Beam Dynamics Aspects of Crab Cavities in the Large Hadron Collider

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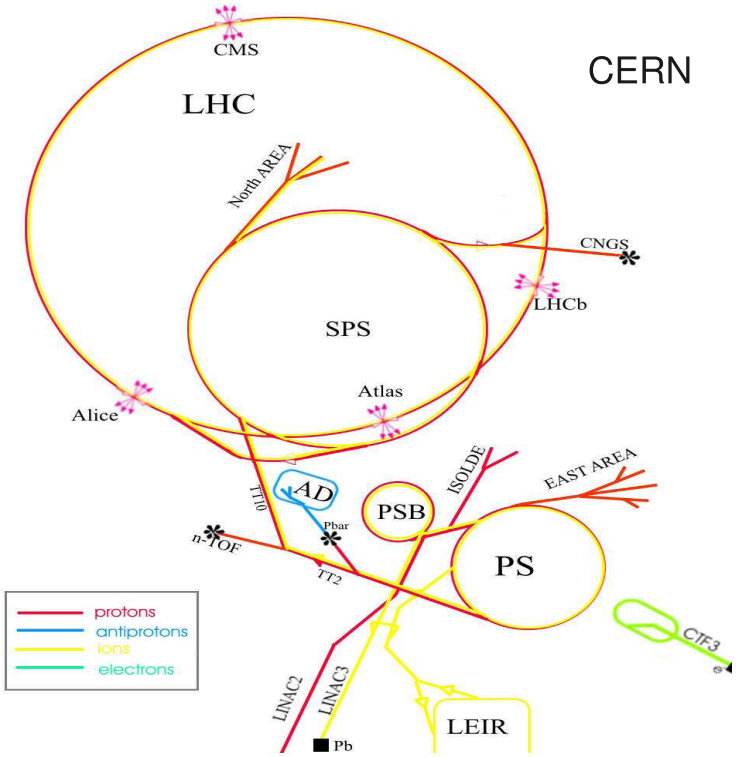
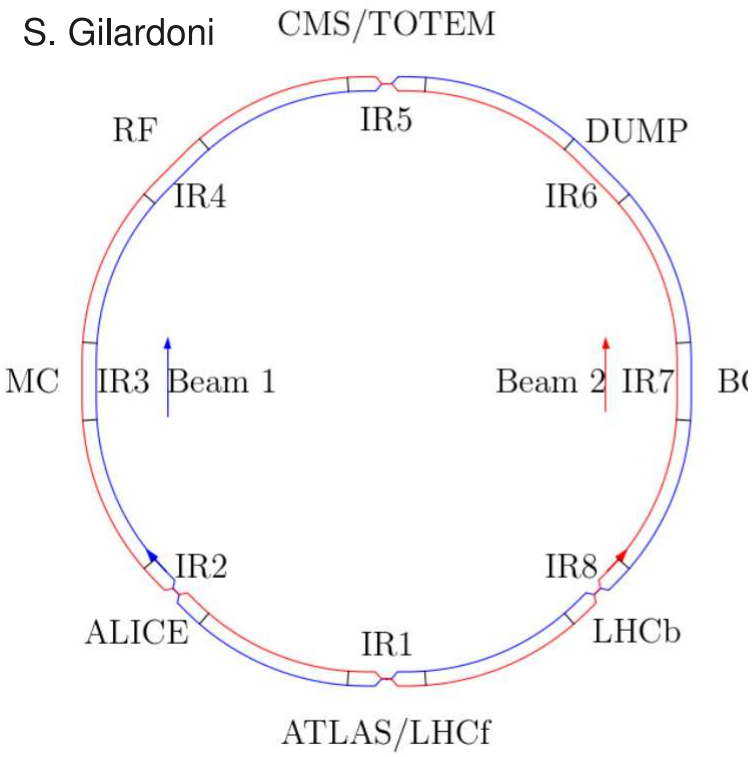
Content

- Introduction of crab cavity (CC)
- Local and global scheme
- Optics and scenarios
- Dynamic Aperture (DA), aperture and beta-beating
- Luminosity
- Emittance growth
- Crab dispersion & Collimation
- Crab Crossing Tune Shift and Synchro-betatron resonances
- Impact of beam-beam long-range effects
- Summary
- Other work: code, solenoid, polarity check, LHeC...

