2nd Joint HiLumi LHC-LARP Annual Meeting

RF multipoles: modeling and impact on the beam

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Crab Cavity RF Multipoles

- 3 compact crab cavities are currently under design in the framework of the HiLumi LHC project.
- Due to lack of axial symmetry they present high order multipolar components of the main field.
- In this case the multipoles are complex numbers, however the $\Im$ part of the multipoles is zero within the accuracy of the calculation i.e. $\phi_{RFmult} = 0$.
- They are in phase with the main crabbing mode.

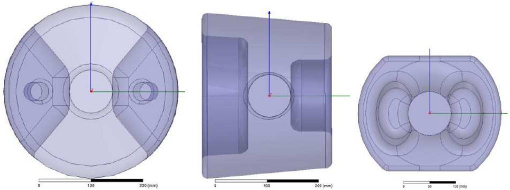


Figure: RWCAV (left), QWCAV (middle), 4RCAV (right).

Table: RF Multipoles for V_{cc} =10 MV in [mTm/m^{n-1}].

	MBRC	RWCAV	QWCAV	4RCAV
b_2	55	0	114	0
b_3	7510	3200	1260	900
b_4	82700	0	1760	0
b_5	2.9×10^6	-0.52×10^6	-0.15×10^6	-2.44×10^6
b_6	52×10^6	0	-1.66×10^6	0
b_7	560×10^6	-140×10^6	0	-650×10^6

Courtesy of A. Grudiev (IPAC12)

HL-LHC optics

HiLumi LHC optics version used `SLHCV3.1b` and SixTrack mask `jobslhc31b_rnd_mbdc.mask`

- β^*=15 cm
- Current optics demands V_{CC}/IP/side~ 10 MV. Studies ongoing to minimize the required voltage (see B. Dalena's talk in this session)
- Single crab cavity voltage V_{CC} ~3 MV $\Longrightarrow$ 3 CC/IP/side are needed.
- Errors and corrections are applied to IRs and ARCS (60 seeds).
  - `tripD1D2.errors` $\Longrightarrow$ `MQX, MBR, MBX`
  - `MB.errors` $\Longrightarrow$ `MB`

Dynamic aperture (DA) simulations are done using the SixDesk Run Enviroment.

- Amplitudes ranging from 4-40 σ depending on the case
- 5 angles (15, 30, 45, 60 and 75 deg)
- $\frac{dp}{p} = 0.27‰$

Single RF Multipole Element Implementation in SixTrack

- To perform long term stability simulations RF multipoles were modeled and included in the SixTrack code as single elements.
- The RF multipoles are as well available in MADX (thanks to A. Latina) and the conversion MADX-SixTrack is operative.

Normal Quadrupole

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

Normal Sextupole

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

Normal Octupole

$$\Delta x' = -b_4\left(x^3 - 3xy^2\right)\cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,oct}}\right)$$
$$\Delta y' = b_4\left(3x^2 y - y^3\right)\cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,oct}}\right)$$
$$\Delta \delta = \frac{b_4}{4}\left(x^4 - 6x^2y^2 + y^4\right)\sin\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,oct}}\right)\frac{\omega}{c}$$

Skew Quadrupole

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

Skew Sextupole

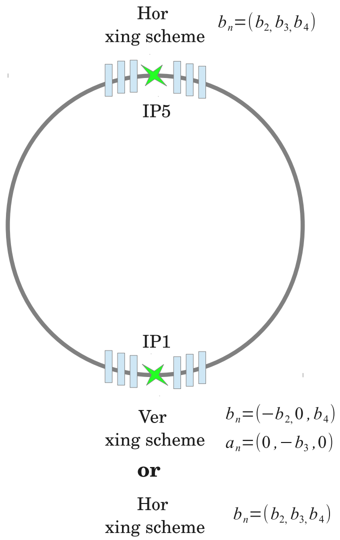
$$\Delta x' = -2 b_3 x y \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,sext}}\right)$$
$$\Delta y' = b_3\left(y^2 - x^2\right)\cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,sext}}\right)$$
$$\Delta \delta = -\frac{b_3}{3}\left(y^3 - 3yx^2\right)\sin\left(\frac{\omega z}{c} + \phi_s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

Skew Octupole

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

Crossing Schemes

- 2 scenarios considered,
  - H_{IP5}-V_{IP1}
  - H_{IP5}-H_{IP1}
- In the case of vertical crossing scheme at IP1 the multipoles will be rotated b_2 by 90°, b_3 by 60° and b_4 by 45° wrt to IP5.
- Note that in H_{IP5}-V_{IP1} the b_2 cancels out, while in H_{IP5}-H_{IP1} they add up.



