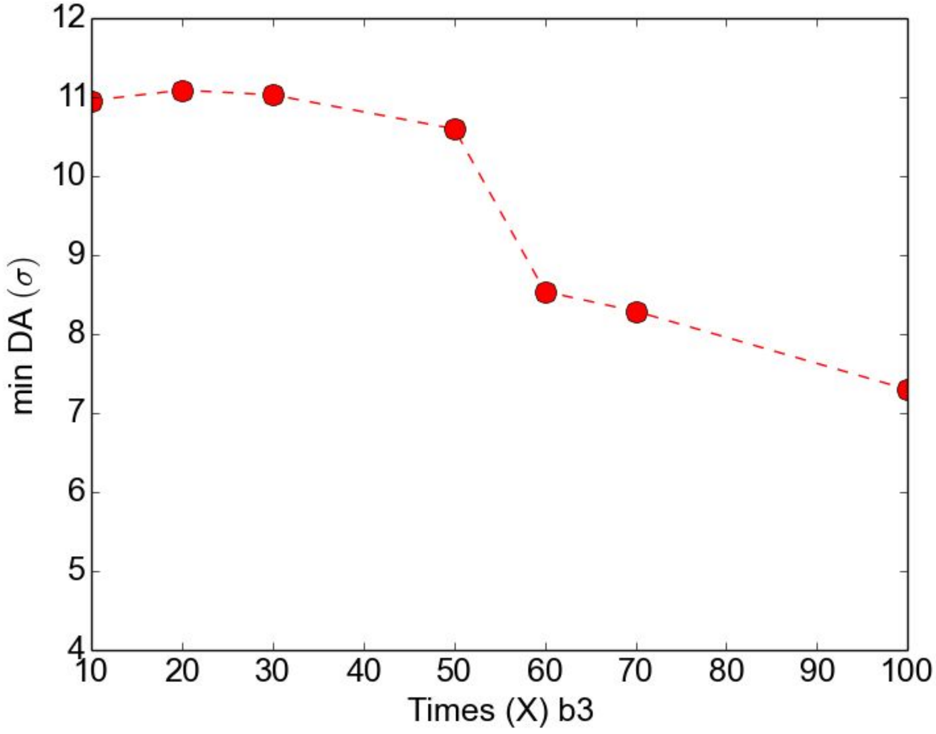
- © seems to mainly be because of cancelling between IR1 and IR5
- Careful for cases when **pos/neg** is not the case: vv/hh crossing, different sign on other cc

Limits on b3

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



- 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

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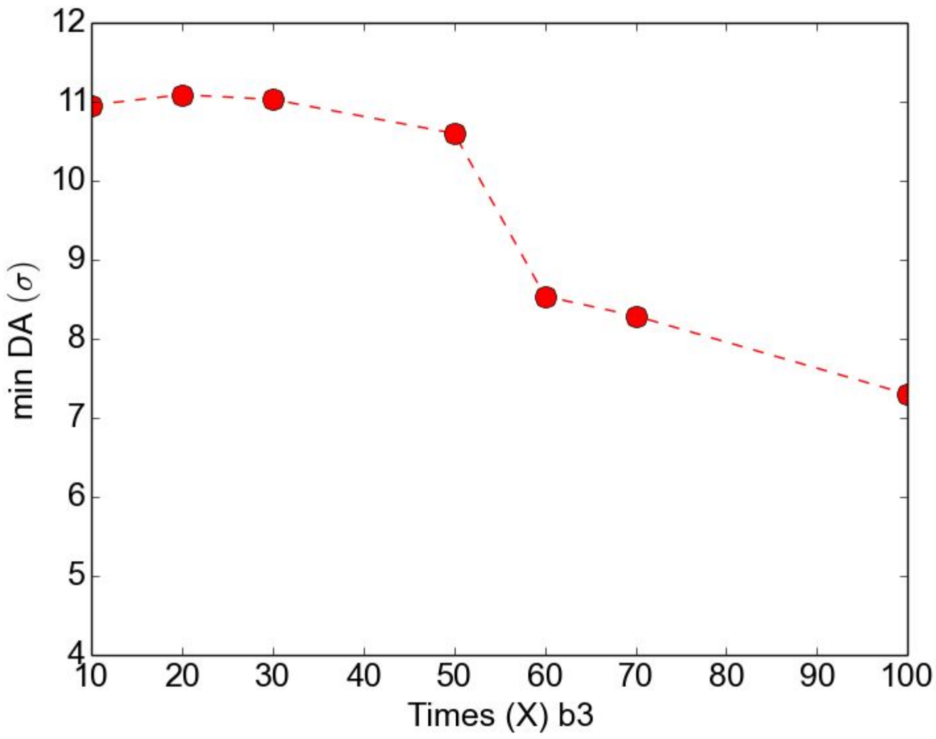

