Single crab cavity test scenario in LHC

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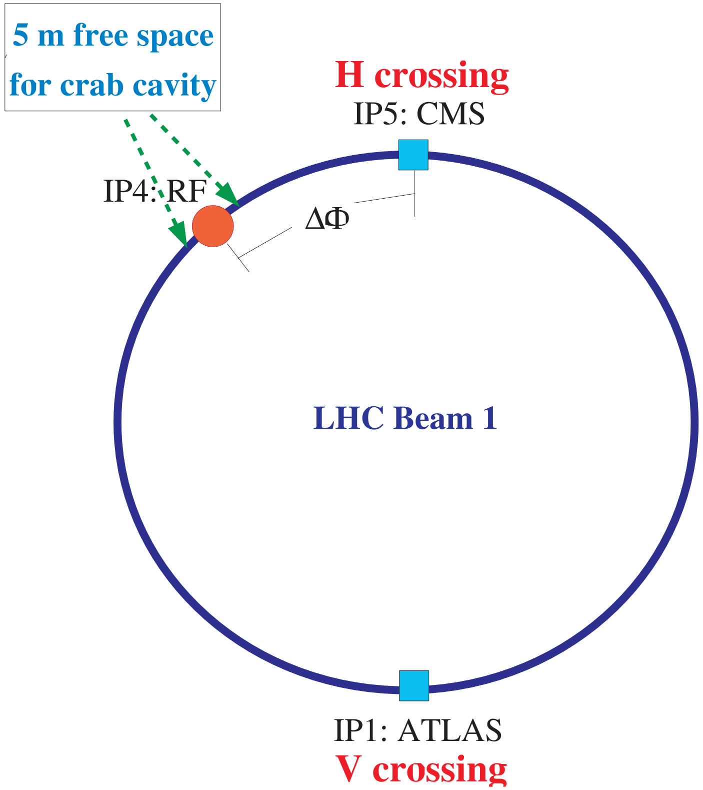
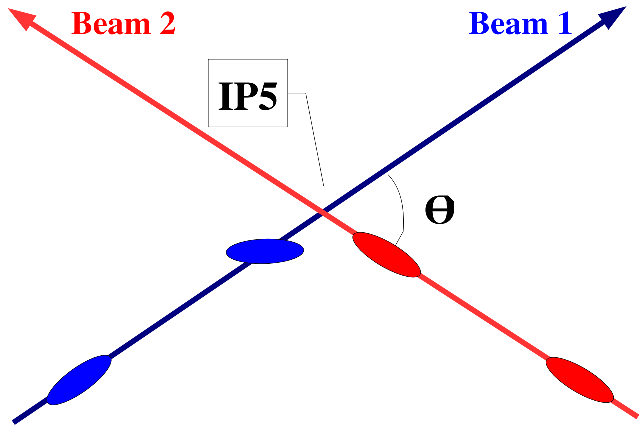
- Test scenario & IR4 Optics
- Luminosity gain
- Dynamic aperture, aperture & β-beating
- Emittance growth
- Collimation
- BB tune shift & synchro-betatron resonances
- Impact of beam-beam long-range effects

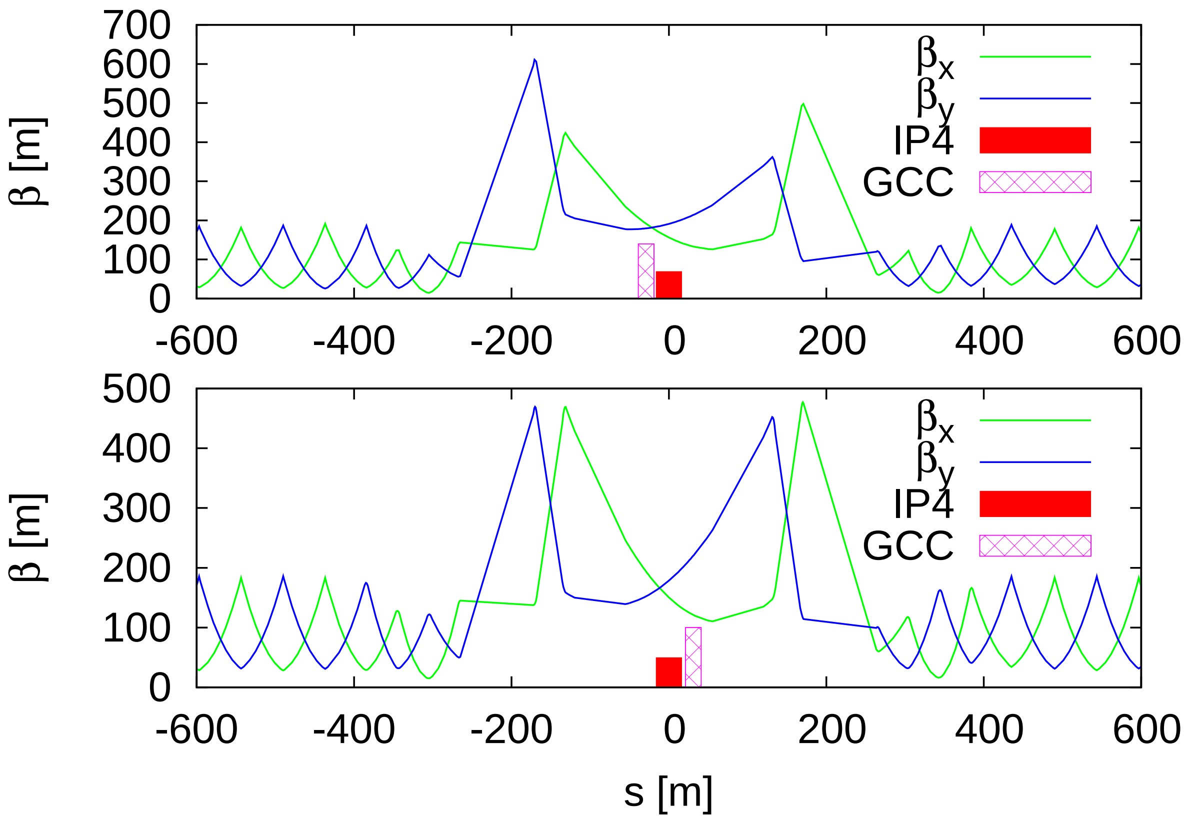
Proposed test scenario





- Only one global CC at IP4 to crab beam 1 at IP5
- Aim for 10% (max 25%) luminosity gain

IR4 Optics



1) Increase β_{CC} (up to 3 km) –> 2.3 MV

2) Move Q_x near int. (factor 3 reduction for $Q_x = 0.1$)

Luminosity analytical treatment

Geometric loss: $R = \frac{1}{\sqrt{1+\left(\frac{\sigma_z}{\sigma_x^*} tan(\theta/2)\right)^2}}$

$$\rho_x(x) = \frac{1}{\sigma_x\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma_x^2}\right)$$

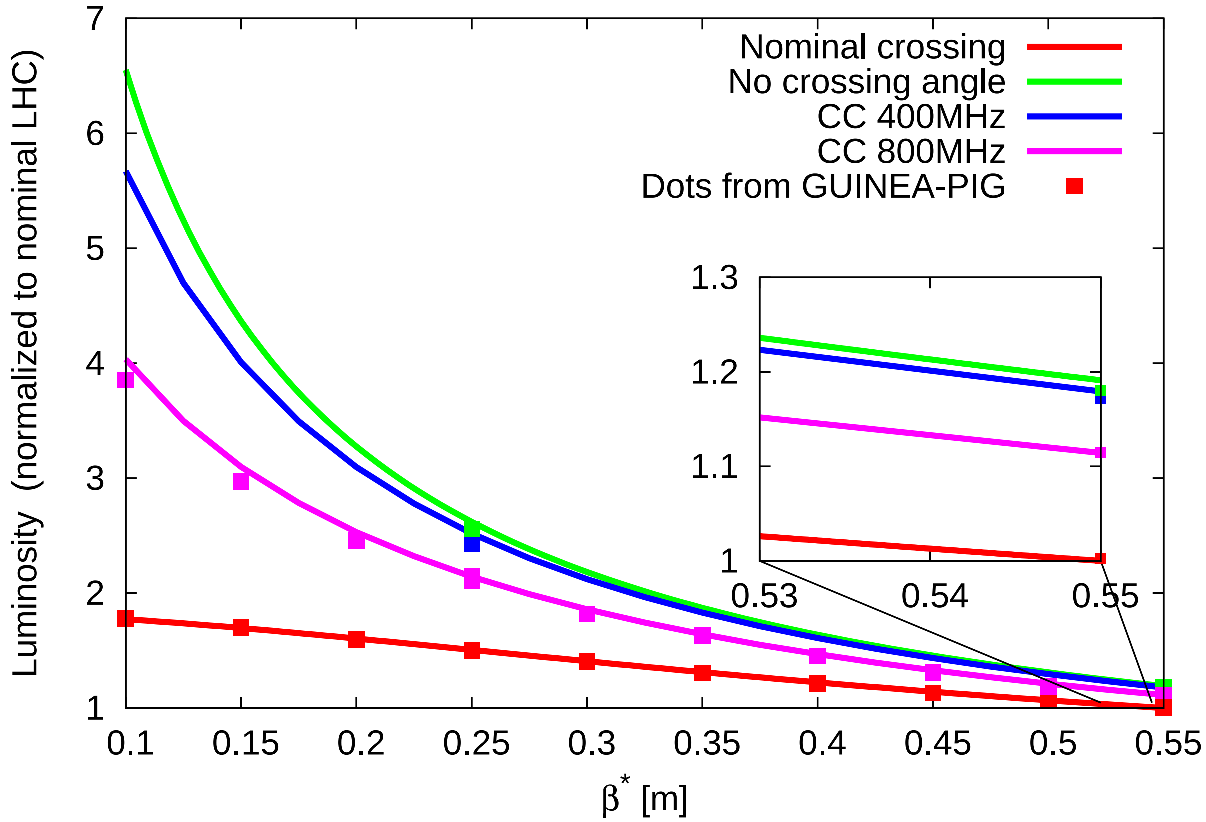
$$\rho_z(z) = \frac{1}{\sigma_z\sqrt{2\pi}} \exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

$$V_1 = \frac{c^2 \cdot p_s \cdot \tan(\frac{\theta}{2})}{q \cdot \omega_{crab} \cdot R_{12}}$$

$$\Delta x_{1,2} = \pm R_{12} \cdot \frac{qV_1}{c \cdot p_s} \cdot sin\left(\frac{2\pi f_{crab}(s \mp ct)}{c}\right)$$