Optics Aberrations produced by CC RF Multipoles

Analytical formulas for optical aberrations for H and V crossing schemes,

- Tune shift,

$$|\Delta Q_{x,y}| = \frac{1}{4\pi}\beta_{x,y}\frac{b_2}{B\rho}$$

- Tune shift with amplitude,

$$|\Delta Q/J_x| = \frac{3}{8\pi}\beta^2_{x,y}\frac{b_4}{B\rho}.$$

- Chromaticity shift,

$$|\Delta\xi_{x,y}| = \frac{1}{4\pi}D_x\frac{2b_3}{B\rho}\beta_{x,y}$$

$$|\Delta\xi_{x,y}| = \frac{1}{4\pi}D_y\frac{2a_3}{B\rho}\beta_{x,y}$$

- Coupling,

$$|\Delta Q_{\text{min}}| = \sqrt{\beta_x\beta_y}\frac{2b_3}{B\rho}D_y\sigma_\delta$$

$$|\Delta Q_{\text{min}}| = \sqrt{\beta_x\beta_y}\frac{2a_3}{B\rho}D_x\sigma_\delta$$

Analytical Estimations

- Computed optics aberrations due to CC RF multipoles up to octupole.
- Values calculated per CC(V_{cc}=10 MV)/IP/side.
- Assumed spurious dispersion D_x =1 m.

Table: Horizontal CC

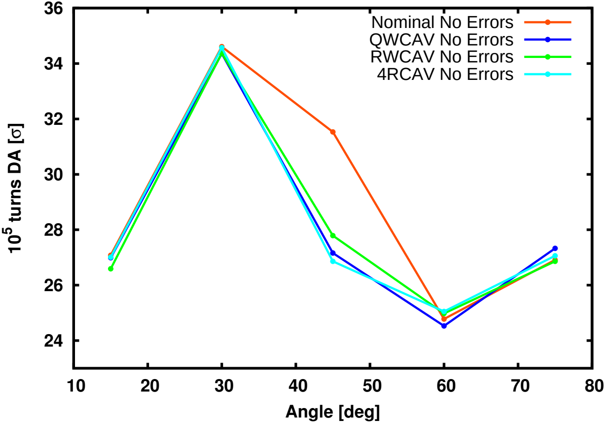
	RWCAV	QWCAV	4RCAV
$\|\Delta Q_{x,y}\|$	0	1.4×10^{-3}	0
$\|\Delta\xi_{x,y}\|$	7.96×10^{-2}	3.13×10^{-2}	2.24×10^{-2}
$\|\Delta Q_{\min}\|$	0	0	0
$\|\Delta Q^{3\sigma}_{x,y}\|$	0	5.06×10^{-6}	0

Table: Vertical CC

RWCAV	QWCAV	4RCAV
0	1.4×10^{-3}	0
0	0	0
2.9×10^{-4}	1.14×10^{-4}	8.17×10^{-5}
0	5.06×10^{-6}	0

DA Simulations: Case H_{IP5}-V_{IP1} w/o errors

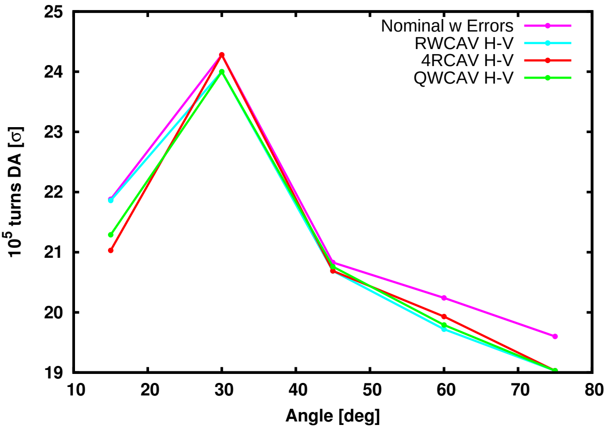
All 3 CCs present similar behavior with $DA_{min} \sim 24.5\sigma$ and almost identical to the case w/o CC RF multipoles.



In a H-V crossing scheme the tuneshift due to the b_2 is cancelled.

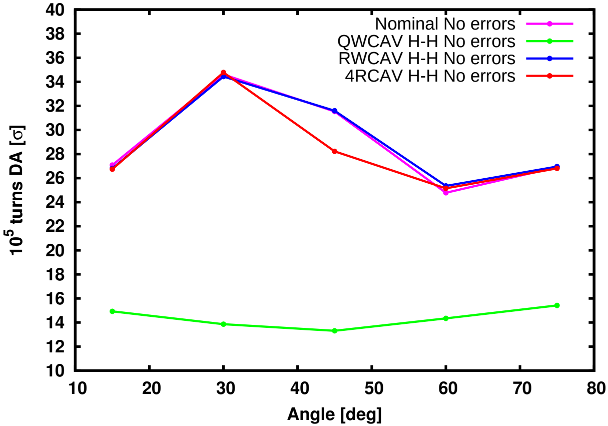
DA Simulations: Case H_{IP5}-V_{IP1} with errors

All 3 CCs present similar behavior with $DA_{min} \sim 19.0\sigma$. Errors and corrections in IRs and ARCS decrease the DA_{min} by 5σ. In addition there is a decrease of $\sim 0.75\sigma$ for all CC cases wrt to the nominal scenario.