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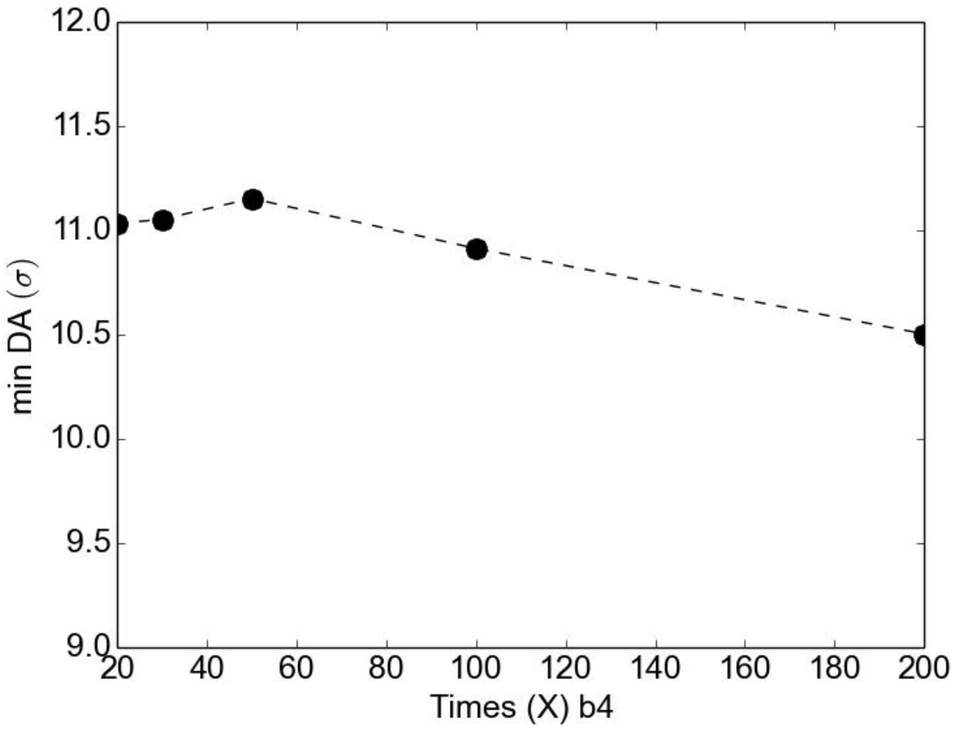
- Limit for case b3 was more well defined but still far away from the design

Limits on b4

Increasing values of b4 until it DA goes down. Original value: 1048 mTm/m^



- Increase values up to 200xb4 (209,600 mTm/m-3)
- Start to seeing decrease but until the very end:
    - Loss of 0.5 σ ~200,00 mTm/m-3