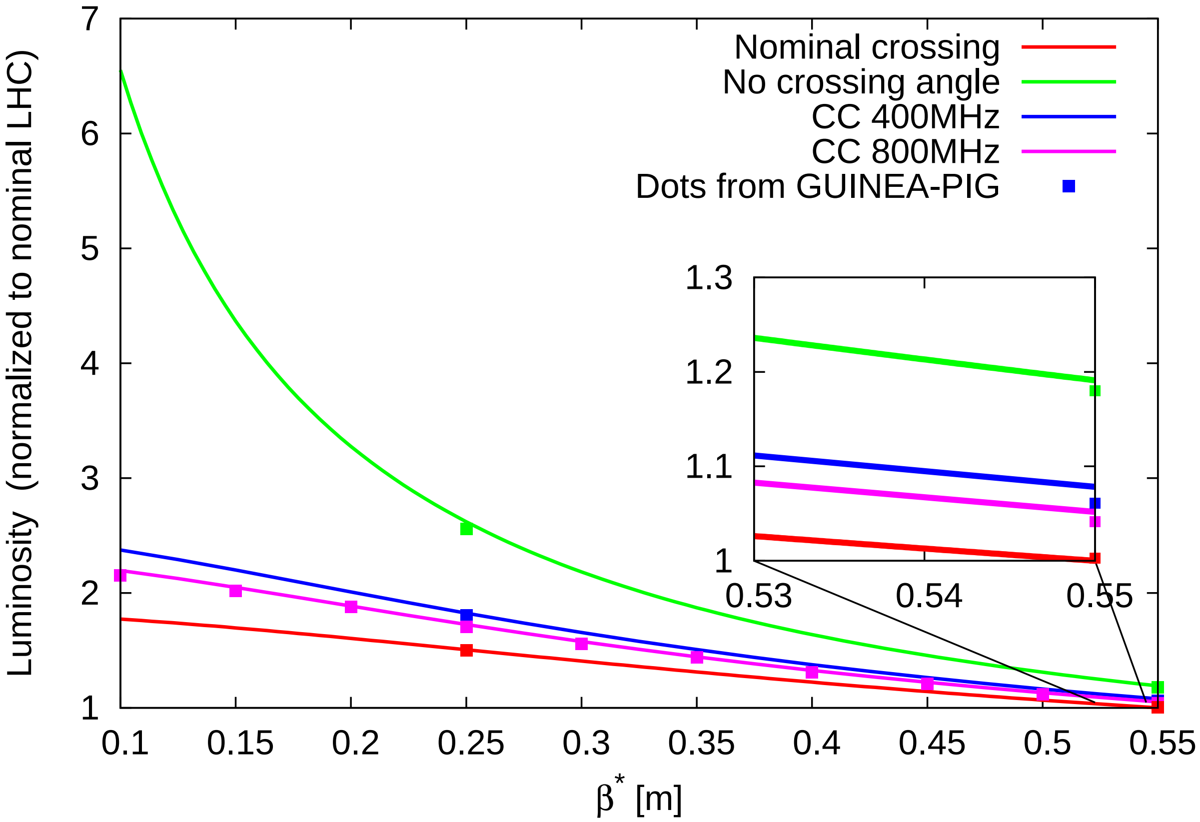
$$L = \frac{cN_b^2 f_{rev} n_b}{\sqrt{\pi}\sigma_y} \cos^2(\theta/2) \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \rho_x(x_1)\rho_z(s_1 - ct)\rho_x(x_2)\rho_z(s_2 + ct) dx ds dt$$

Luminosity for two beams crabbed



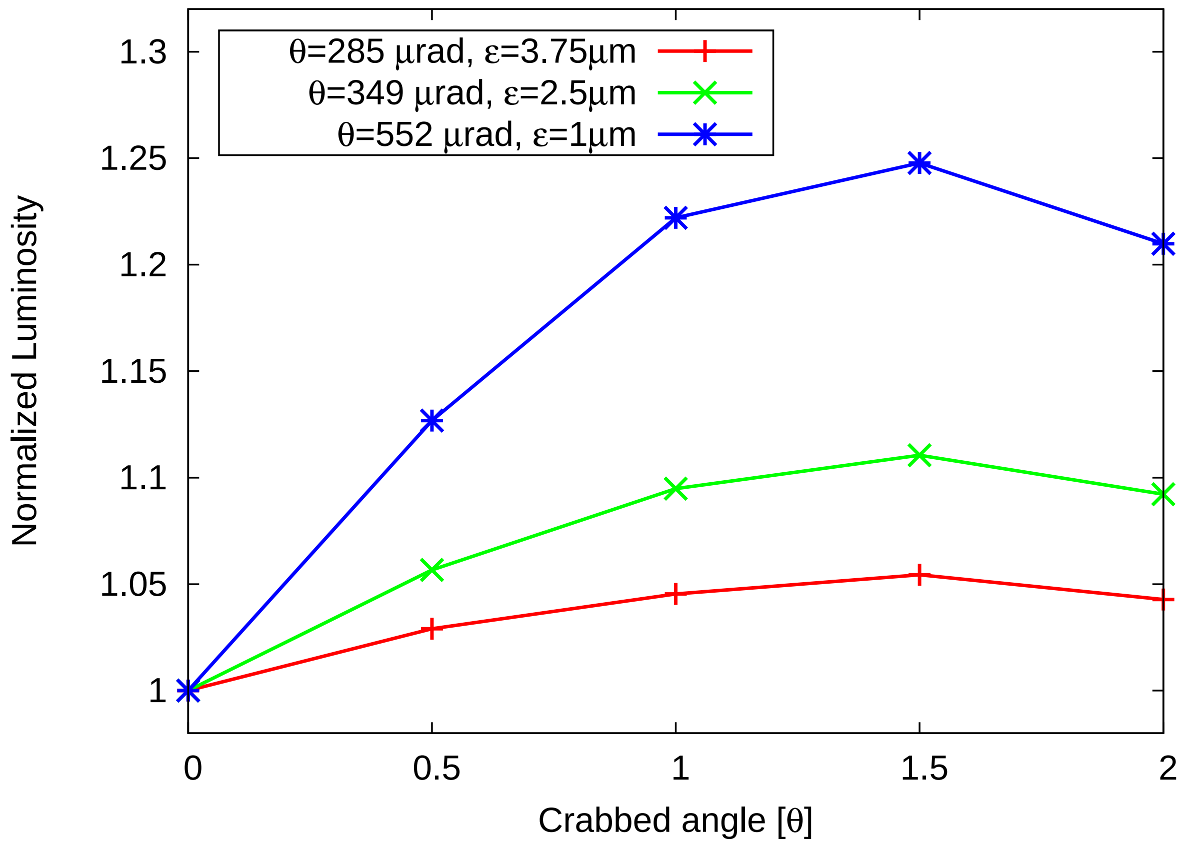
- Normalised luminosity (up to 3 times increase)
- Analytical formulae (curves) and GUINEA-PIG simulations (dots) **agree well**

Luminosity for single beam crabbed



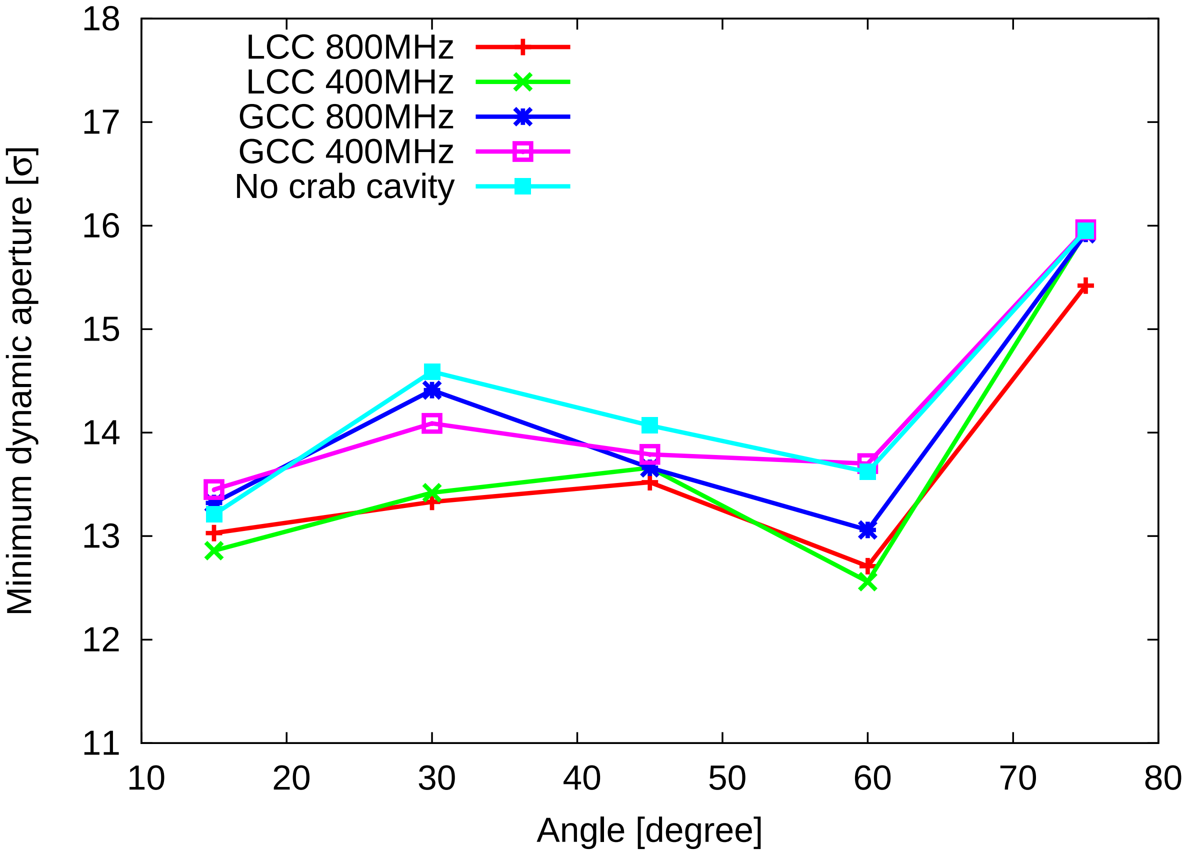
Normalised luminosity, analytical formulae (curves) and GUINEA-PIG simulations (dots) **agree well**

