Summary of the experimental test with the SPS crab cavities wrt field quality measurement and specifications for HL-LHC

E. Cruz-Alaniz

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HL-LHC Collaboration Meeting Fermilab, Chicago 16th October, 2019

Study of Crab Cavities

- **Goal**: Implementation of CC left and right of IP1 and IP5 to create a bunch rotation and restore head-on collisions to increase luminosity.

- **SPS – Experiments done in 2018**
  - 2 cavities at 1 MV of type DQW
  - 7 MDs

- **HL-LHC Simulations**
  - Implement crab cavities left/right of IR1 and IR5 in HLLHCV1.3 lattice version
  - HV crossing
  - 3.4 MV per cavity

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R. Calaga, Monday talk

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Studies

- **Analyse results on experiments on SPS and study possible impact on HL-LHC**

- **RFmultipoles**:
  - Why are they present and how do we measure them?
  - Do they affect the beam stability on the SPS and the HL-LHC?
  - What are the tolerances?

- **Diagnostics**
  - What instrumentation do we use in the SPS to analyse performance of the CCs?
  - For the HL-LHC can we use the beam instrumentation present?
  - What are the performances of the instrumentation in the presence of a crabbed bunch?

RFmultipoles

- What are the RF multipoles?:

Compact models to accommodate space between two beams → Loose of axial symmetry → Higher Order Multipoles (RF multipoles) are present

RFmultipoles

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Compact models to accommodate space between two beams → Loose of axial symmetry → Higher Order Multipoles (RF multipoles) are present

- How do we measure them?
  - Similar as magnetic multipoles

$$B_y + iB_x = B_{\text{ref}} \sum_{n-1}^{N} [b_n(r_0) + ia_n(r_0)] \left(\frac{x+iy}{r_0} \right)^{(n-1)}$$

  - Get multipoles from measuring the force (LF model) or the electric field (Panofsky-Wenzel model)
  - RFmultipoles are oscillating at a frequency 400 MHz and kick depends on longitudinal position. Complex numbers: real (z=0 sees maximum deflection), Imaginary (z=0 sees no kick)
  - **Expect impact on beam dynamics but cannot correct them. Study impact with Dynamic Aperture**

RFmultipoles

- Previous studies: values shown for **different designs**

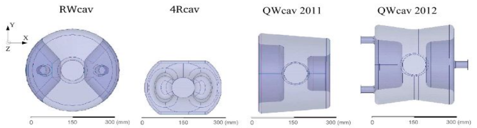


FIG. 1. Geometry of the four HL-LHC CC prototypes under design: ridged waveguide cavity (RWcav) [10]; four rod resonator cavity (4Rcav) [11]; quarter-wave resonator cavity 2011 (QWcav 2011) [12] and double quarter-wave resonator (QWcav 2012) [13].

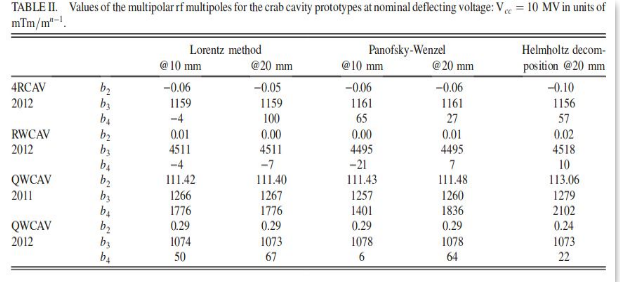


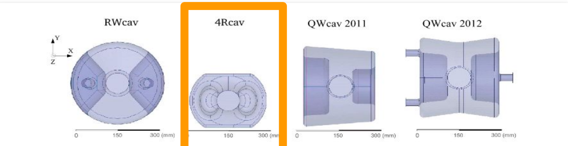
TABLE II. Values of the multipolar rf multipoles for the crab cavity prototypes at nominal deflecting voltage: $V_{cc} = 10$ MV in units of $\mathrm{mTm/m}^{n-1}$.

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

J. Barranco et al, PRAB 19, 101003

RFmultipoles

- Previous studies: values shown for different designs, implementation on MADX and Sixtrack, **dynamic aperture studies**.



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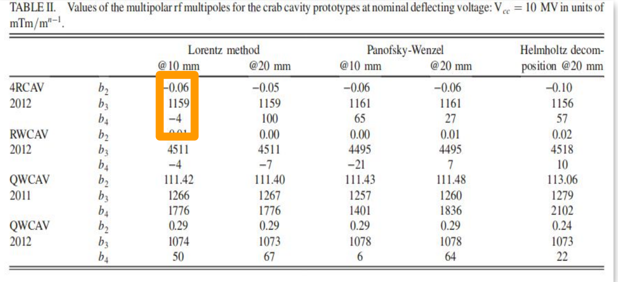

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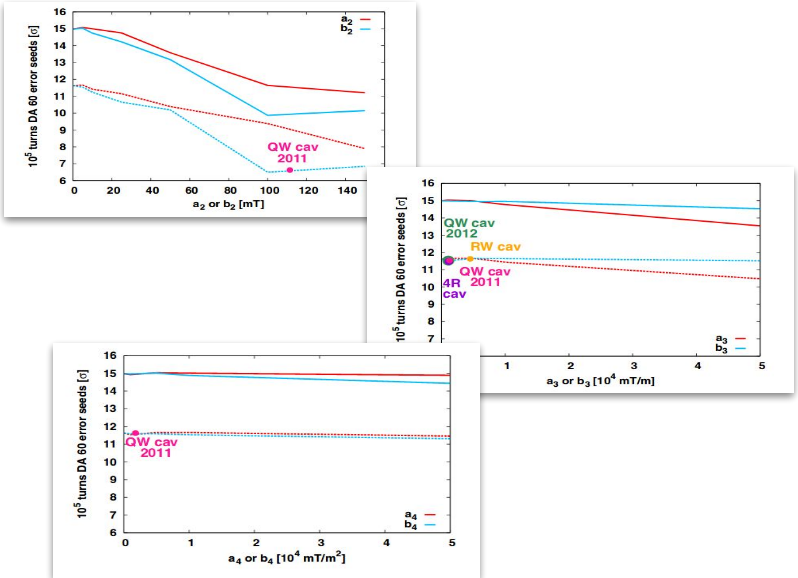

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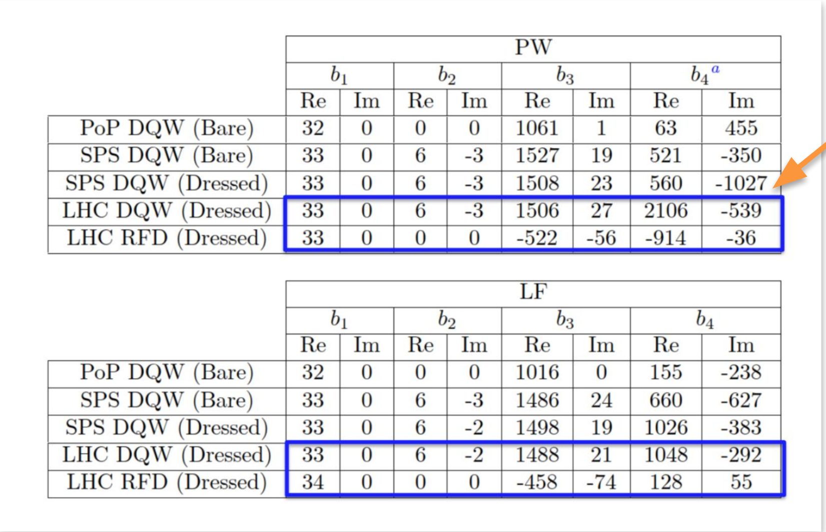
- Previous studies: values shown for different designs, implementation on MADX and Sixtrack, **dynamic aperture studies**.
- **New studies:**



	PW							
	b_1		b_2		b_3		b_4[a]	
	Re	Im	Re	Im	Re	Im	Re	Im
PoP DQW (Bare)	32	0	0	0	1061	1	63	455
SPS DQW (Bare)	33	0	6	-3	1527	19	521	-350
SPS DQW (Dressed)	33	0	6	-3	1508	23	560	-1027
LHC DQW (Dressed)	33	0	6	-3	1506	27	2106	-539
LHC RFD (Dressed)	33	0	0	0	-522	-56	-914	-36

	LF							
	b_1		b_2		b_3		b_4	
	Re	Im	Re	Im	Re	Im	Re	Im
PoP DQW (Bare)	32	0	0	0	1016	0	155	-238
SPS DQW (Bare)	33	0	6	-3	1486	24	660	-627
SPS DQW (Dressed)	33	0	6	-2	1498	19	1026	-383
LHC DQW (Dressed)	33	0	6	-2	1488	21	1048	-292
LHC RFD (Dressed)	34	0	0	0	-458	-74	128	55