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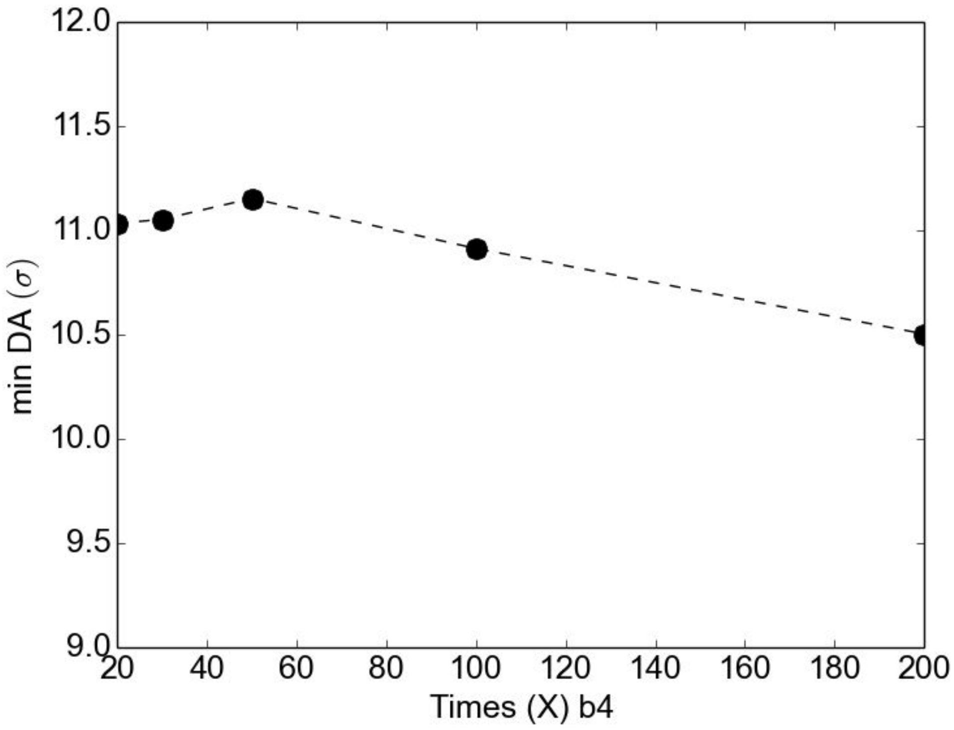

- Increase values up to 200xb4 (209,600 mTm/m-3)
- Start to seeing decrease but until the very end:
    - Loss of 0.5 σ ~200,00 mTm/m-3

- Found small impact of b4 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

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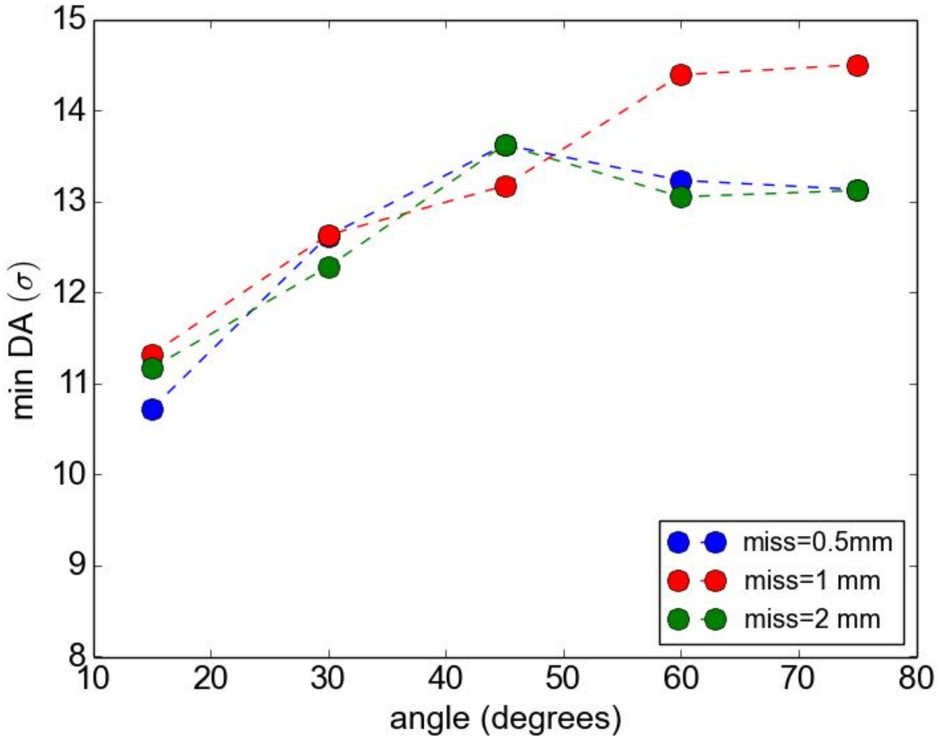
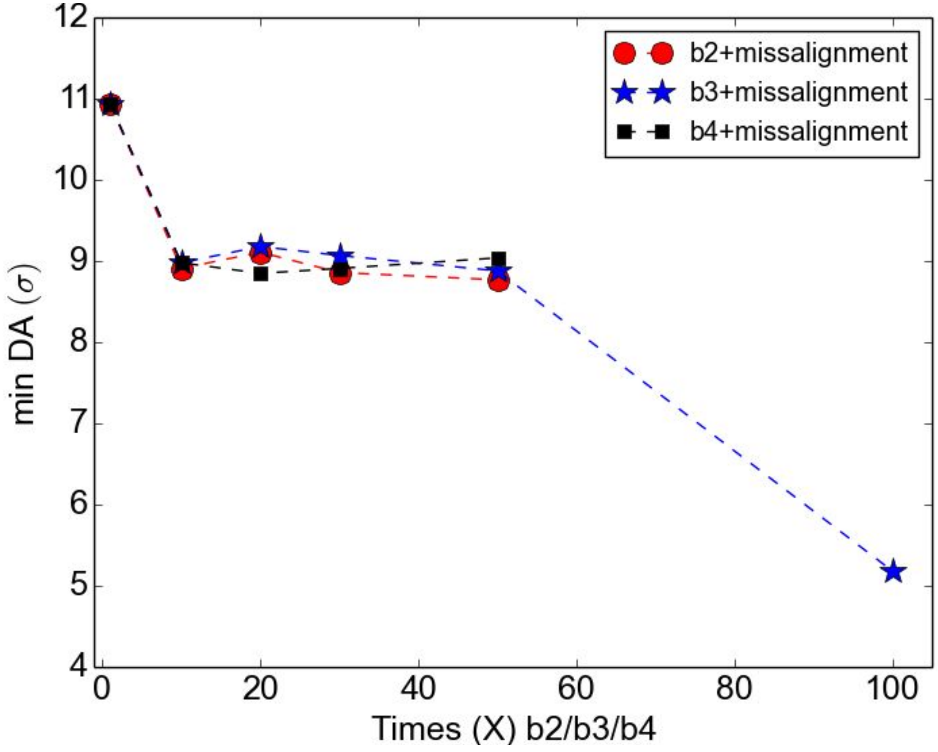


