Beam Dynamics Aspects of Crab Cavities in LHC and CLIC

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Luminosity in colliders

The performance of a collider is typically evaluated by the luminosity ($\mathscr{L}$) achieved. It is a proportional factor between the cross section (σ_p) and the number of interaction per unit of time $\frac{dR}{dt}$,

$$\frac{dR}{dt} = \mathscr{L} \times \sigma_p.$$

Analytically the luminosity writes,

$$\mathscr{L} = f_{\mathrm{rev}} n_b \frac{n_1 n_2}{4\pi\sigma_x\sigma_y} S,$$

with S the geometric factor that counts for the loss of luminosity due to the crossing scheme (other correction factors are omitted here).

Is this effect neglilible? Some numbers[1]

LHC 4 TeV (2012) → S=0.84.
LHC 7 TeV (2015) → S=0.82.
LHC 7 TeV (2023) → S ~0.37
CLIC 1.5 TeV (???) → S=0.10.

Way to recover from this loss? Crab crossing

[1] Courtesy R. Calaga

Crab Cavities to recover Luminosity

- The crab cavity concept was first proposed by R. Palmer[2] for linear collider to recover head on collisions and avoid luminosity loss. A crab cavity is a deflection cavity operated with a 90° phase shift (crabbing).
- However for LHC was only considered from late mid-2000. First beam physics reviewed paper,

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Beam dynamics aspects of crab cavities in the CERN Large Hadron Collider

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[2] R.B. Palmer,"Prospects for high energy e-e-linear colliders", Annual Review of Nuclear and Particle Science 40, 6 529-592 (1990).

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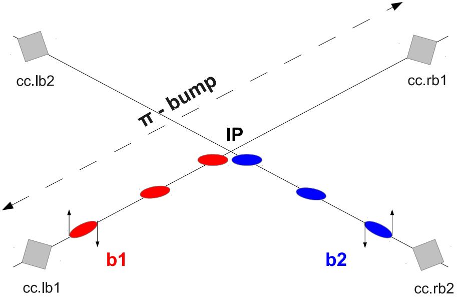
- However for LHC was only considered from late mid-2000. First beam physics reviewed paper,
- The voltage needed depends on the relative position CC-IP, crossing angle and RF frequency.

$$V_{\mathrm{CC}} = \frac{\frac{\theta_c}{2} E_0 c}{R_{12}^{\mathrm{CC\text{-}IP}} q \omega_{\mathrm{RF}}}.$$



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CC in HiLumi LHC

- One of the key ingredients of the HiLumi LHC is the use of crab cavities to recover $\mathscr{L}$. Tests with beam in the SPS are planned from 2016.
- 3 compact crab cavities under design. Different geometries. 3 MV, 400 MHz.
- Due to lack of axial symmetry they present high order multipolar components of the main field. The $\Im$ part of the multipoles is zero within the accuracy of the calculation i.e. $\phi_{\mathrm{RFmult}} = 0$. But in phase with the main crabbing mode.
- Analytical evaluation of the optical aberrations showed a non neglilible tune shift for QWCAV.
- Two scenarions considered: $\mathrm{H_{IP5}}$-$\mathrm{V_{IP1}}$ and $\mathrm{H_{IP5}}$-$\mathrm{H_{IP1}}$.

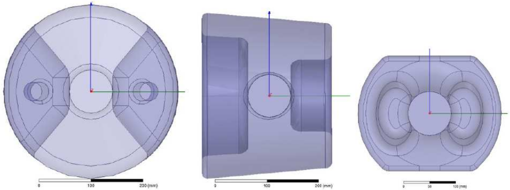

Figure: RWCAV (left), QWCAV (middle), 4RCAV (right).

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)

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- 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,

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

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

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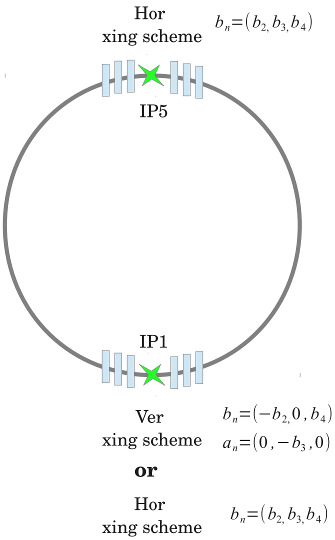


Single RF Multipole Element Implementation in SixTrack

- First time ever long term stability studies including CC RF multipoles.
- They were modeled and included in the SixTrack code up to octupolar component.