Luminosity gain, low ϵ (TOTEM) + large θ



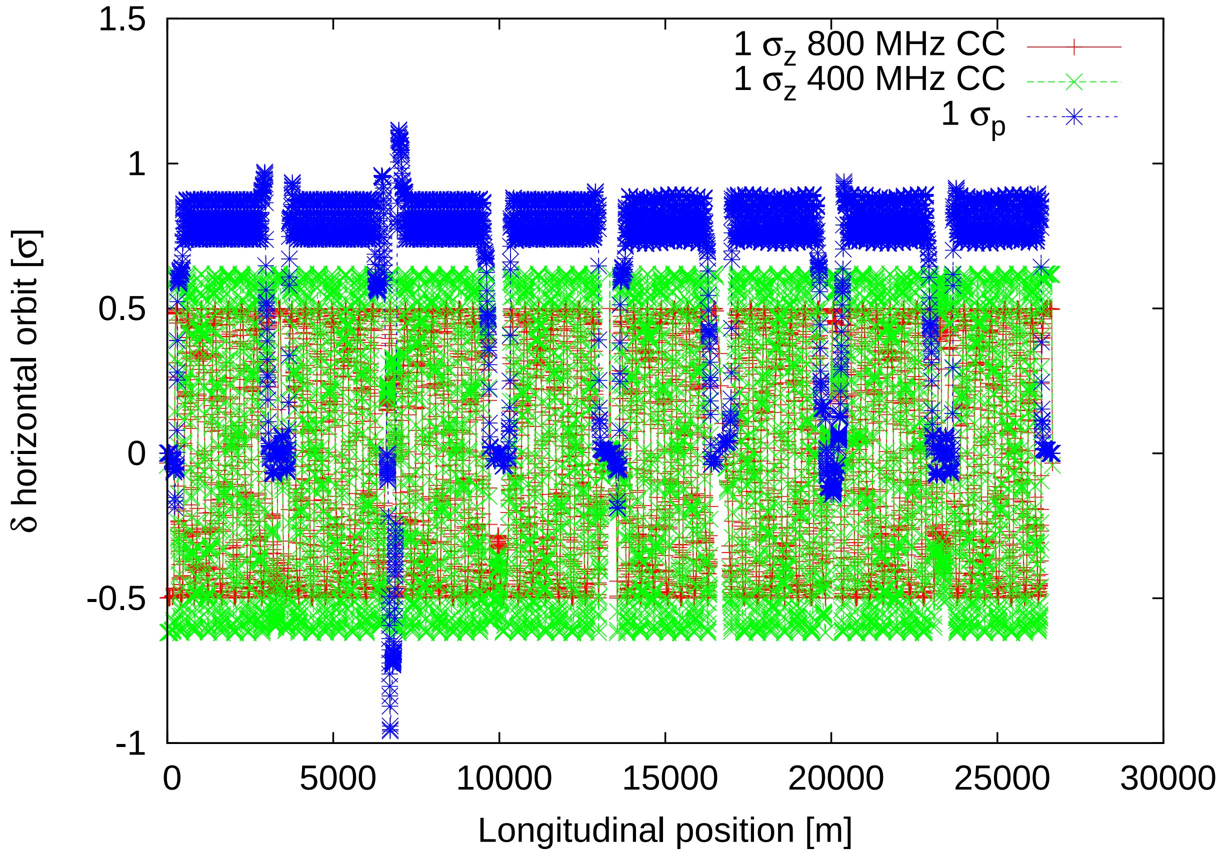
- Nominal LHC, $\beta^* = 0.55$ m, $\theta = 285 - 552\ \mu$rad
- The luminosity gain is 12-25% for lower emittance

Dynamic aperture



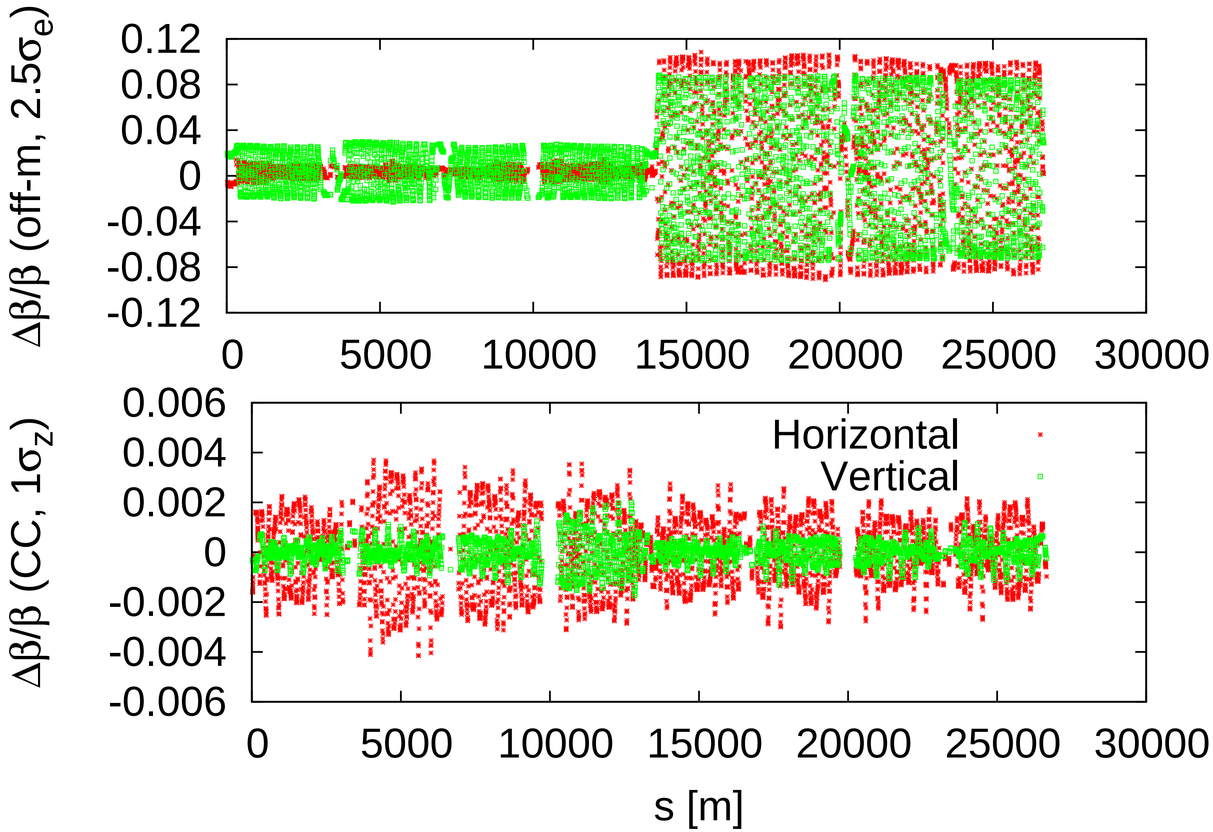
- Min DA over 60 error seeds; 100,000 turns
- Maximum decrease of 1 σ (average)

Aperture



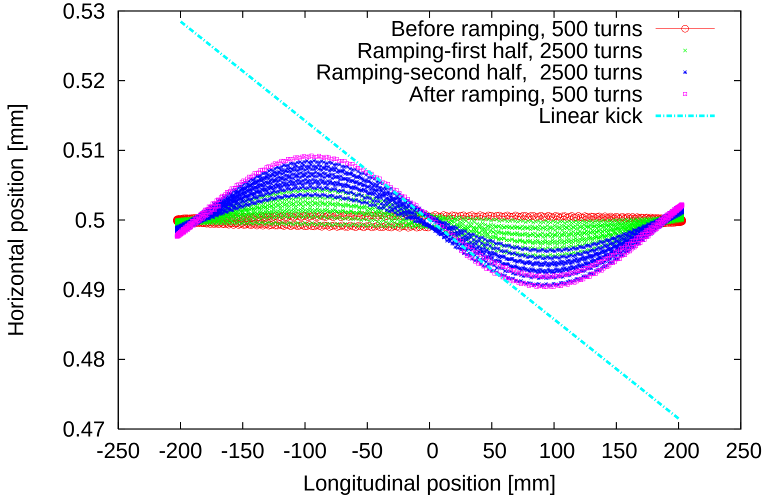
Global scheme for nominal LHC, beam occupy an additional 0.5σ aperture

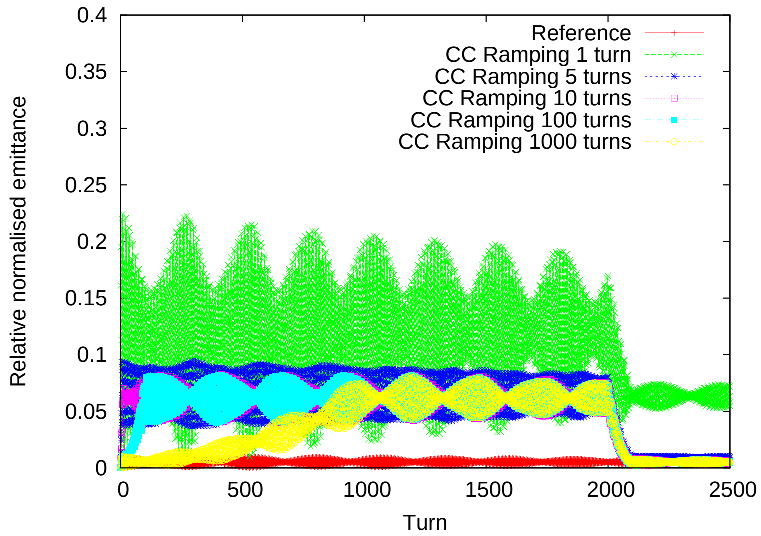
z-dependent Beta-beating



Off-momentum β-beat with a relative momentum offset of 0.00027 (top); z-dependent 'β-beat' due to the global crab cavity (bottom).