- For original values there's an effect on misalignment but min DA stays around 11σ

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)



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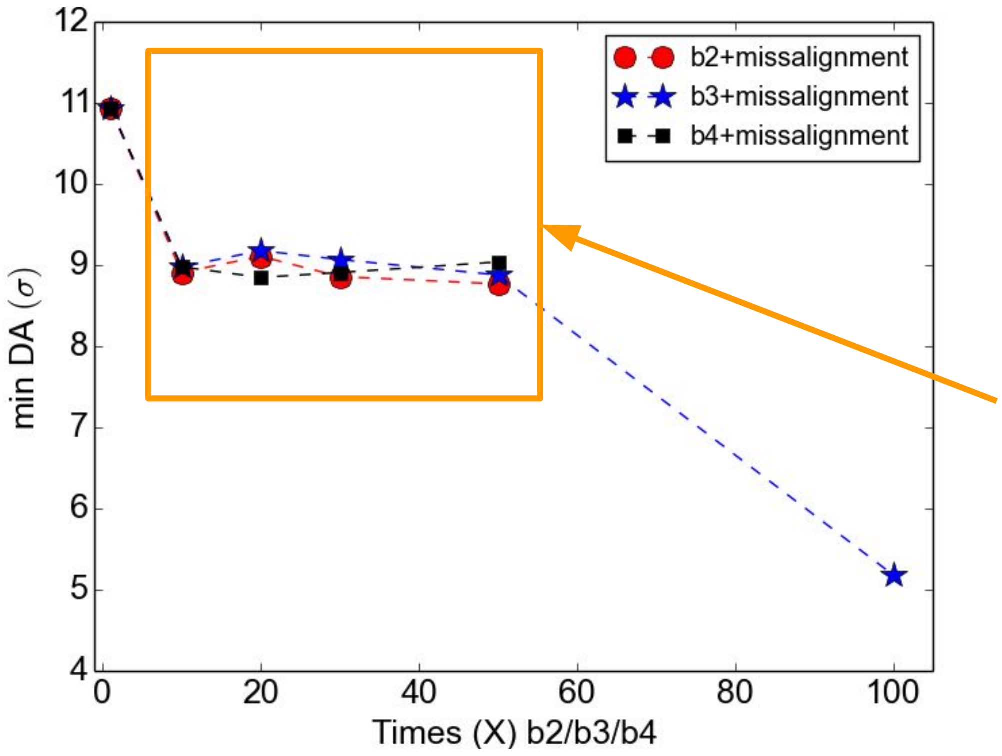