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

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

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

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

Skew Sextupole

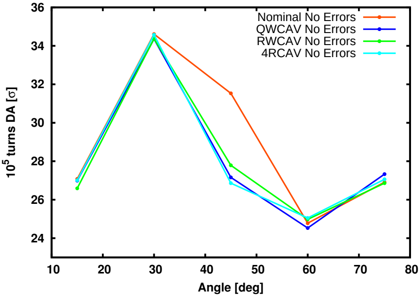
$$\Delta x' = -2b_3 xy \cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,sext}}\right)$$
$$\Delta y' = b_3\left(y^2 - x^2\right)\cos\left(\frac{\omega z}{c} + \phi_s + \phi_{\mathrm{RF,sext}}\right)$$
$$\Delta\delta = -\frac{b_3}{3}\left(y^3 - 3yx^2\right)\sin\left(\frac{\omega z}{c} + \phi_s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

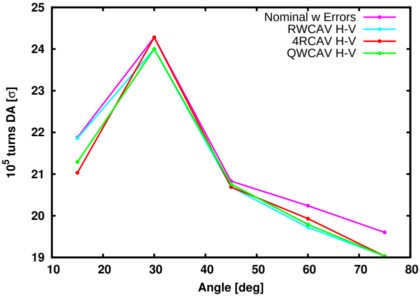
Skew Octupole

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

HL-LHC DA Simulations w CC RF mult: H-V xing scheme

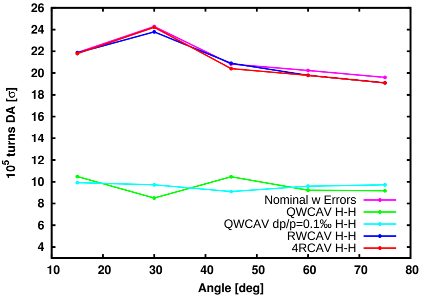
- Dynamic Aperture is the **boundary of the stable motion** in circular accelerators. It is determined by massive tracking campaigns where particles are tracked during 10^5 turns at different initial amplitudes and angles.
- Two scenarios: 1) perfect machine and 2) with errors and corrections are applied to IRs and ARCS (60 seeds).
- In a H_{IP5}-V_{IP1} crossing scheme the overall tune shift due to the b_2 is cancelled for the QWCAV.

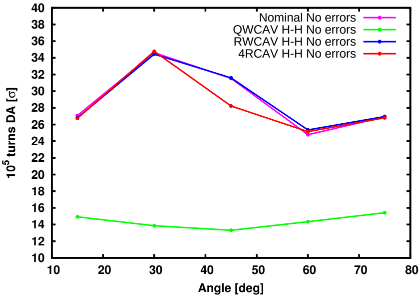




HL-LHC DA Simulations w CC RF mult: H-H xing scheme

- In a H_{IP5}-H_{IP1} the large tune shift will produce resonance crossing with a significant drop of the DA ($\sim 11\sigma$)



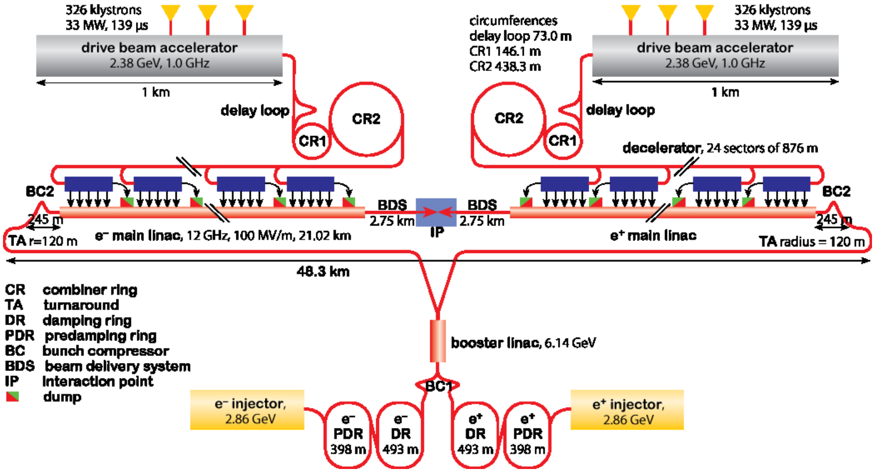


Conclusion: high order multipoles can affect significantly the LHC DA either direct tune shift (b_2) or feed down effects. First rough alignment tolerances (simulations not shown here) provided,

- 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

Compact LInear Collider (CLIC)

Multi-TeV e^+-e^- collider (2 beam acceleration → accelerating gradient 100 MV/m)



Traveling Waist Regime in CLIC FFS

We observed in simulations an unexpected loss of luminosity of $\Delta\mathscr{L}/\mathscr{L}_{headon}$ ~-10%. After careful study this loss was explained from the evolution of the beam waist during the collision or traveling waist regime[4]. This effect is explained from the aberrations induced due to a z-dependent off-center horizontal orbit in the Final Focus sextupoles produced by the crab cavity.

$$\frac{\partial w_y}{\partial z} = -\beta_y^* \sum_i^{n_s} \sum_j^{n_{cc}} R_{12}^{\mathrm{CC}_j\text{-sext}_i} \beta_{y_i} \xi_c K_i L_i.$$