J. Mitchell, R. Calaga, WP2 Meeting

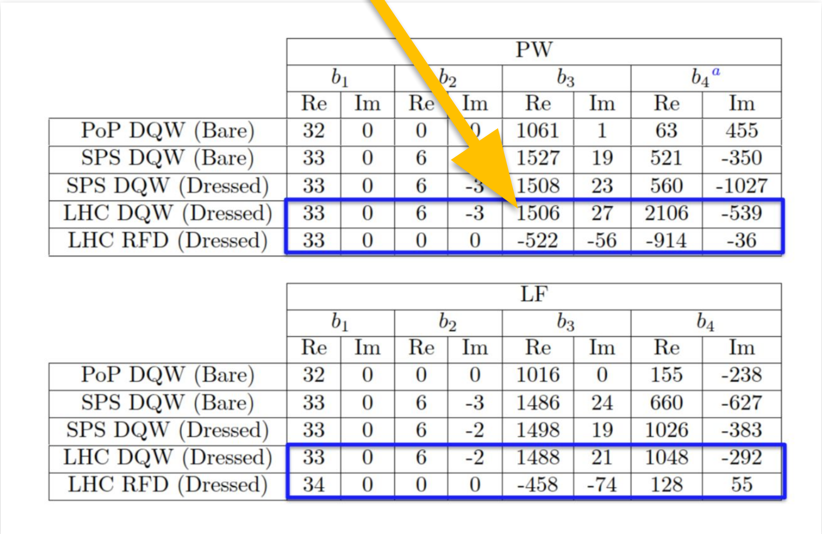
- Converged to final designs: DQW for IR5 (vertical crossing), RFdipole for IR1 (horizontal crossing).
- **Model measurements for both**
- Some values are significantly different than for last DA studies (DQW vs 4RCAV).

  b2: 0.06 -> 6

  b4: -4 ->2106
- b3 with misalignment
- Different values (and signs) between RFdipole and DQW, how does this affect?
- Implement these values. What are the tolerances for?
- **Experiments have been done in the SPS. How does the beam-based measurement compare with the model one?**

RFmultipoles – Beam Based Measurement

- Sextupolar component is quite large and potential to disrupt beam dynamics; motivation to check strength of this value with **beam-based measurements**
- Vertical crab cavity in SPS -> **skew sextupolar** component



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M. Carla, IPAC19, MOPTS090

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- Vertical crab cavity in SPS -> **skew sextupolar** component
- **How do we measure it?** Skew sextupole provides a non-linear coupling force

$$\boxed{\begin{cases} \Delta p_x = K \cdot xy \\ \Delta p_y = K \cdot x^2 \end{cases}}$$

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- Vertical crab cavity in SPS -> **skew sextupolar** component
- **How do we measure it?** Skew sextupole provides a non-linear coupling force:
  - Kick in the horizontal plane, measure measure vertical betatron motion
  - Use perturbation theory
  - Measure from V00 and V20 spectral lines, kick proportional to a3

$$V_{2,0} = iK\frac{j_x\beta_x^p\sqrt{\beta_y^o\beta_y^p}}{4}\left[\frac{e^{i(\phi_y^o-\phi_y^o+2\phi_x^p)}}{1-e^{i(2Q_x-Q_y)}}+\frac{e^{i(-\phi_y^o+\phi_y^p+2\phi_x^p)}}{1-e^{i(2Q_x+Q_y)}}\right]$$

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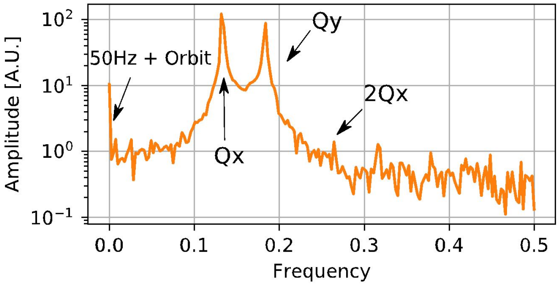
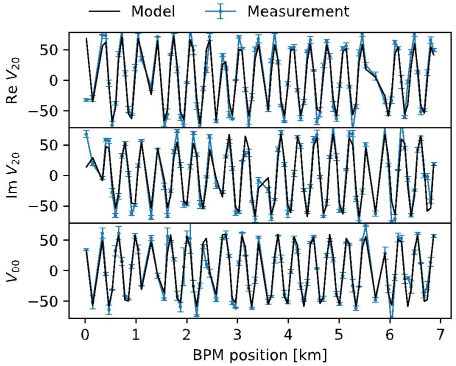


RFmultipoles – Beam Based Measurement

M. Carla, IPAC19, MOPTS090

- **Results:**
  1. Octupole test -> No skew sextupole, feedown from octupole using a vertical bump



	V_{00} (m^{-2})	V_{20} (m^{-2})	Model (m^{-2})
Octupole	2.1e-2	2.3e-2	2.5e-2

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- **Results:**

M. Carla, IPAC19, MOPTS090

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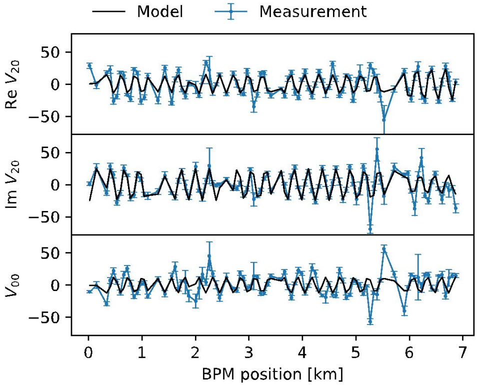
2. CC test -> Measurement for a CC voltage of 0.1 MV and 1 MV



	V_{00} (m^{-2})	V_{20} (m^{-2})	Model (m^{-2})
Octupole	2.1e-2	2.3e-2	2.5e-2
CC ~1 mV	1.0e-2	1.1e-2	3.5e-3

- Measured value is 3 times larger; good fit between model and measurement (plot) but phase had to be introduced of around ~45º.
- Current investigation of other possible sources: octupole feedown, second order sextupole effects.

RFmultipoles – Impact on SPS

- DA studies: 26 GeV, $\Delta p/p=10^{-3}$, 10^6 turns, w/o non-linear model magnets
- CC: V=2 MV, vertical kick, phase-cancelling mode: 0 and 180, in-phase mode: 0 and 0
- RF multipoles: vertical mode normal quadrupole and octupole, skew sextupole
- 4RCAV values: {b2,a3,b4} = {-0.06,1159,-4} $\mathrm{mTm/m^{n-1}}$

A. Alekou, IPAC19, MOPGW095

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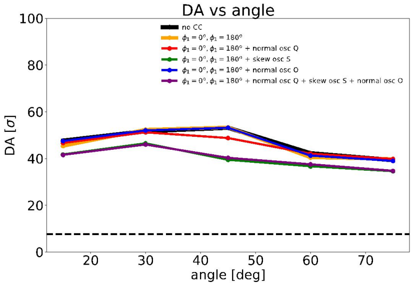

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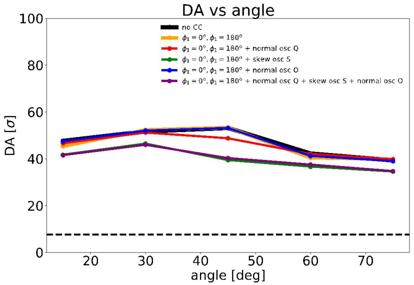

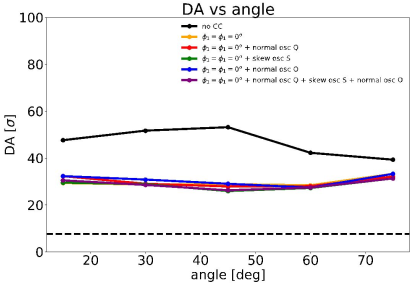

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  - Larger effect but mainly from the CC themselves

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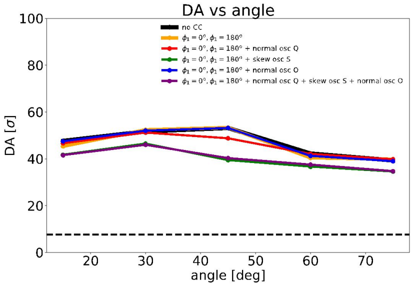