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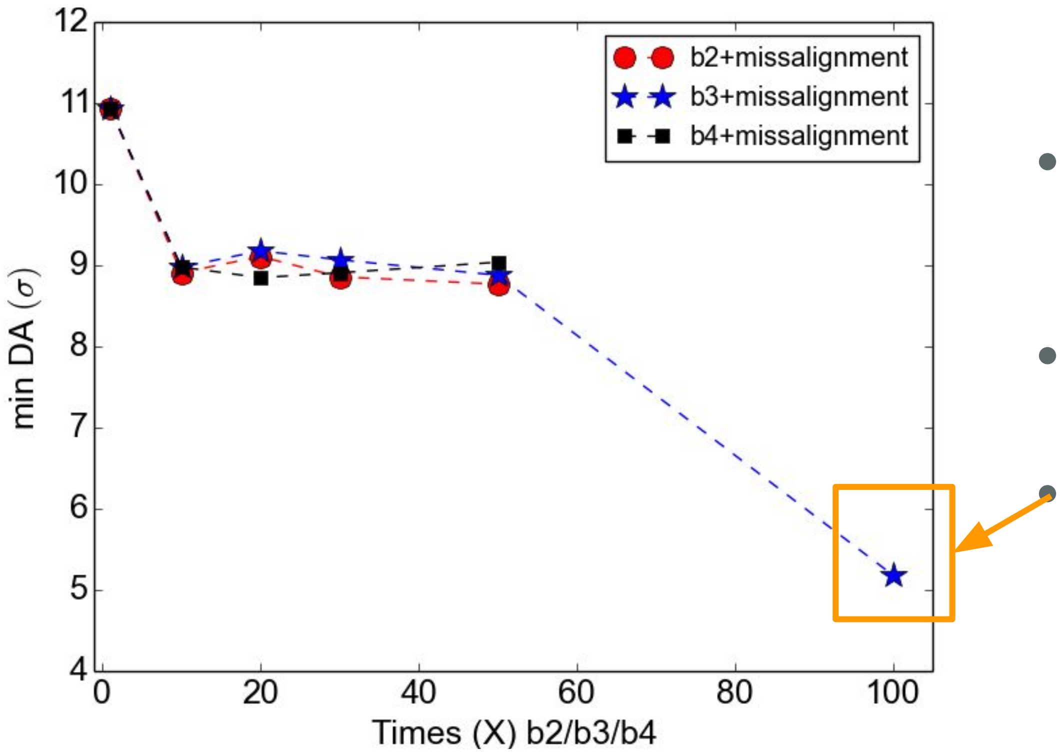

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- From 10-50x for all bn DA drops 2σ but stays around the same value (~9σ)
- When misalignment meets (0 misalignment) limit drops accordingly (7σ->5σ)

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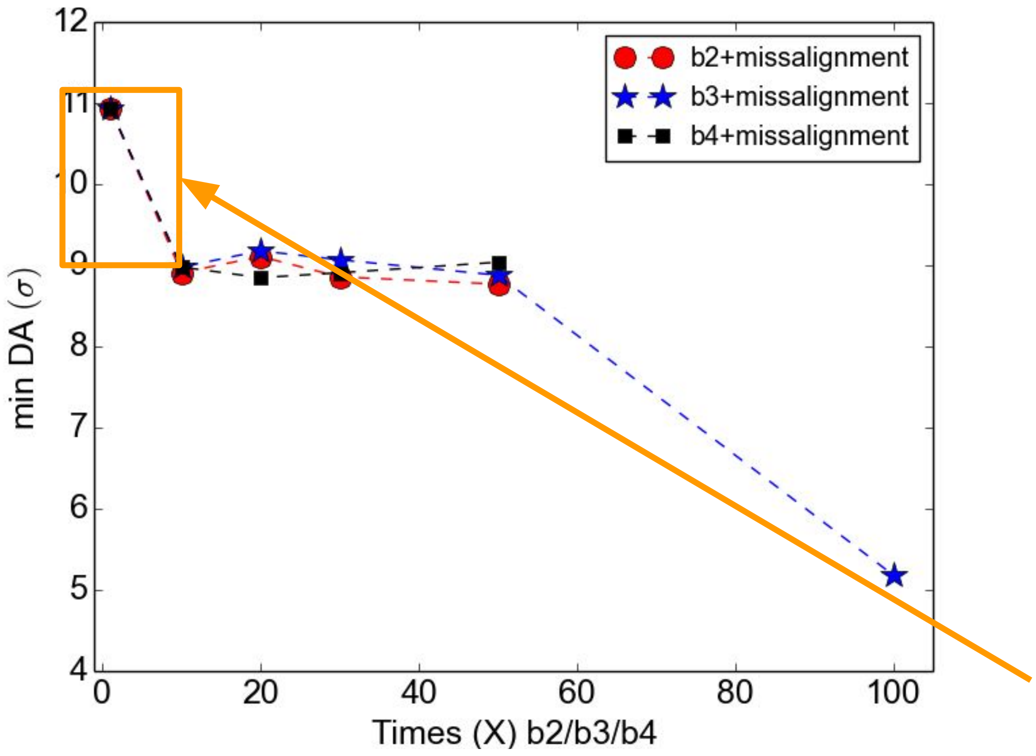