Emittance growth





- Left: check of crab cavity ramping
- Right: relative horizontal emittance growth indicateds ramping time > 10 turns

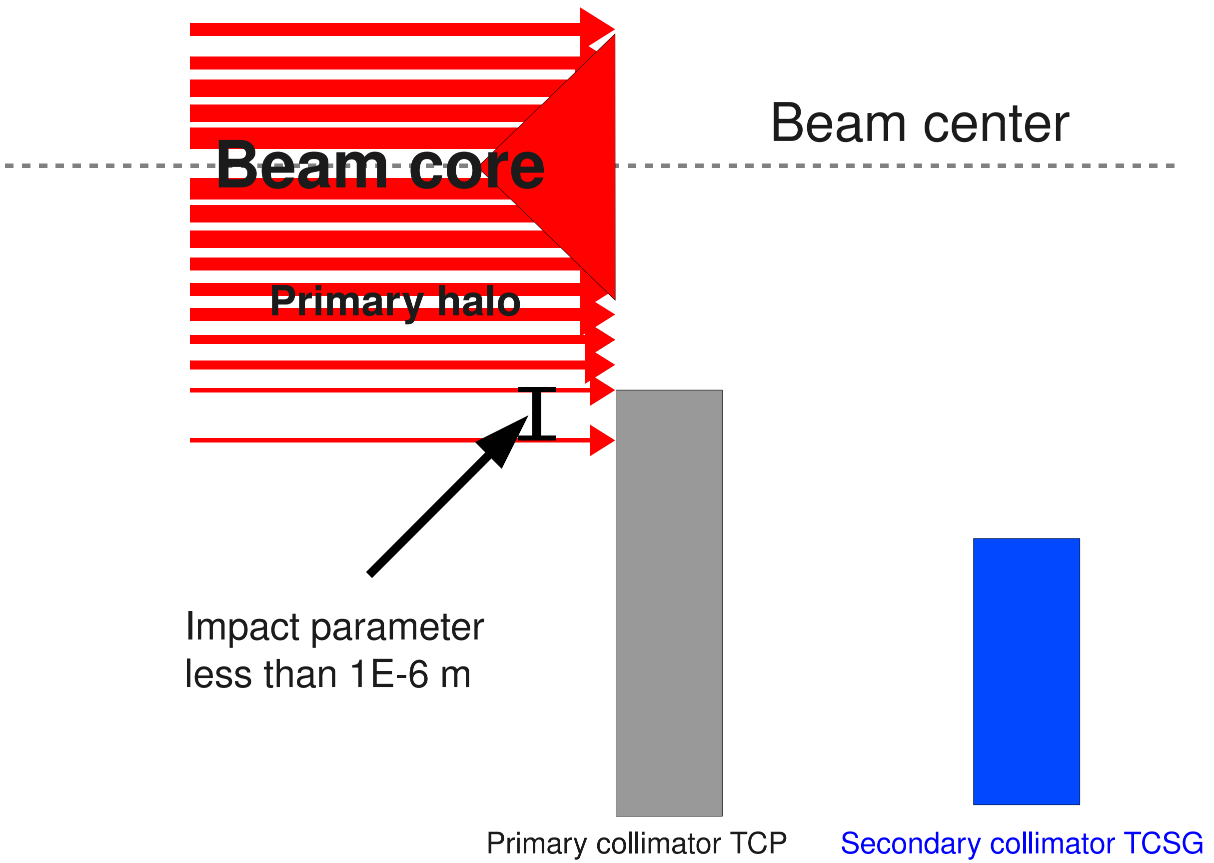
Collimation simulation: overview

- Nominal collimation simulation: betatron halo (5 M particles) @ 5.958σ + 0.0015σ smear, with 1×10^{-6}m impact parameter on the primary collimator TCP.C6L7.B1 at IR7

- Horizontal beam halo (5,760,000 particles in all), ON-momentum

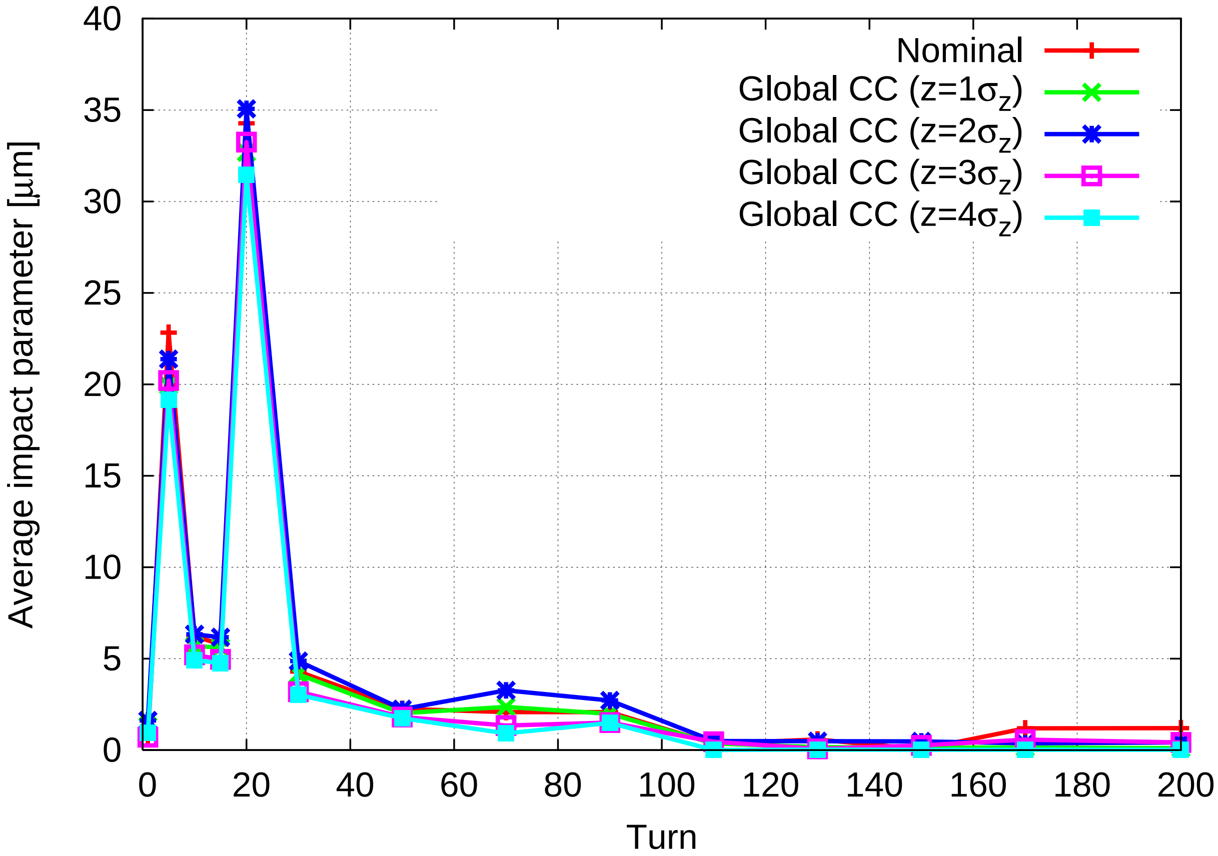
	Nominal	GCC ($1\sigma_z$)	GCC ($2\sigma_z$)	GCC ($3\sigma_z$)
Δx@Pri. Col. [σ]	0	-0.47	-0.285	0.3
Initial halo [σ]	5.958	5.509	5.668	5.662
Initial smear [σ]	0.0015	0.0015	0.0015	0.0015
I.P., 1^{st} turn [μm]	1	1.3	1.5	1
I.P., all turns [μm]	14	14	14.9	14.7
Particle absorbed	70%	69.1%	69.0%	68.4%

Impact parameter (1)



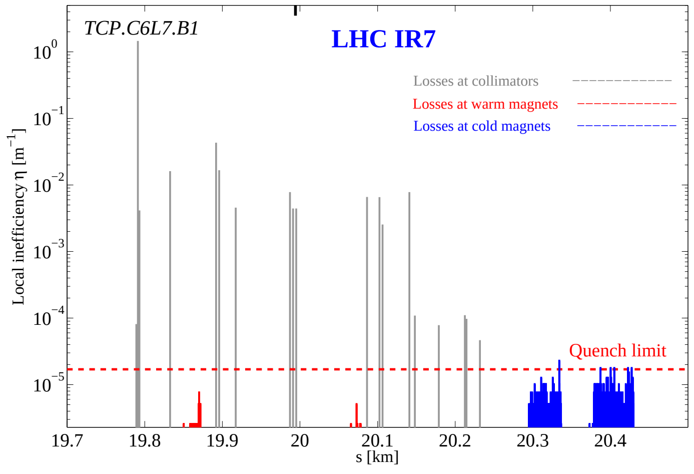
Sketch & 1×10^{-6}m requirement on impact parameter

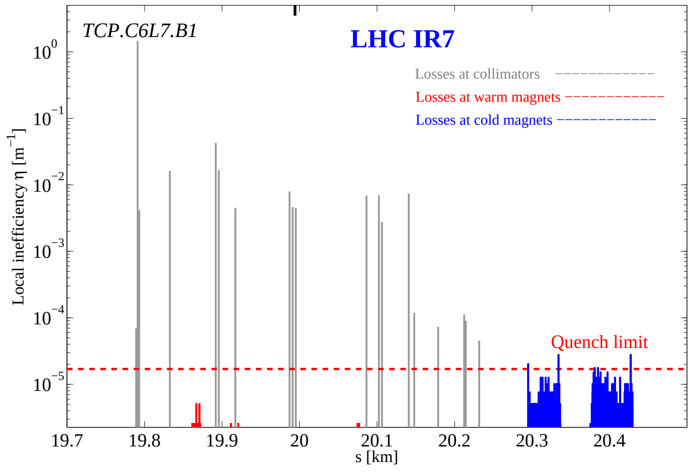
Impact parameter (2)



- Average first-time impact parameter
- 1 μm impact parameter for the first turn

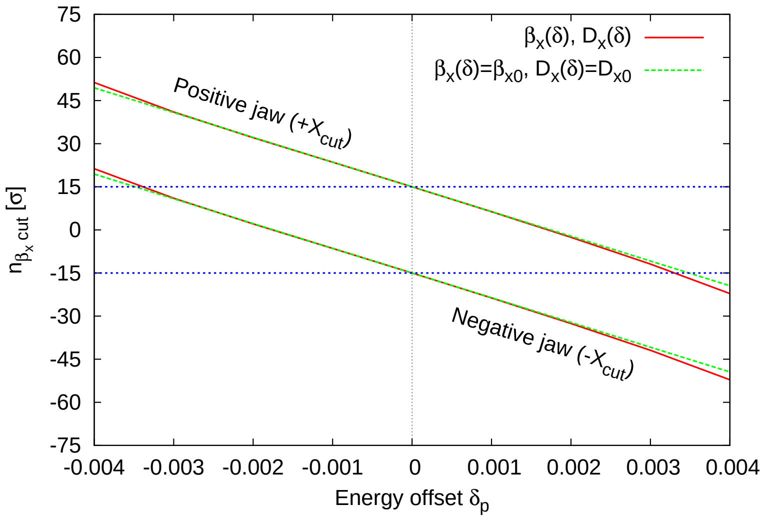
Local loss map (IR7), similar with no CC

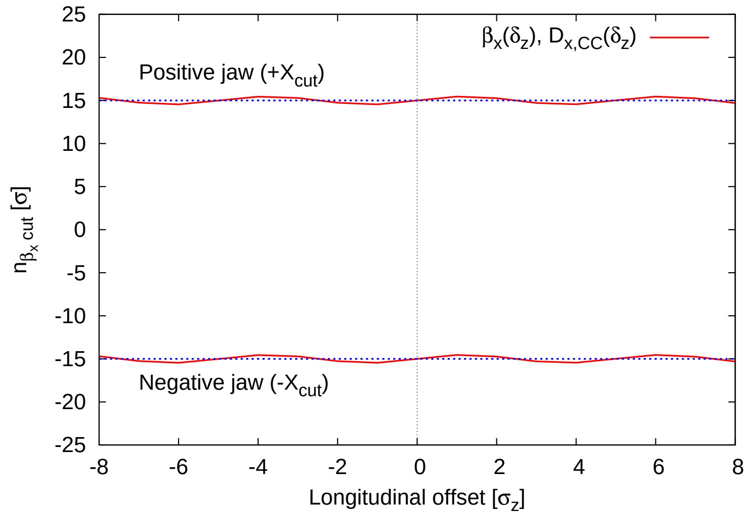




- Left: without crab cavity
- Right: z= $1\sigma_z$, with crab cavity
- Quench limit: full nominal LHC beam & 0.2 hour lifetime