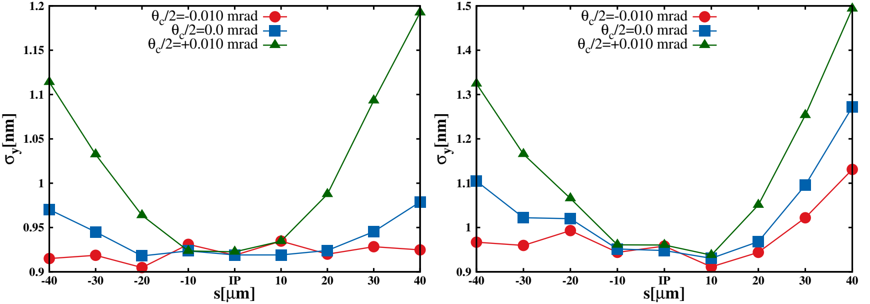
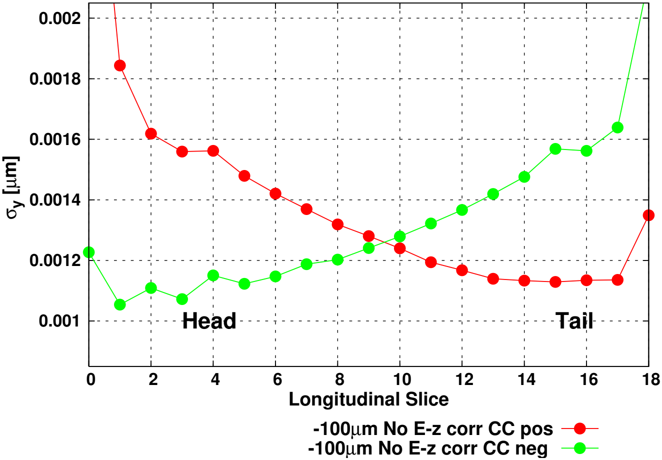


Figure: Left case w/o E-z correlation from the linac and right with correlation.

[4] V.E. Balakin et al. (Branch Inst. Nucl. Phys., Protvino, 1992).

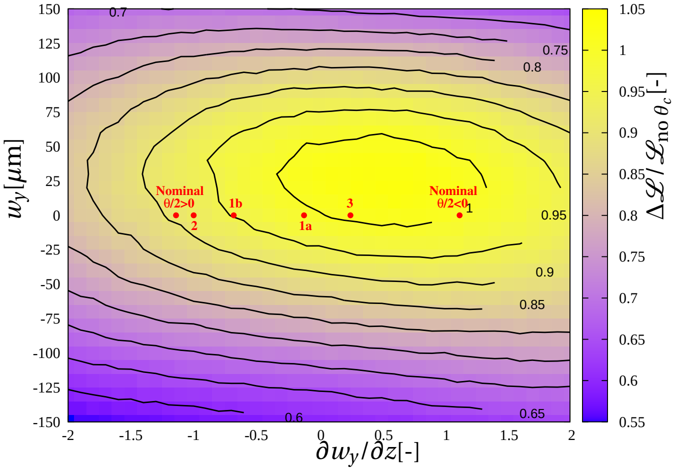
Traveling Waist Scheme at CLIC Final Focus

Traveling waist in motion!



Fixing the problem

Three options: 1) change the main linac+BDS orientation to revent the crossing angle, 2) place the CC in a more convenient place from optics point view and 3) adding a second CC (less prefered).



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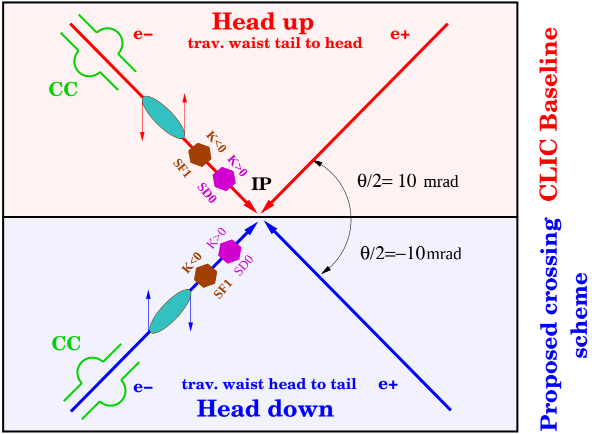

Conclusions

- Crab cavities are proved to be indispensable to recover head on luminosity in the presence of crossing angle.
- CCs are one of the main ingredients of the next HiLumi LHC. CC beam dynamis are progressing accordingly.
- CC design should aim for low high order multipoles to avoid optics distortions.
- The crossing scheme at CLIC previously a free parameter is now fixed to avoid luminosity loss. This study was recently approved by PRSTAB for publication.