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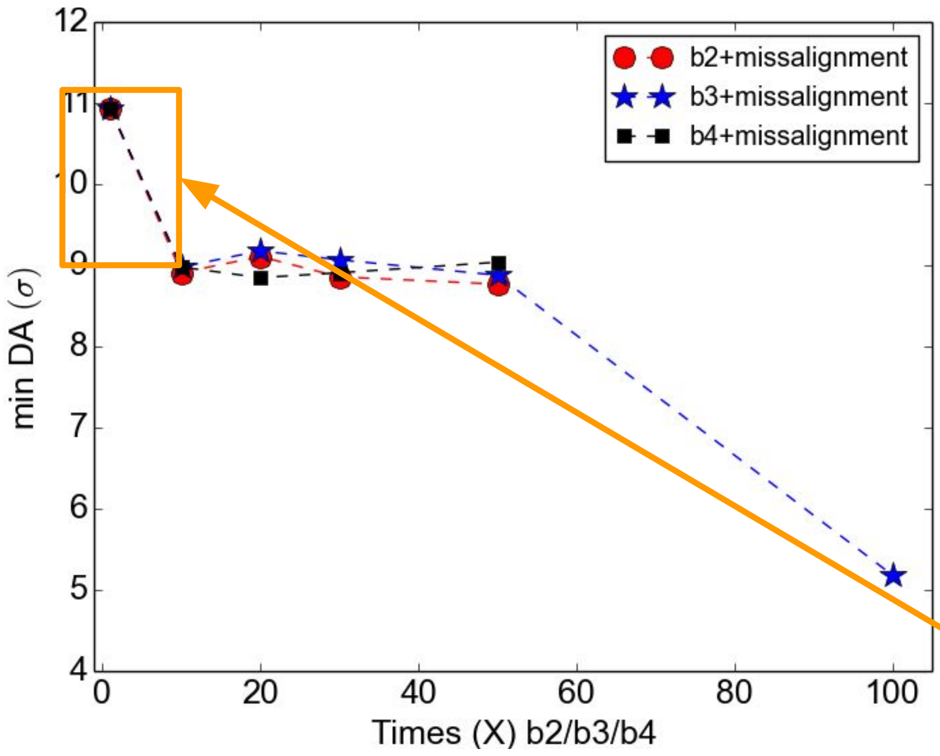
- From 10-50x for all bn DA drops 2σ but stays around the same value (~9σ)
- When misalignment meets (0 misalignment) limit drops accordingly (7σ->5σ)
- Perhaps more interestingly is the zone when the two initial sigma drops for each bn

Misalignment effects

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



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- Not obvious reduction of DA for different misalingments and default values
- But lost of 2σ 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 4: Higher Order Multipole Components