Collimator hierarchy: TCP.6L3.B1

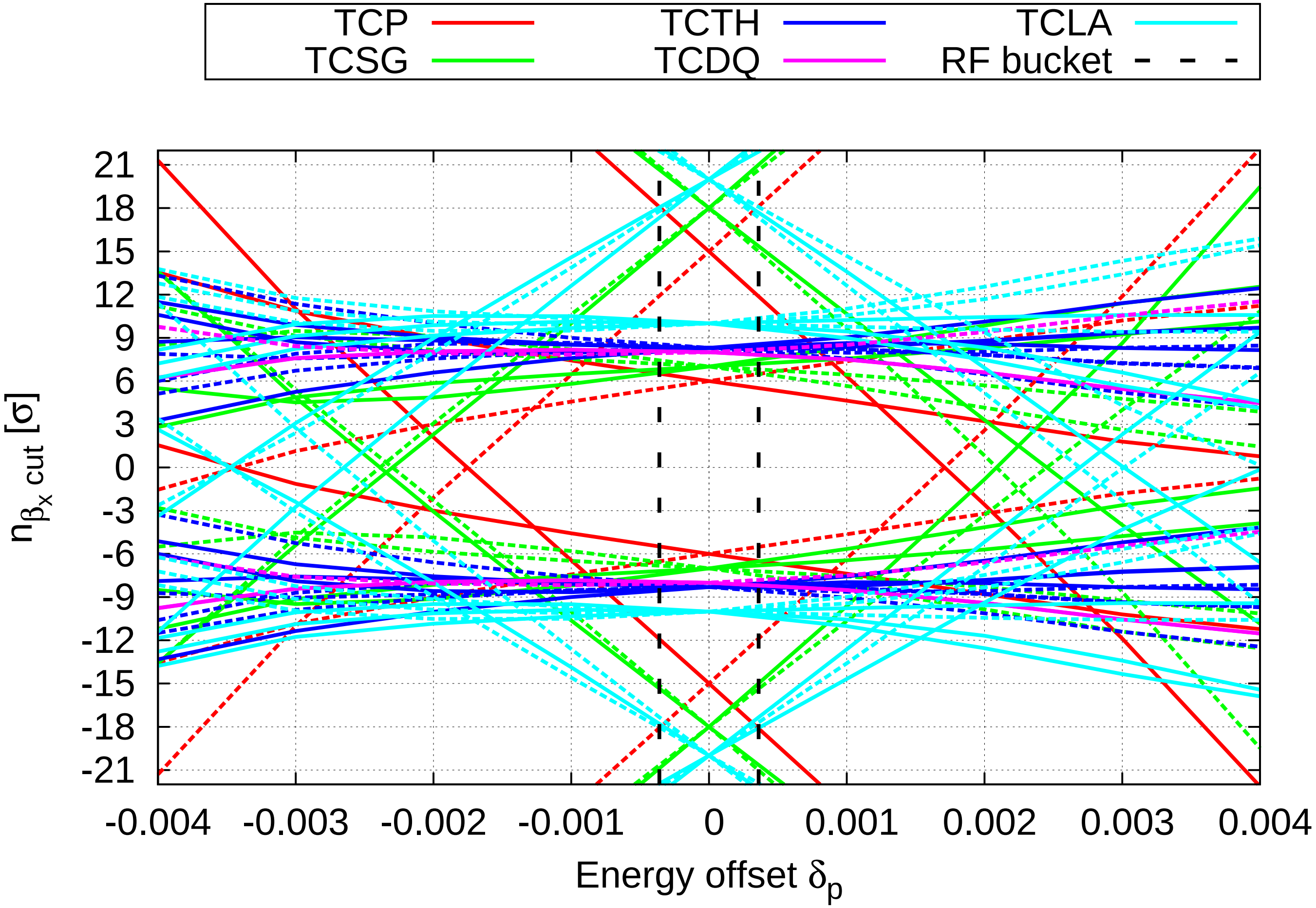




$$n_{\beta,cut}(i_{coll}) = \frac{1}{\sqrt{\epsilon_r \beta_r(i_{coll},\delta)}} \cdot (\pm r_{cut}(i_{coll}) - D_r(\delta)\cdot\delta - x_{D_{cc}}(z,s))$$

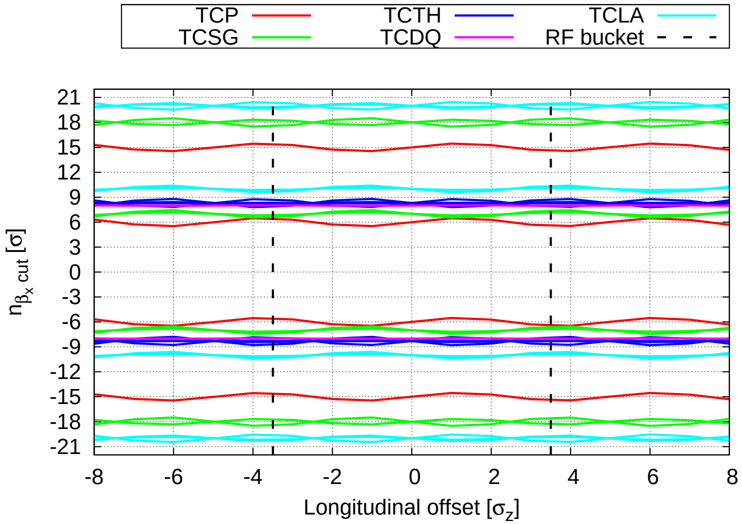
- L:Off-momentum beat (δ_p-dependent D_x and β)
- R:Crab beat (z-dependent dispersion D_{cc} and β)

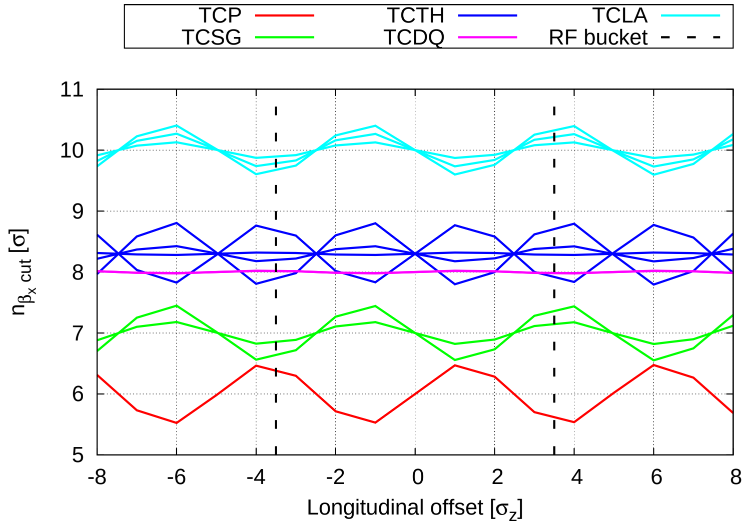
Collimator hierarchy (D_x): no crab



Off-momentum beat (δ_p-dependent D_x and β)

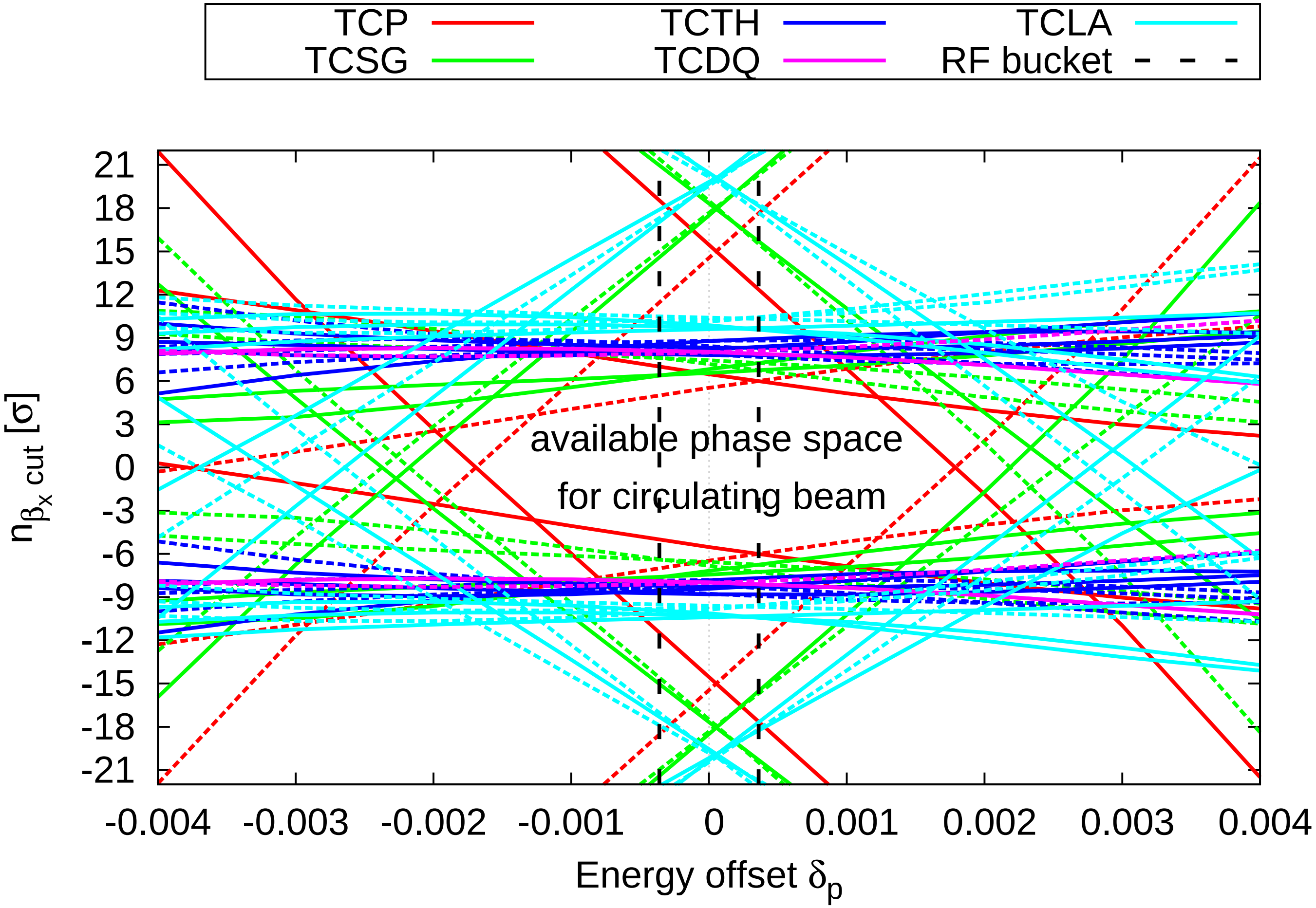
Collimator hierarchy (CC): δp=0, CC





- Worst case @ $1\sigma_z$
- Crab beat (z-dependent dispersion D_{cc} and β)