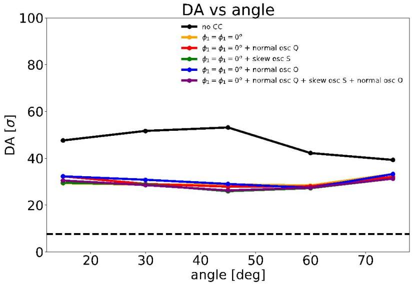

- Phase-cancelling mode:
  - Only effect when including a3
- In-phase mode:
  - Larger effect but mainly from the CC themselves
- Minimal effect when adding nominal values of RF multipoles
- Biggest effect coming from the sextupole component. Increase to check effect

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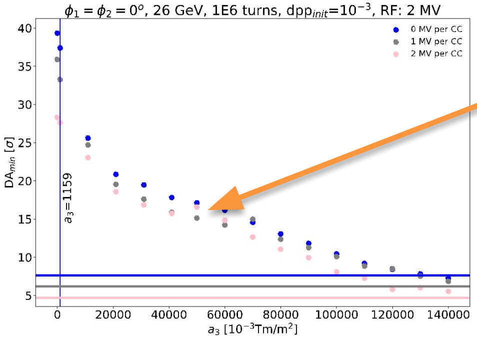
- **Increase a3**

A. Alekou, IPAC19, MOPGW095



- Minimum DA reduces by a factor of two (30σ- 15σ) for a3 values 50 times the original

A. Alekou, IPAC19, MOPGW095

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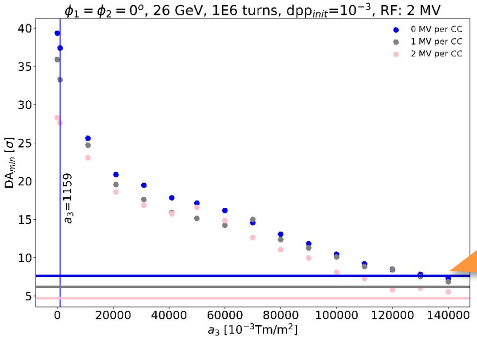


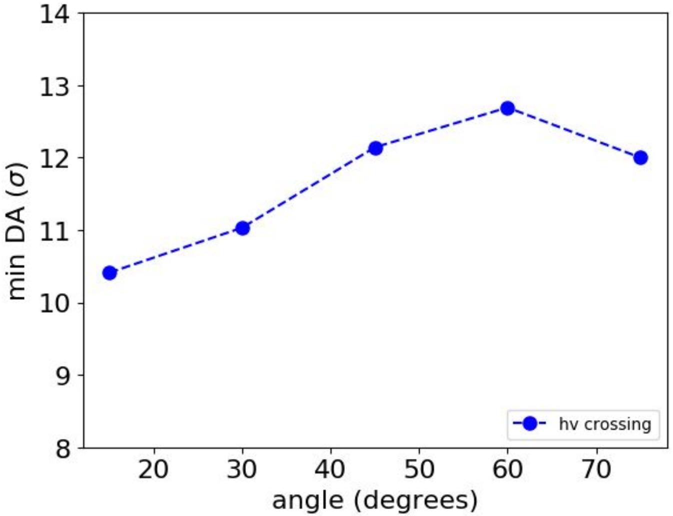
- Minimum DA reduces by a factor of two (30σ- 15σ) for a3 values 50 times the original

- Even for values of 140,000 mTm2 (2 orders of magnitude larger than original) we are limited by physical aperture (horizontal lines), not by DA

A. Alekou, IPAC19, MOPGW095

RFmultipoles – Impact on HL-LHC

- DA studies: 10^6 turns, 5 angles, 60 seeds, 6D, no beam-beam



- Min DA over 60 seeds with VH crossing and with crab cavities off

DA ~ 10.4 σ

- Added corresponding voltage in crab cavities: ~3.4 V left and right for horizontal cc in IR1 and vertical in IR5

No significant effect

- Added nominal RF multipoles from updated values

Changes some values but min DA stays the same

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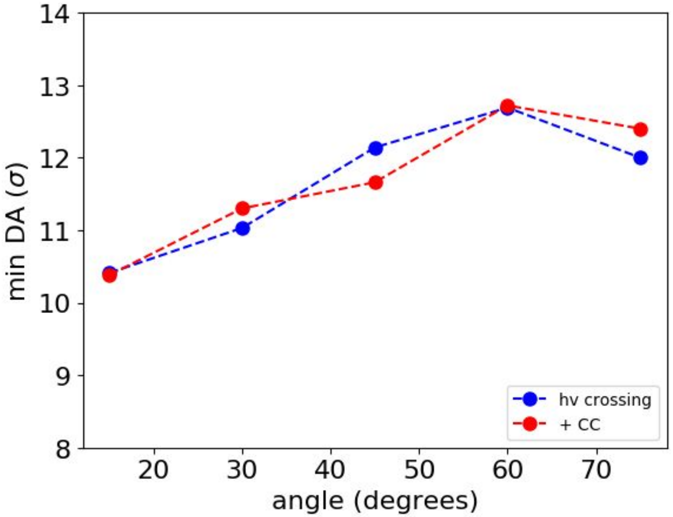

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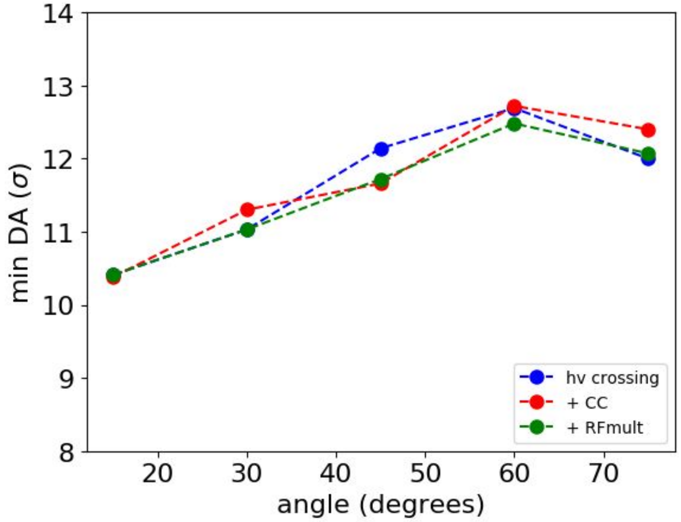

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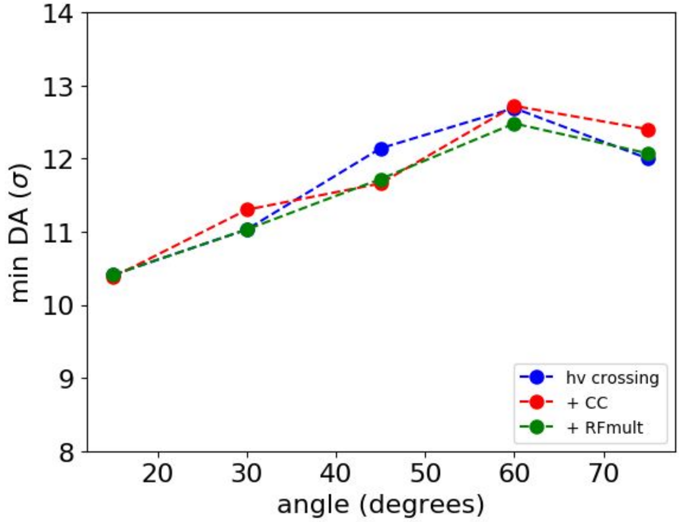

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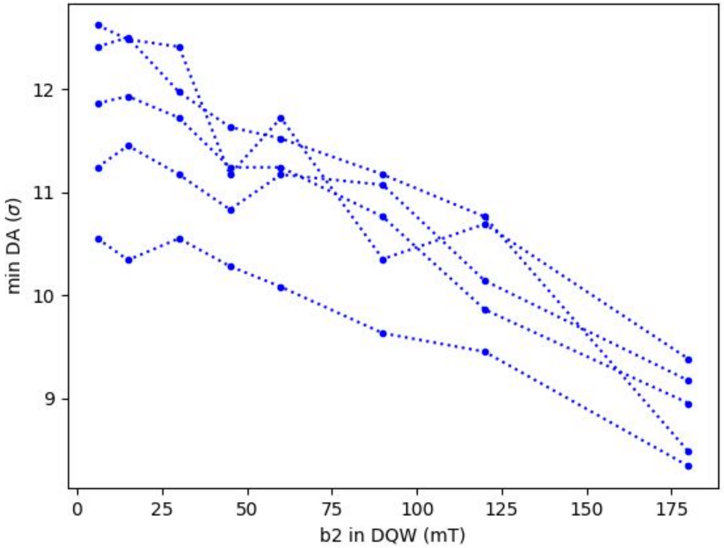
- **When does it become a problem?**
- **Measure tolerance in multipole values and/or alignments**