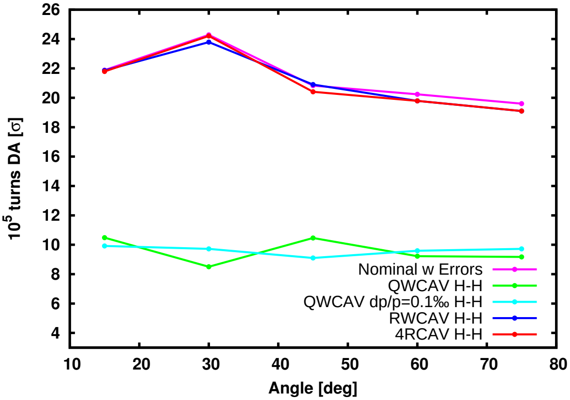
DA Simulations: Case H_{IP5}-H_{IP1} w/o errors

In a H-H crossing scheme there is no b_2 cancellation so the expected tuneshift is $\Delta Q_{x,y} \sim 5\ 10^{-3}$. In the QWCAV there will be likely resonance crossing leading to a $DA_{min,QWCAV} \sim 14\sigma$. The other two CCs are almost identical with the nominal case with $DA_{min} \sim 25.5\sigma$.



DA Simulations: Case H_{IP5}-H_{IP1} with errors

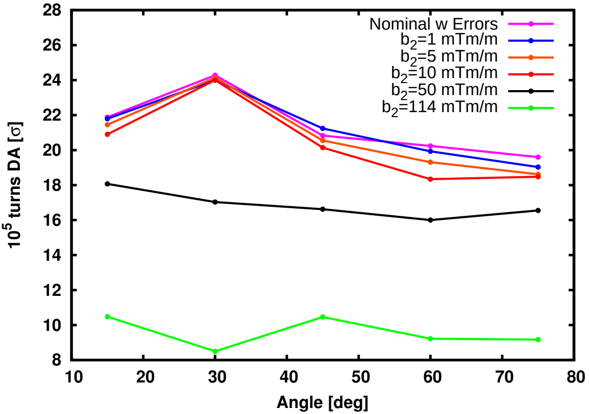
In a H-H crossing scheme there is no b_2 cancellation so the expected tuneshift is $\Delta Q_{x,y} \sim 5\ 10^{-3}$. In the QWCAV there will be likely resonance crossing decreasing $DA_{min,QWCAV} \sim 8\sigma$.



Comparing $\frac{dp}{p} = 0.1‰$(i.e. $\sim 1\sigma_E$) results vs $0.27‰$(i.e. $\sim 2.5\sigma_E$), there is not significant change in the DA.

DA Simulations: Case H_{IP5}-H_{IP1} QWCAV with b_2 scaled

Just recently alignment of the CC inside cryo-module tolerances topic was raised. As first rough approximation we use the QWCAV case to scale b_2 to define an upper limit assuming we arbitrary set allowable $\Delta DA_{min} \sim 1\,\sigma$ to characterize the tolerable $d_{x,y}$ for different b_3.
It is found that $b_{2,max}$= 5 mTm/m in order to keep the DA drop around 1 sigma in the QWCAV case.

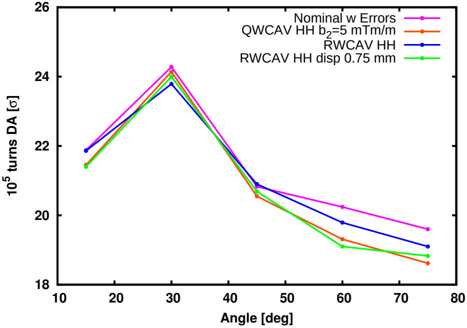


DA Simulations: Case H_{IP5}-H_{IP1} b_3 with misalignments

Assuming the previous arbitrary upper limit of tolerable b_2 misalignments for each CCs for ΔDA< 1σ in an H-H crossing schememem are,

- QWCAV (only HV) $|d_{x,y}| < 2$ mm
- RWCAV (HH or HV) $|d_{x,y}| < 0.75$ mm
- 4RCAV (HH or HV) $|d_{x,y}| < 2.7$ mm

Again very good agreement is found between analytical estimation and real tracking results.



Conclusions & Outook

- Single elements RF multipoles has been implemented in SixTrack. Normal and skew multipoles up to octupolar component are now available.
- Optics aberrations due to RF multipoles have been evaluated analytically.
- Very good agreement is found between the analytical estimations and tracking results.
- Two different crossing schemes considered: H_{IP5}-H_{IP1} and H_{IP5}-V_{IP1}.
- The effect of the initial dp/p (0.1-0.27‰) does not play a significant role in the DA simulations.
- In the H_{IP5}-V_{IP1} the CC RF mult effect on the DA is only ΔDA ~0.75σ.
- In the H_{IP5}-H_{IP1} scheme the large tuneshift for the QWCAV is an issue.
- Preliminary arbitrary alignment tolarences of CC cryo-module and orbit control are given to limit the DA drop.
- The implementation of RF multipoles Taylor Maps by David Brett (PhD from Manchester U.) in SixTrack is very advanced.