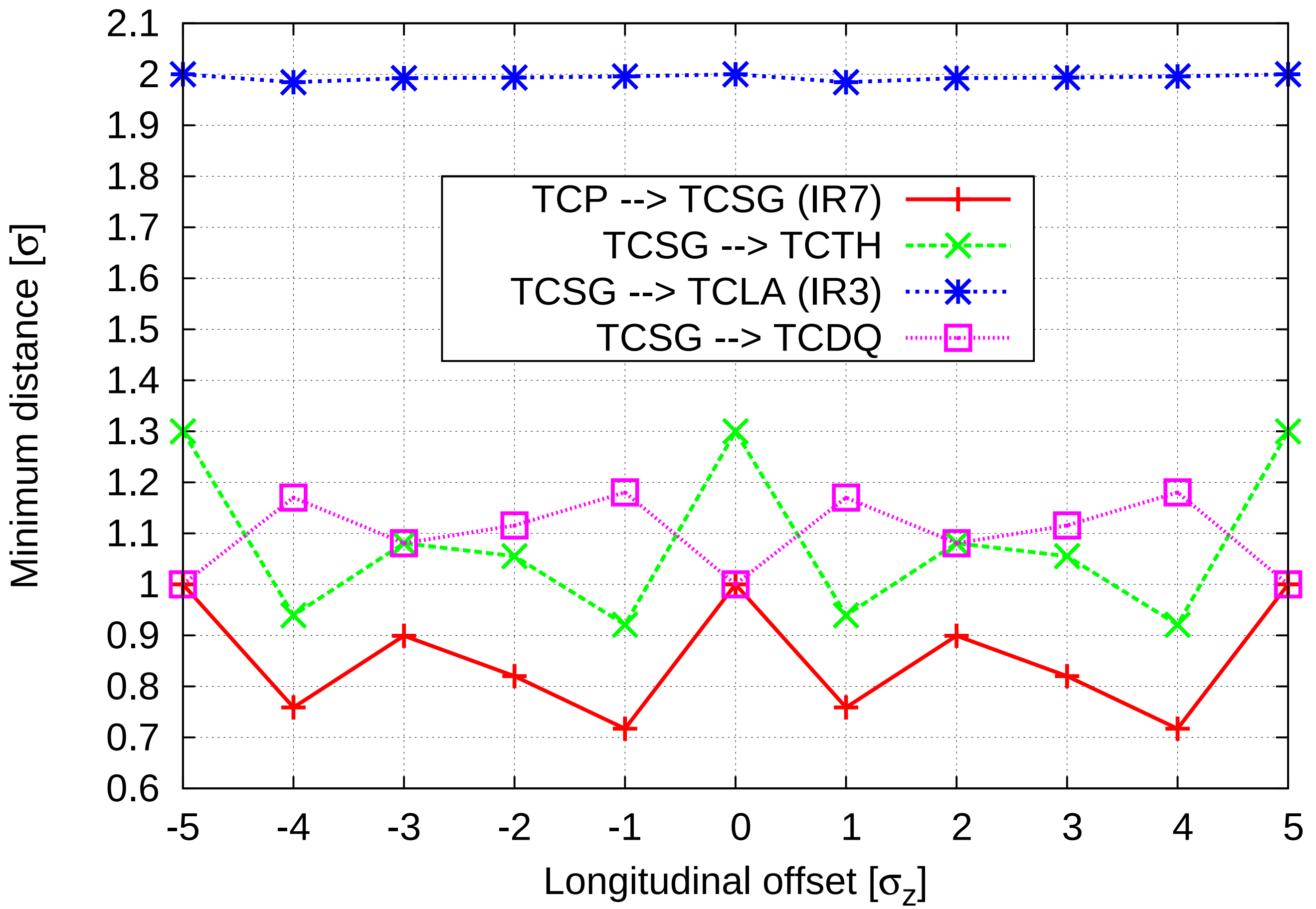
Collimator hierarchy with crab cavity



Crab beat @$1\sigma_z$ + Off-momentum beat (δ_p)

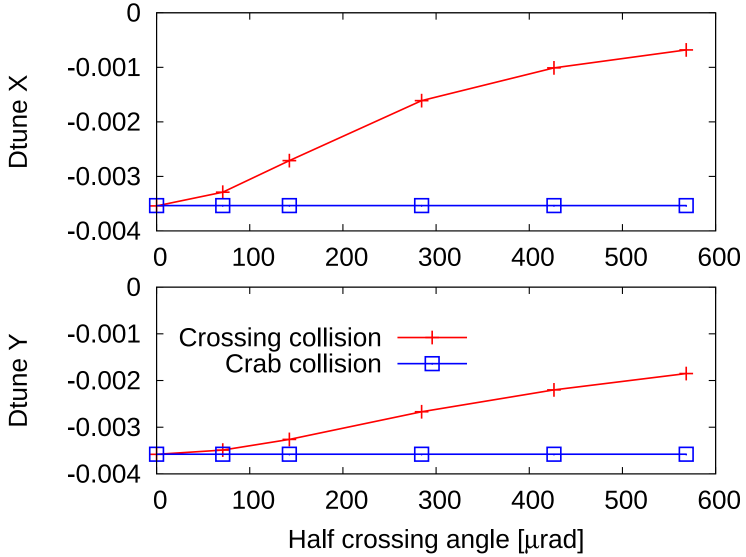
Small change

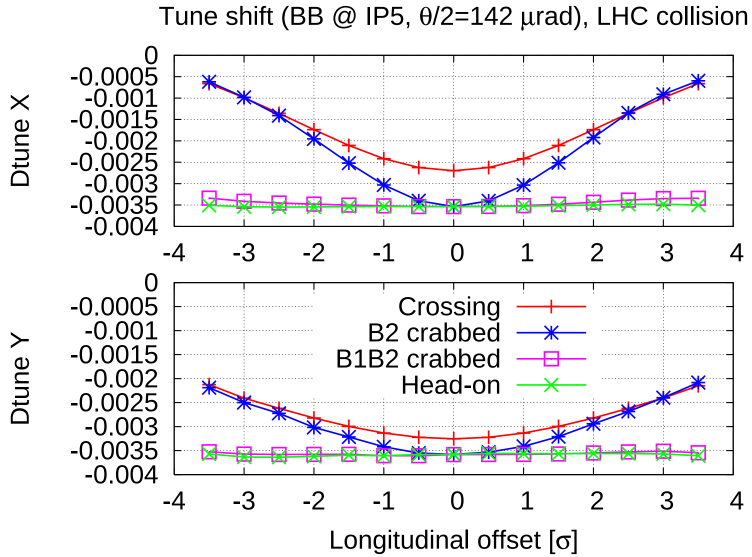
Min. P-S distance between collimators



- Crab beat + Off-momentum beat
- From 1 to 0.7σ in the worst case (acceptable)

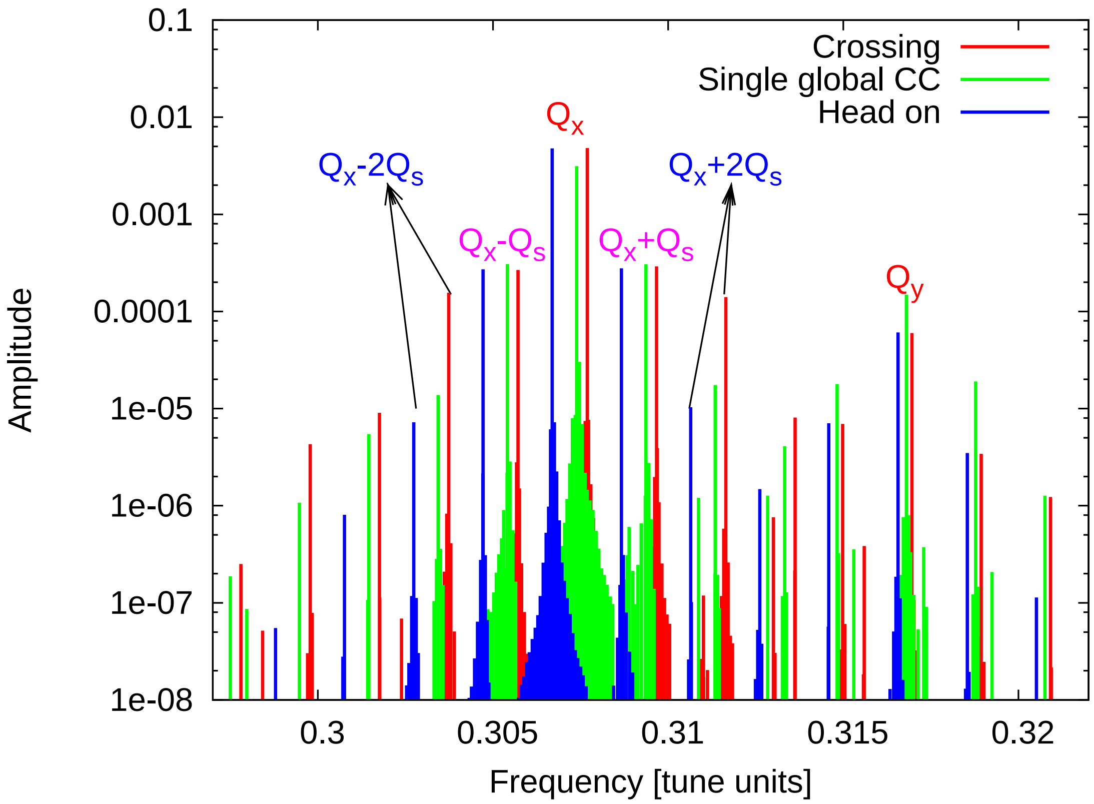
Head-on BB tune shift, H-crossing at IP5