RFmultipoles – Limits on b2

- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
- Increase b2 until it becomes a problem
- Original values: **b2=0 mT** in IR1 (RFdipole) and **b2=6 mT** in IR5 (DQW)



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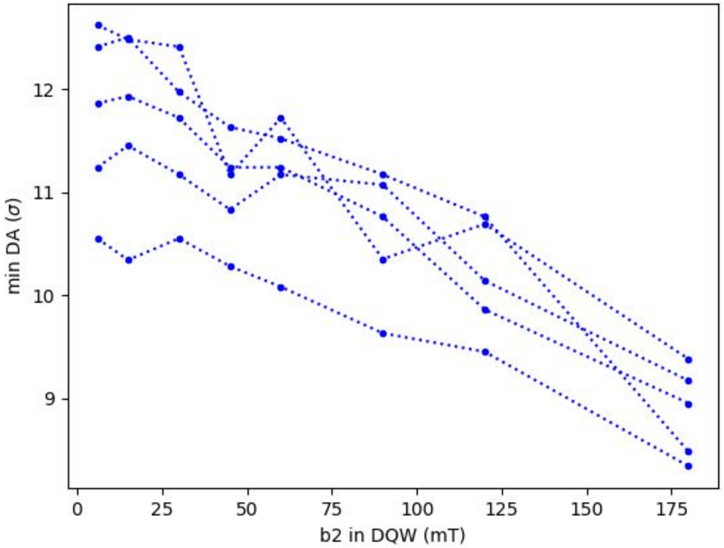

- Noticeable DA decrease for all angles
- **Min DA** defined by lowest angle (15 degrees)

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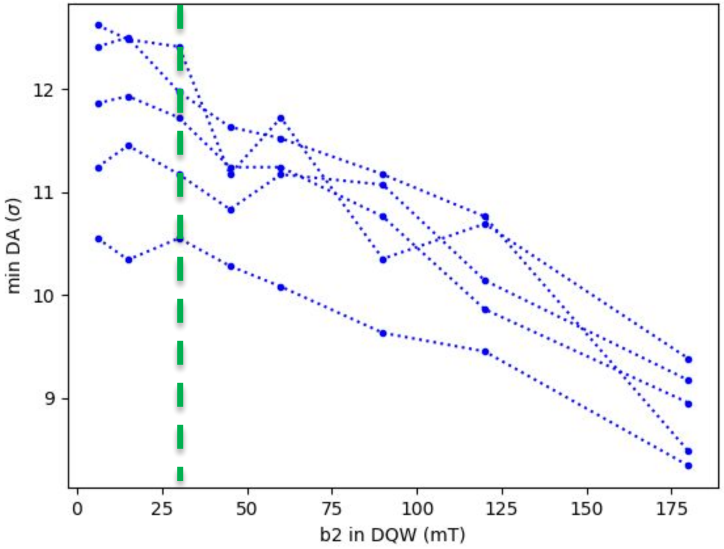


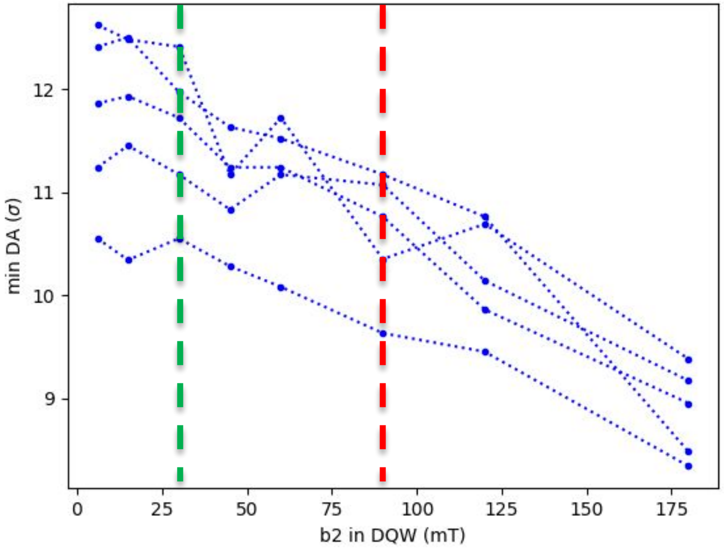
- Noticeable DA decrease for all angles
- **Min DA** defined by lowest angle (15 degrees)
- Limit depends of how we define it
- Soft limit, start losing DA:

  ~5xb2=30 mT

E. Cruz-Alaniz

RFmultipoles – Limits on b2

- DA studies: 10^6 turns, 5 angles, 60 seeds, 6D, no beam-beam
- Increase b2 until it becomes a problem
- Original values: **b2=0 mT** in IR1 (RFdipole) and **b2=6 mT** in IR5 (DQW)



- Noticeable DA decrease for all angles
- **Min DA** defined by lowest angle (15 degrees)
- Limit depends of how we define it
- Soft limit, start losing DA:

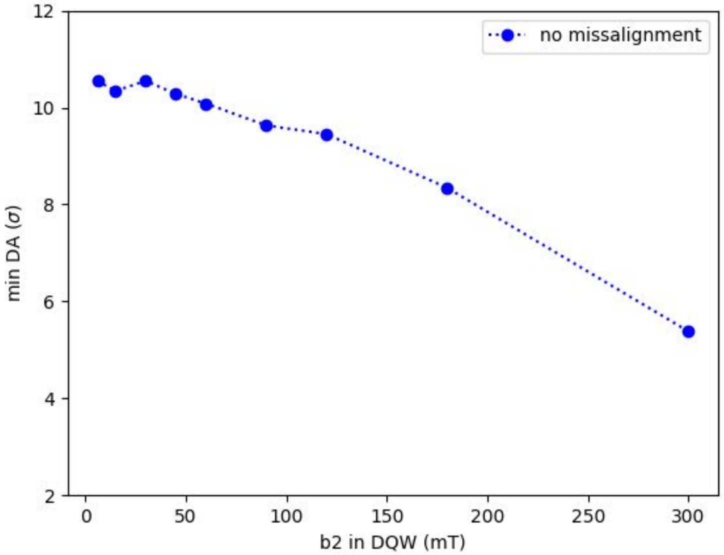
  ~5xb2=30 mT
- Hard limit, loose 1σ:

  ~15xb2=90 mT

E. Cruz-Alaniz

RFmultipoles – Limits on b2

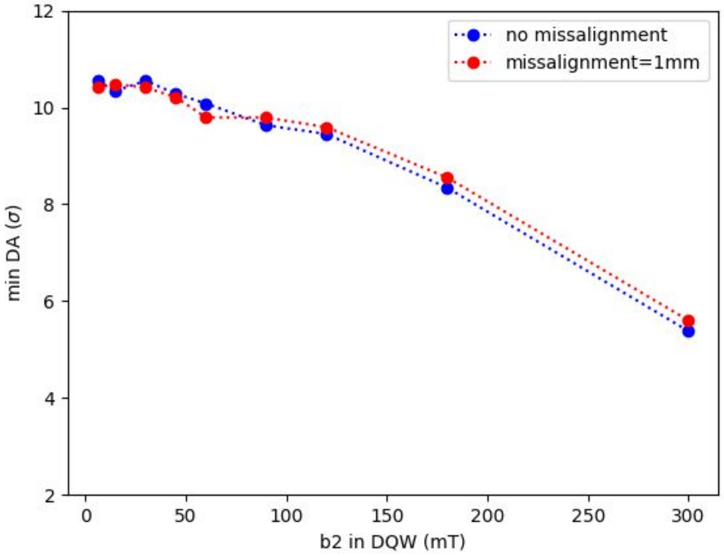
- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
- Increase b2 until it becomes a problem
- Original values: **b2=0 mT** in IR1 (RFdipole) and **b2=6 mT** in IR5 (DQW)



- Add misalignments and beam-beam

RFmultipoles – Limits on b2

- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
- Increase b2 until it becomes a problem
- Original values: **b2=0 mT** in IR1 (RFdipole) and **b2=6 mT** in IR5 (DQW)