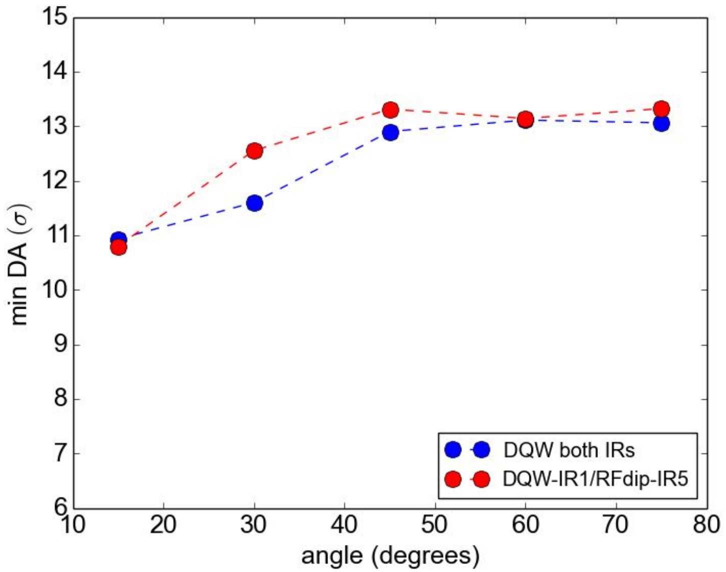
Parameter	From RF Cavity	From Magnets	Units
b_2	0.0017	18.4	mT/m
b_3	2871	5.0×10^5	mT/m^2
b_4	14.9	4.0×10^6	mT/m^3
b_5	2.0×10^6	7.3×10^8	mT/m^4

Values at 3.3 mV

- b2 and b4 lower
- But b3 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

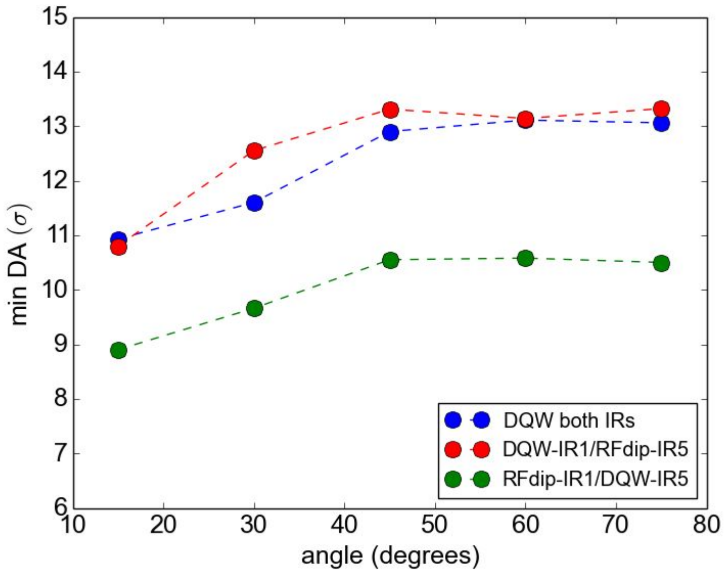


- Same crossing HV has the same DA

  11σ

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

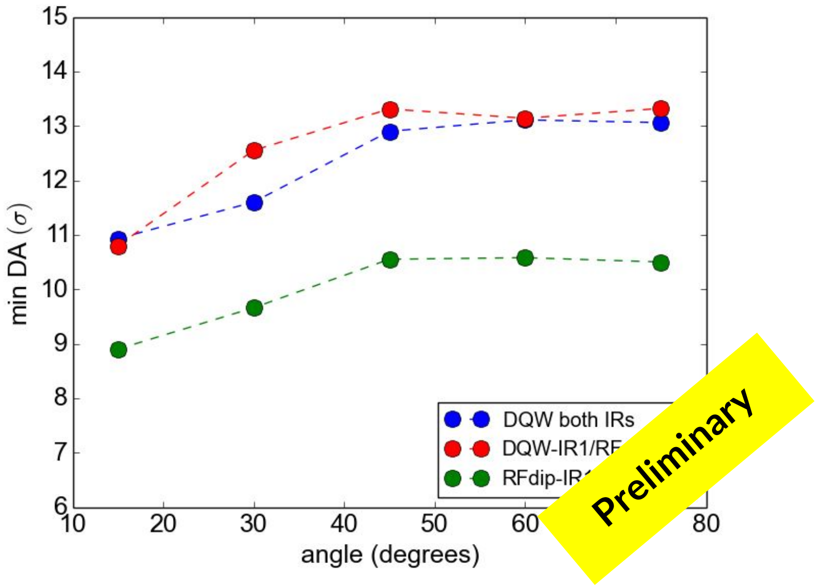
  Min DA = 11σ

- 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

  Min DA = 11σ

- HV is (surprisingly low) with:

  Min DA=9 σ

- 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 b2 were very stable, mainly due to pos/neg in the VH configuration.
    - For b3 a (comfortable) limit was found around 50 times the original value
    - For b4 cases remained very stable until very high values

- More urgent impact might come from the misalignments. 1 mm misalignments show impact of 2σ 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.