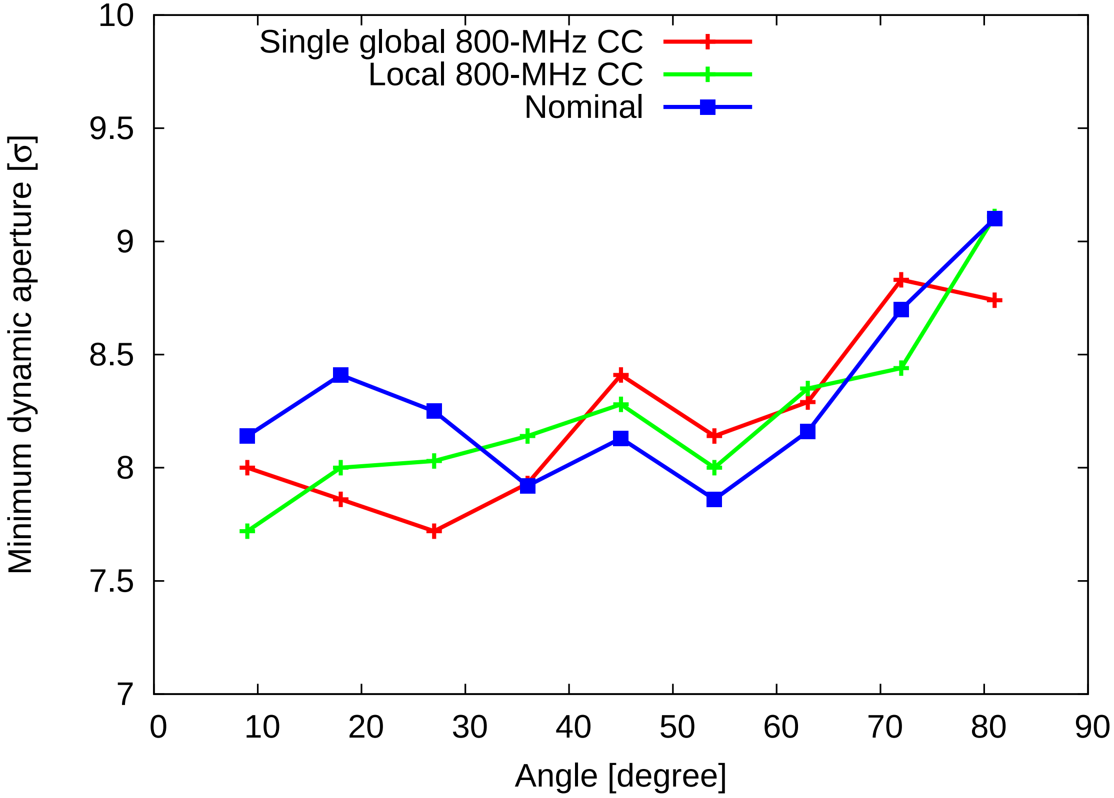
- Left: Hori. (top) and ver. tune shift (bottom); Crab crossing tune shift = head-on collision case
- Right: Hori. (top) and ver. detuning (bottom) at different longitudinal position inside the bunch

Synchro-betatron resonances



For a particle launched with 1σ offset. The second sideband suppressed by the single global 800-MHz crab cavity (synchrotron tune $Q_s = 0.00197$, and chromaticity $Q'_{x,y} = 2$).

Long-range effects: dynamic aperture



Minimum dynamic aperture over 60 error seeds for nominal LHC optics with or without crab cavity; with all the head-on and long-range beam-beam interactions at IP1, IP2, IP5 and IP8. The dynamic aperture tracking is performed for **100,000 turns**.

Conclusions (1)

- Various beam dynamics issues have been studied
- LHC optics can fulfill the requirements to install CC
- Minimum dynamic aperture acceptable
- Global crabbing scheme requires an additional 0.5σ aperture
- z-dependent ‘beta beating’ very small
- With only one 800-MHz global crab cavity, the luminosity gain can be as large as 25% for reduced beam emittance
- Emittance growth study for the CC voltage ramping shows that a ramping period of longer than 10 turns sufficient

Conclusions (2)

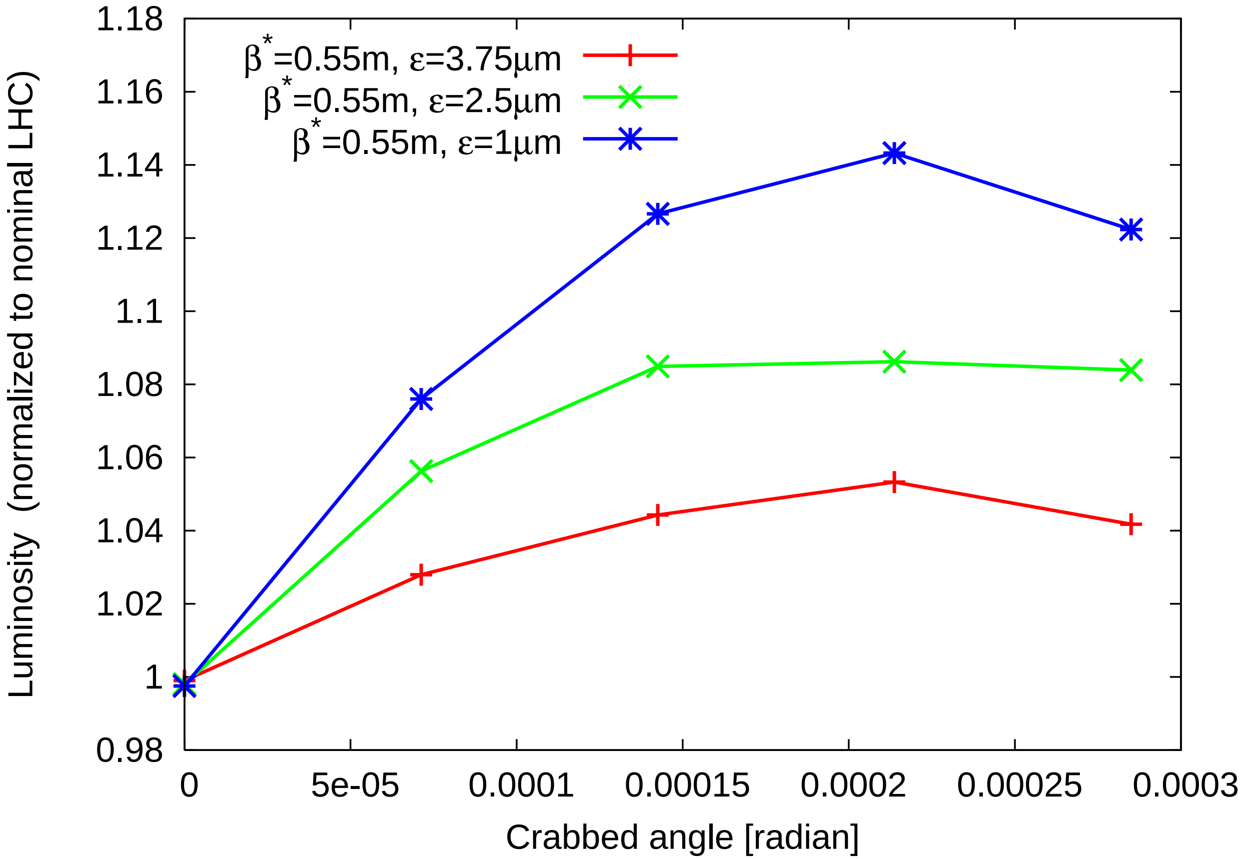
- Local cleaning inefficiency of the LHC collimation system not affected by CC presence
- Available phase space for the circulating beam only moderately disturbed by the global crab cavity
- Hierarchy of primary (TCP), secondary (TCSG), tertiary (TCTH), beam dump (TCDQ) horizontal collimators and shower absorbers (TCLA) is maintained
- Crab collision case with both beams crabbed, simulated beam-beam tune shift = head-on collision tune shift
- Second-order synchro-betatron resonances introduced by the crossing collision suppressed by the crab cavities.

Conclusion

All results of our beam-dynamics study support the feasibility of the minimal crab-cavity test operation in the LHC.

Thank you for your attention!

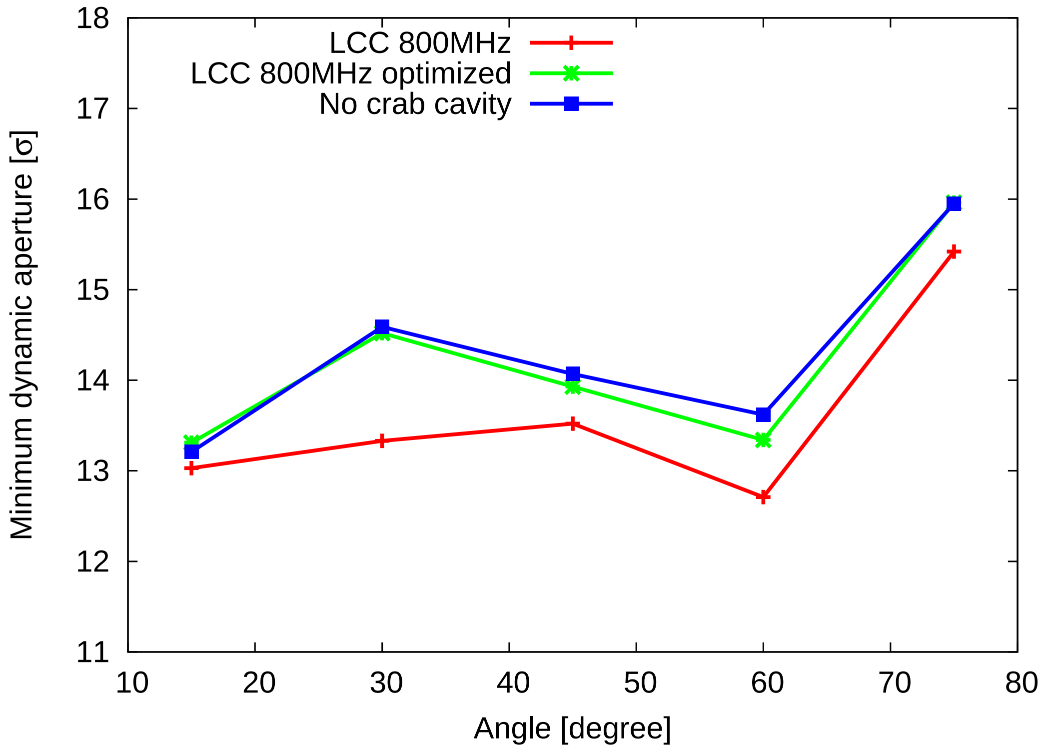
Backup: Luminosity gain with low ϵ



Nominal LHC with $\beta^* = 0.55$ m, $\theta = 285$ μrad

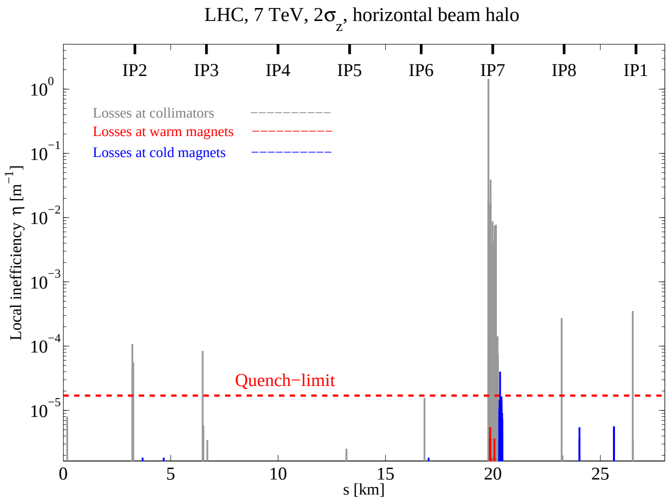
The luminosity gain is 10-14% for lower emittance