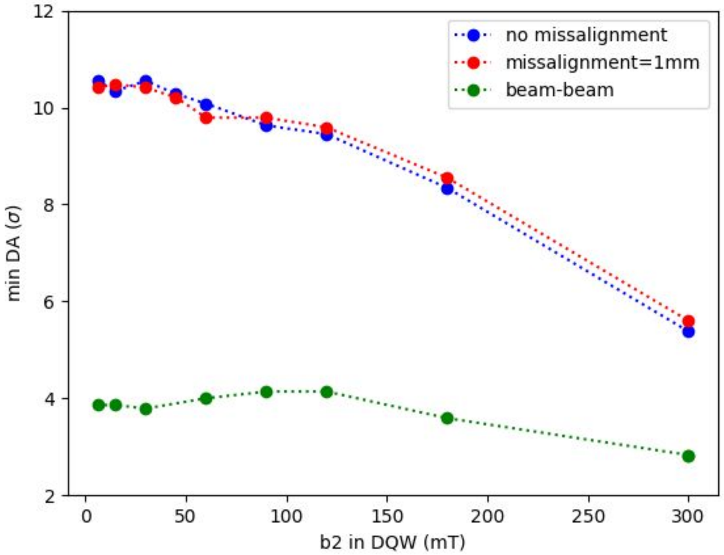
- Add misalignments and beam-beam
- Misalign cavities left and right by 1mm in both IRs

No significant effect

Same limit

RFmultipoles – Limits on b2

- DA studies: 10^6 turns, 5 angles, 6D, ~~no beam-beam~~
- Increase b2 until it becomes a problem
- Original values: **b2=0 mT** in IR1 (RFdipole) and **b2=6 mT** in IR5 (DQW)



- Add misalignments and beam-beam
- Misalign cavities left and right by 1mm in both IRs

No significant effect

Same limit

- Add beam-beam

Losses dominated by beam-beam

Lower DA but until ~300 mT

RFmultipoles – Limits on b2

- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
- Increase b2 until it becomes a problem
- Original values: **b2=0 mT** in IR1 (RFdipole) and **b2=6 mT** in IR5 (DQW)

RFmultipoles – Limits on b2

- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
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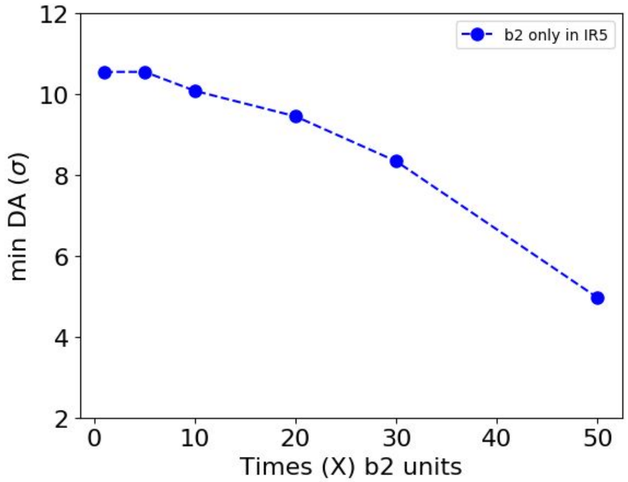
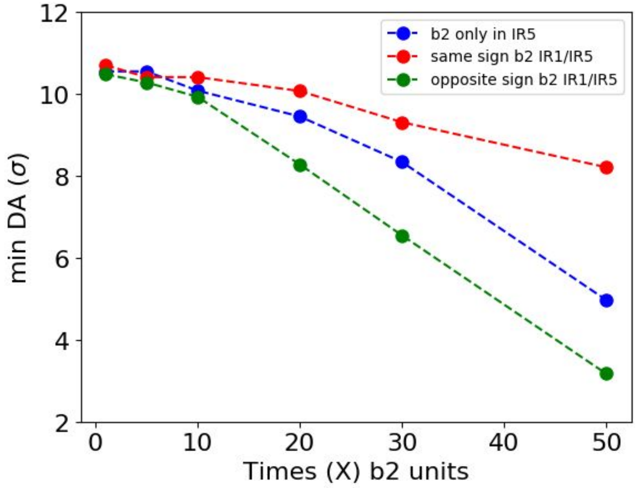


- Add b2 units also in RFdipole
- Estimate same values than for DQW (starting on 6 mT)

RFmultipoles – Limits on b2

- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
- Increase b2 until it becomes a problem
- Original values: **b2=0 mT** in IR1 (RFdipole) and **b2=6 mT** in IR5 (DQW)



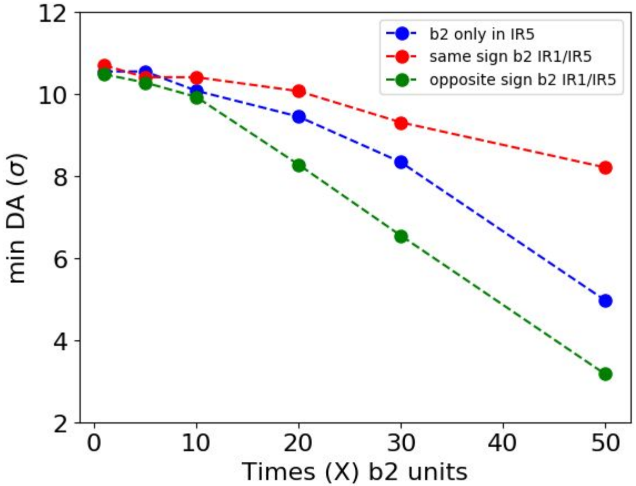
- Add b2 units also in RFdipole
- Estimate same values than for DQW (starting on 6 mT)
- Rotation to vertical: b2-> -b2
- Same sign -> effects cancel each other

  DA more stable
- Different sign -> effects add up

  DA decays much faster

RFmultipoles – Limits on b2

- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
- Increase b2 until it becomes a problem
- Original values: **b2=0 mT** in IR1 (RFdipole) and **b2=6 mT** in IR5 (DQW)



- Add b2 units also in RFdipole
- Estimate same values than for DQW (starting on 6 mT)
- Rotation to vertical: b2-> -b2
- Same sign -> effects cancel each other

  DA more stable
- Different sign -> effects add up

  DA decays much faster

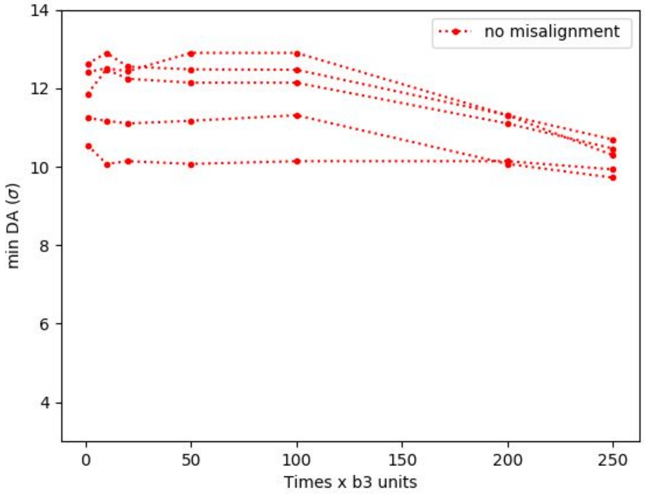
- Limits change when adding b2 units in IR1
  - Can even improve stability

RFmultipoles – Limits on b3

- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
- Increase b3 until it becomes a problem
- Original values: **b3=-522 mT/m** in IR1 (RFdipole) and **b2=1506 mT/m** in IR5 (DQW)

RFmultipoles – Limits on b3

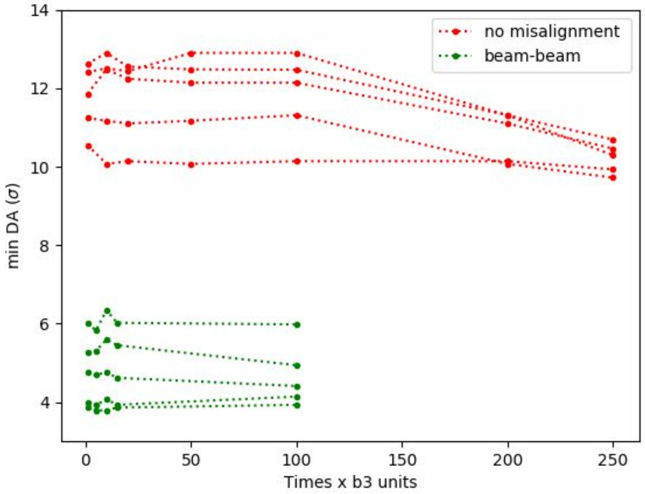
- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
- Increase b3 until it becomes a problem
- Original values: **b3=-522 mT/m** in IR1 (RFdipole) and **b2=1506 mT/m** in IR5 (DQW)



- DA compute for times x b3 (different values for RFdip and DQW)
- Very stable until very large values

RFmultipoles – Limits on b3

- DA studies: 10^6 turns, 5 angles, 6D, ~~no beam-beam~~
- Increase b3 until it becomes a problem
- Original values: **b3=-522 mT/m** in IR1 (RFdipole) and **b2=1506 mT/m** in IR5 (DQW)



- DA compute for times x b3 (different values for RFdip and DQW)
- Very stable until very large values
- When adding beam-beam same case as before. Dominated by the beam-beam rather than the multipole increase

RFmultipoles – Limits on b3

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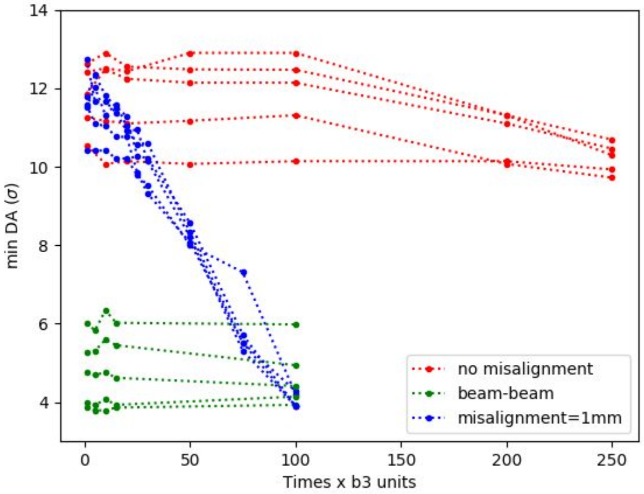
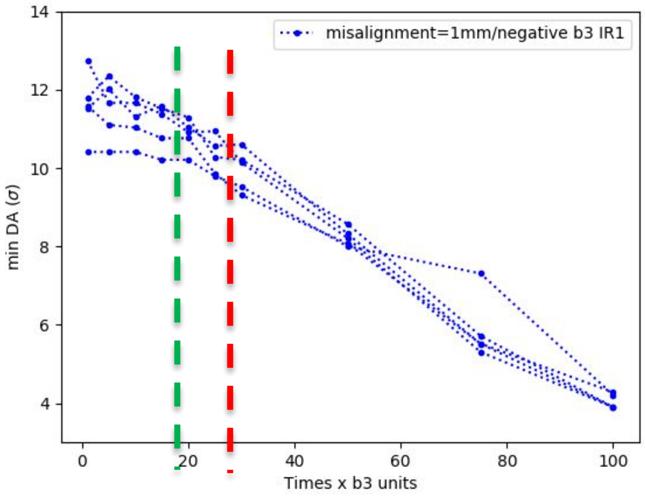


- DA compute for times x b3 (different values for RFdip and DQW)
- Very stable until very large values
- When adding beam-beam same case as before. Dominated by the beam-beam rather than the multipole increase
- When adding misalignments a **much larger impact is observed**

RFmultipoles – Limits on b3

- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
- Increase b3 until it becomes a problem
- Original values: **b3=-522 mT/m** in IR1 (RFdipole) and **b2=1506 mT/m** in IR5 (DQW)



- Limits when increasing a3 and 1 mm misalignment:

  Soft limit, start losing DA;

  ~20xb3=10-15*10^3 mT/m

  Hard limit loose 1σ in min DA

  ~30xb3= 30-45*10^3 mT/m
- Pretty stable

RFmultipoles – Limits on b3

- DA studies: 10^6 turns, 5 angles, 6D, no beam-beam
- Increase b3 until it becomes a problem
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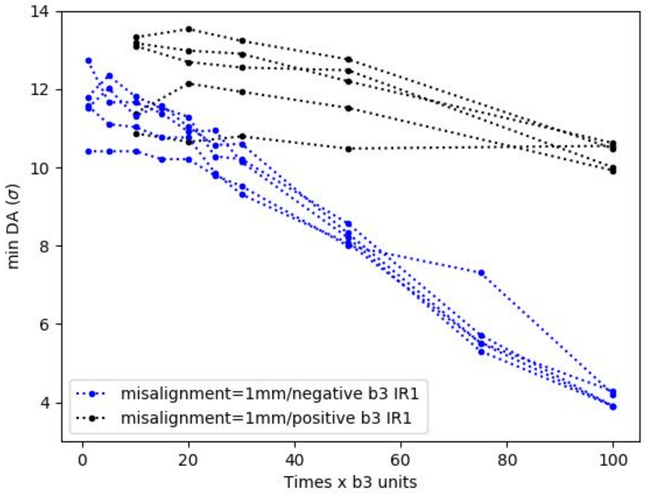

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- Positive values in IR1(RFdip) would push the limits even further and make it more stable

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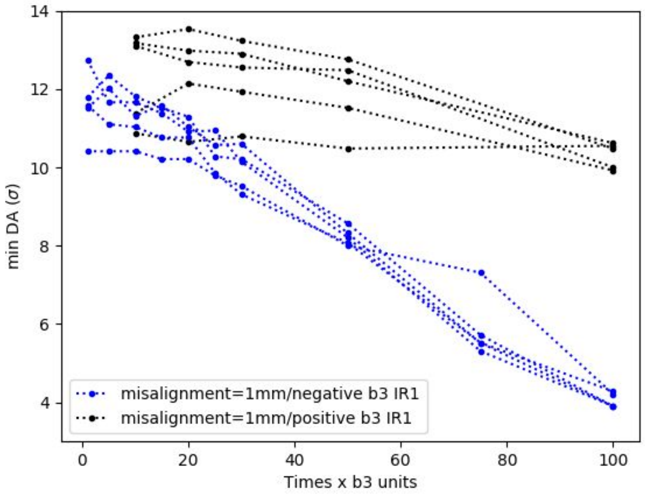

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  ~30xb3= 30-45*10^3 mT/m
- Pretty stable
- Positive values in IR1(RFdip) would push the limits even further and make it more stable

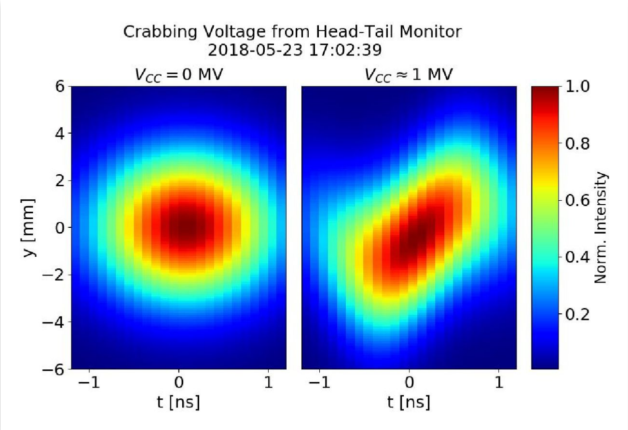
- **Case for b4:** Really stable until very large numbers for all cases (200x current values)

Beam Instrumentation - Measurement

L. Carver, IPAC19, MOPGW094

- **SPS Monitors used for CC measurements:**
  - **Head-Tail Monitor** →
  - **MOPOS**
  - **DOROS**

Measures intra-bunch offset
Primary crabbing diagnostic device in 2018



Beam Instrumentation - Measurement

L. Carver, IPAC19, MOPGW094

- **SPS Monitors used for CC measurements:**
  - **Head-Tail Monitor**
  - **MOPOS**
  - **DOROS**

80 Horizontal BPMs
113 Vertical BPMs

Beam Instrumentation - Measurement

L. Carver, IPAC19, MOPGW094

- **SPS Monitors used for CC measurements:**
  - **Head-Tail Monitor**
  - **MOPOS**
  - **DOROS** →

4 DOROS in Total
2 DOROS in either side of the CC

Beam Instrumentation - Measurement

L. Carver, IPAC19, MOPGW094

- **SPS Monitors used for CC measurements:**
  - **Head-Tail Monitor**
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  - **DOROS**
- Calculate voltage from the monitor’s response (MOPOS example)

Beam Instrumentation - Measurement

L. Carver, IPAC19, MOPGW094

- **SPS Monitors used for CC measurements:**
  - **Head-Tail Monitor**
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  - **DOROS**
- Calculate voltage from the monitor’s response (MOPOS example)
- Measurements in MD7
  - 1 MV in Cavity 1 with fixed phase
  - 1 MV in Cavity 2 with phase varied by 45 degrees

Beam Instrumentation - Measurement

L. Carver, IPAC19, MOPGW094

- **SPS Monitors used for CC measurements:**
  - **Head-Tail Monitor**
  - **MOPOS**
  - **DOROS**
- Calculate voltage from the monitor’s response (M
- Measurements in MD7
  - 1 MV in Cavity 1 with fixed phase
  - 1 MV in Cavity 2 with phase varied by 45 degrees
- CC creates orbit shift from the kick

$$u_i = \frac{\sqrt{\beta_i}}{2\sin(\pi Q)} \sum_{j=i+1}^{i+n} \theta_j \sqrt{\beta_j} \cos(\pi Q - |\psi_i - \psi_j|),$$