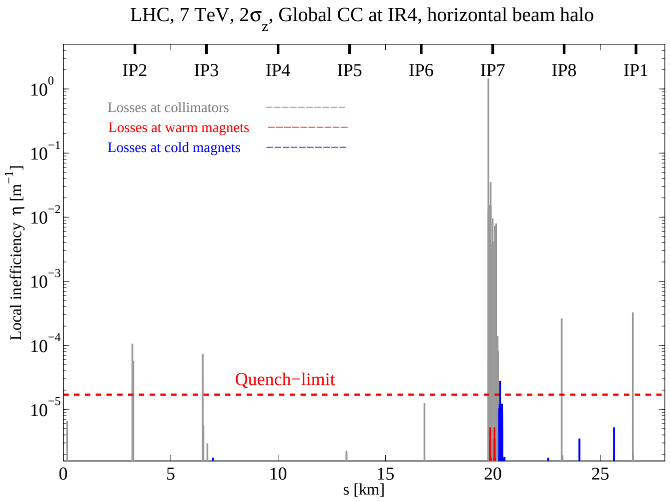
Backup: Recover DA for local scheme



The dynamic aperture could indeed be fully recovered by optimizing the phase advance (in the crossing plane) between the two local crab cavities to be much closer to 0.5 (in units of 2π).

Backup: Local loss map (1)

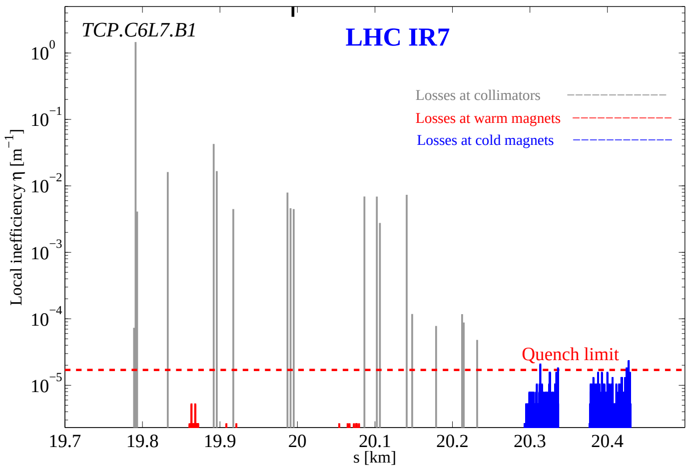


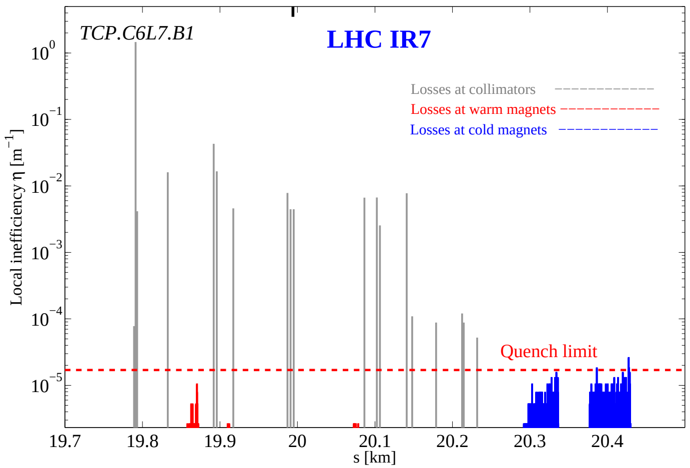


LHC IR7, Left: no crab cavity

Right: with crab cavity

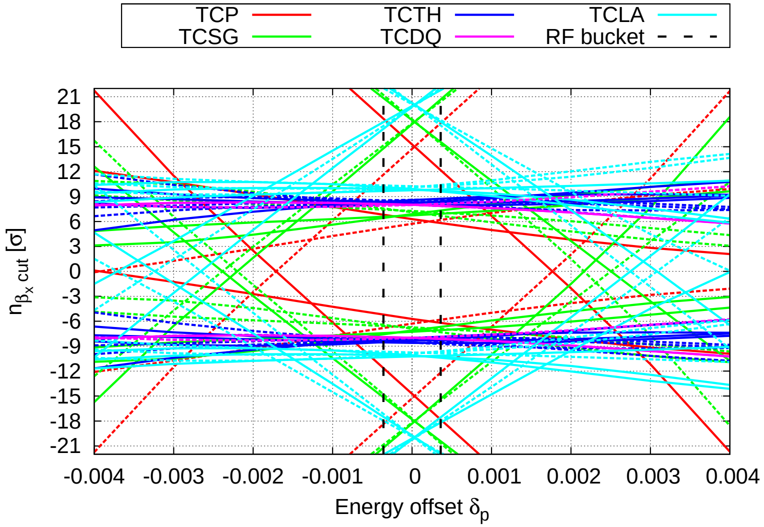
Backup: Local loss map (2)

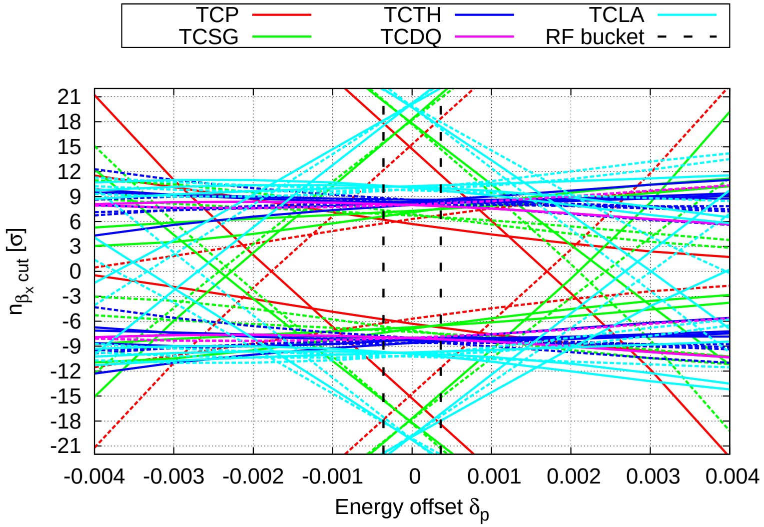




LHC IR7, Left: z= $2\sigma_z$; Right: z= $3\sigma_z$

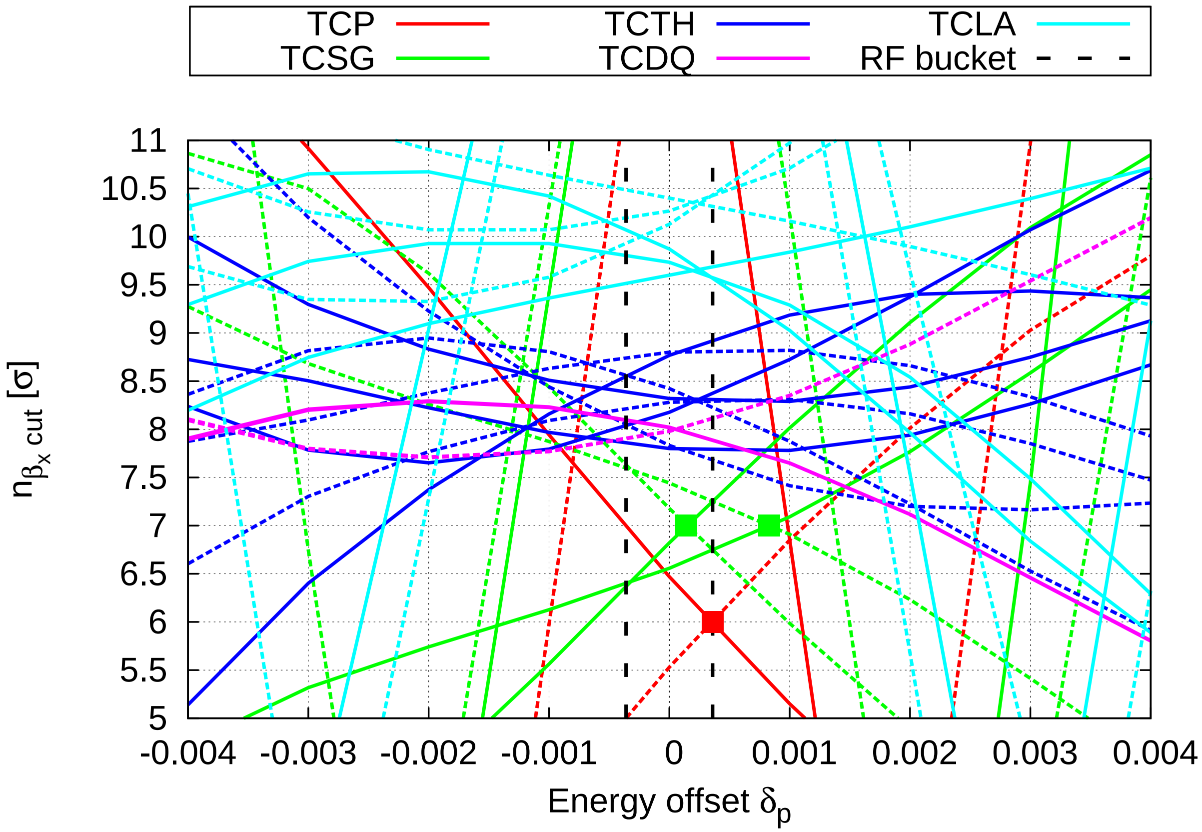
Backup: Phase space





Left: z= $2\sigma_z$; Right: z= $3\sigma_z$

Backup: Phase space (CC@1σ_z + δ_p) zoom



$$n_{\beta,cut}(i_{coll},\delta) = \frac{1}{\sqrt{\epsilon_r \beta_r(i_{coll},\delta)}} \cdot (\pm r_{cut}(i_{coll}) - D_r(i_{coll},\delta)\cdot\delta - x_{D_{cc}}(z,s)).$$

Backup: Global loss map