Beam Instrumentation - Measurement

L. Carver, IPAC19, MOPGW094

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- CC creates orbit shift from the kick
- Measured kick from BPMs and adjust MADX orbit

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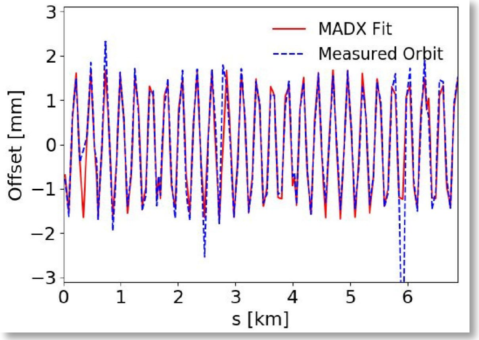

Beam Instrumentation - Measurement

L. Carver, IPAC19, MOPGW094

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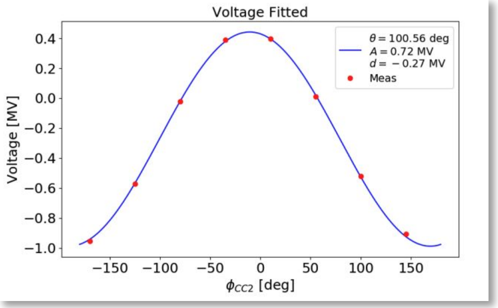
- CC creates orbit shift from the kick
- Measured kick from BPMs and adjust MADX orbit
- Calculate voltage equivalent to that kick



Voltage fitted with MOPOS

Beam Instrumentation – SPS Measurement

L. Carver, IPAC19, MOPGW094

- **SPS Monitors used for CC measurements:**
    - **Head-Tail Monitor**
    - **MOPOS**
    - **DOROS**
- Much lower voltage calculated for MOPOS and DOROS

Device	Measured Voltage (no bunch length)
Power Sensors	0.98 MV
HT Monitor	1.23 MV
MOPOS BPMs	0.72 MV
DOROS Crabs	0.62 MV

Beam Instrumentation – SPS Measurement

L. Carver, IPAC19, MOPGW094

- **SPS Monitors used for CC measurements:**
  - **Head-Tail Monitor**
  - **MOPOS -** 200 MHz Narrow band filter
  - **DOROS -** Low pass filter cutoff at 200 MHZ/High pass 60 MHz
- Much lower voltage calculated for MOPOS and DOROS

Device	Measured Voltage (no bunch length)
Power Sensors	0.98 MV
HT Monitor	1.23 MV
MOPOS BPMs	0.72 MV
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Beam Instrumentation – SPS Measurement

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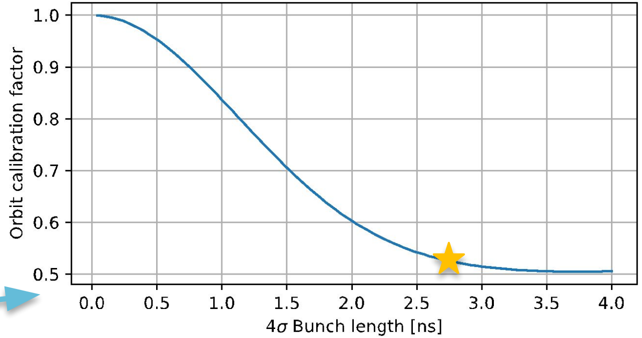
- Normalize with bunch length

L. Carver, IPAC19, MOPGW094



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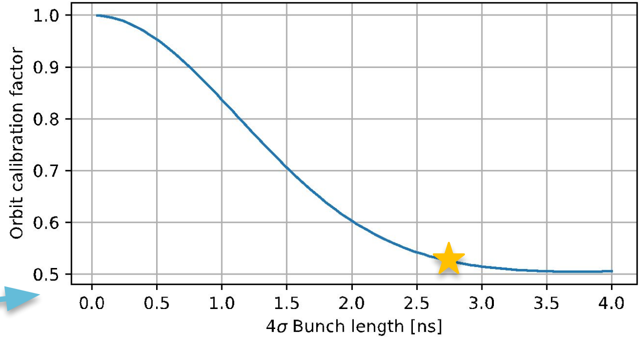
L. Carver, IPAC19, MOPGW094



Device	Measured Voltage (no bunch length)	Measured Voltage (bunch length)
Power Sensors	0.98 MV	0.98 MV
HT Monitor	1.23 MV	1.23 MV
MOPOS BPMs	0.72 MV	1.39 MV
DOROS Crabs	0.62 MV	1.25 MV

Beam Instrumentation – HL-LHC

- **Available Instrumentation:**
  - **BPMs**
  - **Head-Tail Monitor**
  - Wire Scanners (**WS**), Beam Gas Vertex (**BGV**), Beam Synchrotron Radiation Monitor (**BSRT**)

Beam Instrumentation – HL-LHC

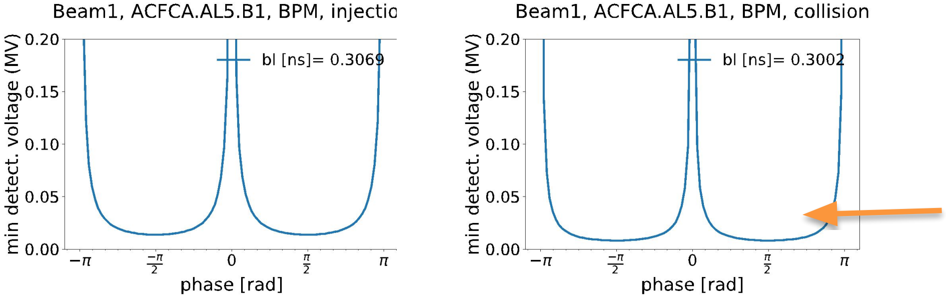
A. Alekou, H. Bartosik, M. Carla

- **Available Instrumentation:**
  - **BPMs**: Measure charge centre with an applied filter – Minimum detectable voltage
  - **Head-Tail Monitor**: Transverse offset along the bunch due to crabbing – Measured reading at monitor's location.
  - Wire Scanners (**WS**), Beam Gas Vertex (**BGV**), Beam Synchrotron Radiation Monitor (**BSRT**): Measure change in beam profile – Bunch profile difference with CC OFF/ON

Beam Instrumentation – HL-LHC

A. Alekou, H. Bartosik, M. Carla

- **Instrumentation Performance:**
  - BPMs: Measure charge centre with an applied filter



- Calculate beam center from the BPM
- Just like the case for SPS, consider BPM filter normalisation wide band low-pass filter with cut off frequency ~70MHz.
- Consider 1 μm BPM resolution
- Calculate minimum detectable voltage that can detect 1 μm for different CC-phases

$$\mathrm{x}_{\mathrm{D_{CC}}}(\mathrm{z},\mathrm{s}) = \sqrt{\beta(\mathrm{s}_0)\beta(\mathrm{s})}\,\frac{\theta}{2\mathrm{sin}\pi\mathrm{Q}}\cos\left(\psi(\mathrm{s},\mathrm{s}_0)-\pi\mathrm{Q}\right)$$

$$\theta = \frac{V}{E}\sin(\kappa z+\phi)$$

Beam Instrumentation – HL-LHC

A. Alekou, H. Bartosik, M. Carla

- **Instrumentation Performance:**
  - ○ BPMs: Measure charge centre with an applied filter

Minimum detectable voltage (MV) for 90 degrees CC phase

Injection	**L1**	**R1**	**L5**	**R5**
B1:	0.0061	0.0113	0.0138	0.0072
B2:	0.0114	0.0061	0.0071	0.0138
Collision	**L1**	**R1**	**L5**	**R5**
B1:	0.0079	0.0074	0.0083	0.0083
B2:	0.0074	0.0079	0.0083	0.0083

- Calculate beam center from the BPM
- Just like the case for SPS, consider BPM filter normalisation wide band low-pass filter with cut off frequency ~70MHz.
- Consider 1 μm BPM resolution
- Calculate minimum detectable voltage that can detect 1 μm for different CC-phases

$$x_{D_{CC}}(z,s) = \sqrt{\beta(s_0)\beta(s)}\frac{\theta}{2\sin\pi Q}\cos\left(\psi(s,s_0) - \pi Q\right)$$

$$\theta = \frac{V}{E}\sin(\kappa z + \phi)$$

- Minimum voltage for a 90 degree CC phase

  0.0061-0.0138 MV injection

  0.0074-0.0083 MV collision

Beam Instrumentation – HL-LHC

A. Alekou, H. Bartosik, M. Carla

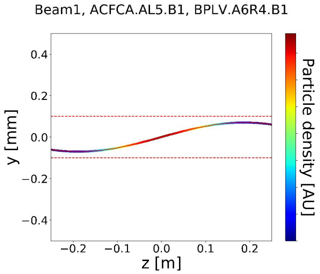
- **Instrumentation Performance:**
  - Head-Tail Monitor: Transverse offset along the bunch due to crabbing

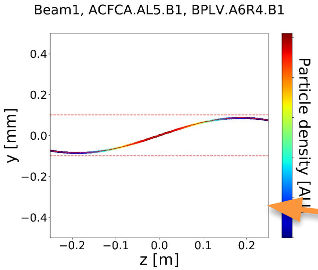
- Originally designed to measure chromaticity and transverse stabilities
- Resolution 0.1 mm

Beam Instrumentation – HL-LHC

A. Alekou, H. Bartosik, M. Carla

- **Instrumentation Performance:**
    - Head-Tail Monitor: Transverse offset along the bunch due to crabbing



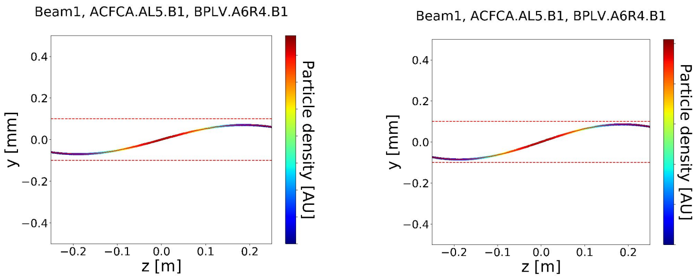


- Originally designed to measure chromaticity and transverse stabilities
- Resolution 0.1 mm
- HT-reading for Beam 1 at injection and collision.

Beam Instrumentation – HL-LHC

A. Alekou, H. Bartosik, M. Carla

- **Instrumentation Performance:**
  - Head-Tail Monitor: Transverse offset along the bunch due to crabbing



Injection	**L1**	**R1**	**L5**	**R5**
HT - B1	0.15	0.26	0.09	0.18
HT - B2	0.21	0.50	0.37	0.26
Collision	**L1**	**R1**	**L5**	**R5**
HT - B1	0.02	0.02	0.07	0.07
HT - B2	0.11	0.10	0.04	0.05

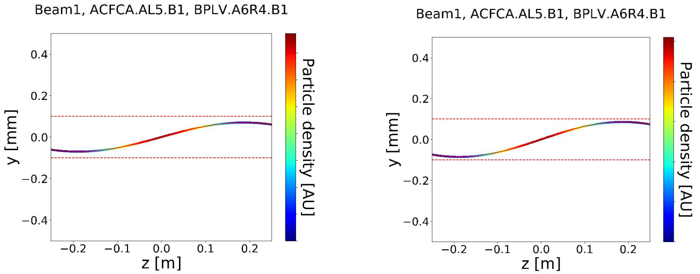
Maximum reading for a 1 MV kick (mm)

- Originally designed to measure chromaticity and transverse stabilities
- Resolution 0.1 mm
- HT-reading for Beam 1 at injection and collision.
- Maximum HT reading when 1 CC pair is ON at 1 MV at injection and collision
- Whether is enough resolution depends of operational voltage

Beam Instrumentation – HL-LHC

A. Alekou, H. Bartosik, M. Carla

- **Instrumentation Performance:**
  - Head-Tail Monitor: Transverse offset along the bunch due to crabbing



Injection	**L1**	**R1**	**L5**	**R5**
HT - B1	0.15	0.26	0.09	0.18
HT - B2	0.21	0.50	0.37	0.26
Collision	**L1**	**R1**	**L5**	**R5**
HT - B1	0.02	0.02	0.07	0.07
HT - B2	0.11	0.10	0.04	0.05

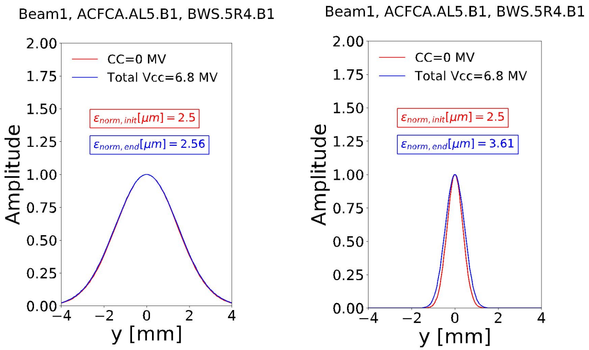
Maximum reading for a 1 MV kick (mm)

- Originally designed to measure chromaticity and transverse stabilities
- Resolution 0.1 mm
- HT-reading for Beam 1 at injection and collision.
- Maximum HT reading when 1 CC pair is ON at 1 MV at injection and collision
- Whether is enough resolution depends of operational voltage
- Electro-optic BPM option is being pursued *(M. Wendt/ Status of beam Instrumentation*)

Beam Instrumentation – HL-LHC

A. Alekou, H. Bartosik, M. Carla

- **Instrumentation Performance:**
  - Wire Scanners (WS), Beam Gas Vertex (BGV), Beam Synchrotron Radiation Monitor (BSRT): Measure change in beam profile



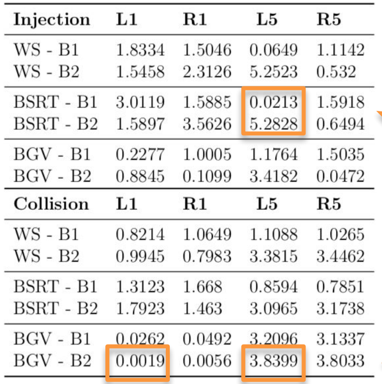
Emittance difference measured with WS

- Measure effect on crabbing on beam profile using a Gaussian distribution in transverse and longitudinal
- Use maximum kick (3.4 MV per CC, 6.8 in total)

Beam Instrumentation – HL-LHC

A. Alekou, H. Bartosik, M. Carla

- **Instrumentation Performance:**
  - Wire Scanners (WS), Beam Gas Vertex (BGV), Beam Synchrotron Radiation Monitor (BSRT): Measure change in beam profile



Injection	L1	R1	L5	R5
WS - B1	1.8334	1.5046	0.0649	1.1142
WS - B2	1.5458	2.3126	5.2523	0.532
BSRT - B1	3.0119	1.5885	0.0213	1.5918
BSRT - B2	1.5897	3.5626	5.2828	0.6494
BGV - B1	0.2277	1.0005	1.1764	1.5035
BGV - B2	0.8845	0.1099	3.4182	0.0472
Collision	**L1**	**R1**	**L5**	**R5**
WS - B1	0.8214	1.0649	1.1088	1.0265
WS - B2	0.9945	0.7983	3.3815	3.4462
BSRT - B1	1.3123	1.668	0.8594	0.7851
BSRT - B2	1.7923	1.463	3.0965	3.1738
BGV - B1	0.0262	0.0492	3.2096	3.1337
BGV - B2	0.0019	0.0056	3.8399	3.8033

Emittance difference (µm) after a 6.8 MV kick (initial emittance 2.5 µm)

- Measure effect on crabbing on beam profile using a Gaussian distribution in transverse and longitudinal
- Use maximum kick (3.4 MV per CC, 6.8 in total)
- Emittance difference at injection:

  0.0213 to 5.28 µm
- Emittance difference at collision

  0.0019 to 3.8399 µm

Conclusions

- DA studies were performed to study **impact of the RF multipoles in the SPS and HL-LHC**
  - Nominal values show little impact in both the SPS (even for larger numbers of a3) and HL-LHC
  - Further studies were done to **explore limits on HL-LHC**:
    - → b2 increasing by 5-15 times current values, b3 increasing by 20-30 times and 1 mm misalignments
    - → Signs between values in two CC models can make a big difference in limits
    - → Cases with beam-beam are dominated instead by this effect
- **Skew sextupolar component** was calculated from **BPM response in the SPS**
    - → Very good agreement for test using octupole feed down
    - → Results for CC **a3 is larger than nominal value**. Large phase used to adjust suggesting other a3 sources – under investigation
- Voltage from CC calculated from the different monitors in SPS shows **good agreement between each other**, but slightly different from power sources.
- Studies were done to calculate the **performance of the current instrumentation on the HL-LHC** with CC
    - → BPMs, minimum detectable voltage at injection and collision, order of ~10 kV
    - → HT, maximum orbit at its location for each CC ON
    - → WS, BSRT, BGV change in beam profile between CC OFF and at 6.8 MV

HiLumi
HL-LHC PROJECT

Thank you!

CERN

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