Introduction on LHC



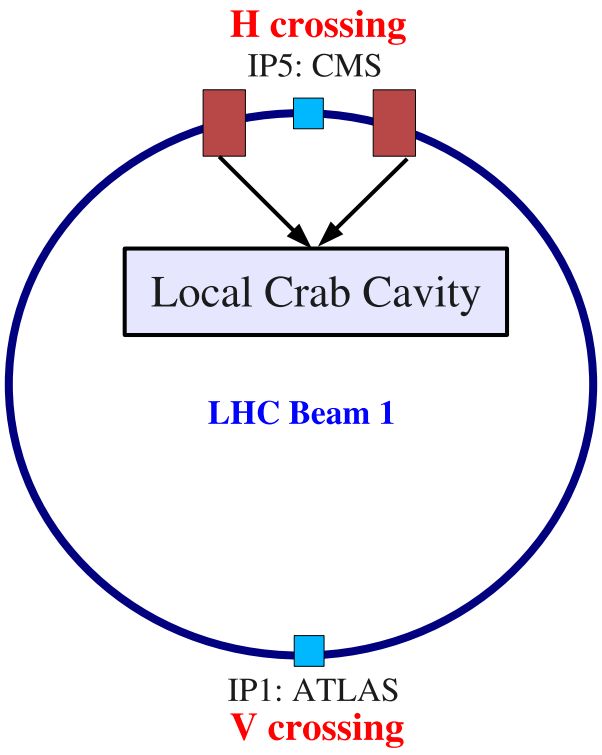


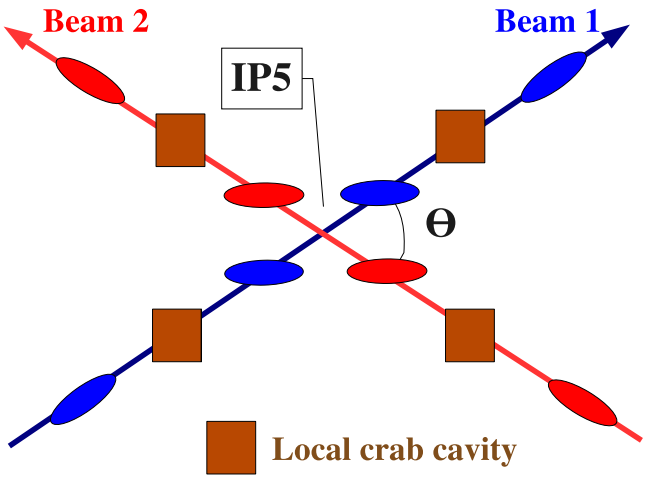
proton-proton and ion-ion collider; next energy-frontier discovery machine; c.m. energy 14 TeV (7x Tevatron); design pp luminosity $10^{34} cm^{-2} s^{-1}$ (30x Tevatron)

Introduction on crab cavity

- Long-range beam-beam effects –> crossing angle
- Crab cavities proposed by Palmer, Oide and Yokoya
- To restore an effective head-on collision at IP
- The required horizontal kick $\Delta p_x = -\frac{\partial H_{crab}}{\partial x} = -\frac{qV}{P_s} \cdot \sin\left(\phi_s + \frac{\omega z}{c}\right)$
- KEKB: global crab cavities (one for each ring)

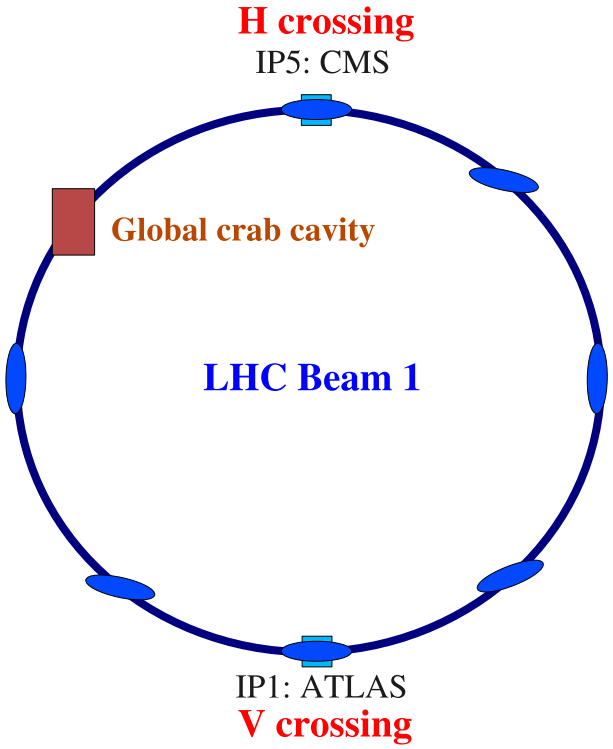
Local scheme





$$V_1 = \frac{c^2 \cdot p_s \cdot \tan(\frac{\theta}{2})}{q \cdot \omega \cdot \sqrt{\beta^* \cdot \beta_{crab}} \cdot \sin(\Delta\varphi_0)} \text{ and } V_2 = -R_{22} \cdot V_1$$

Global scheme

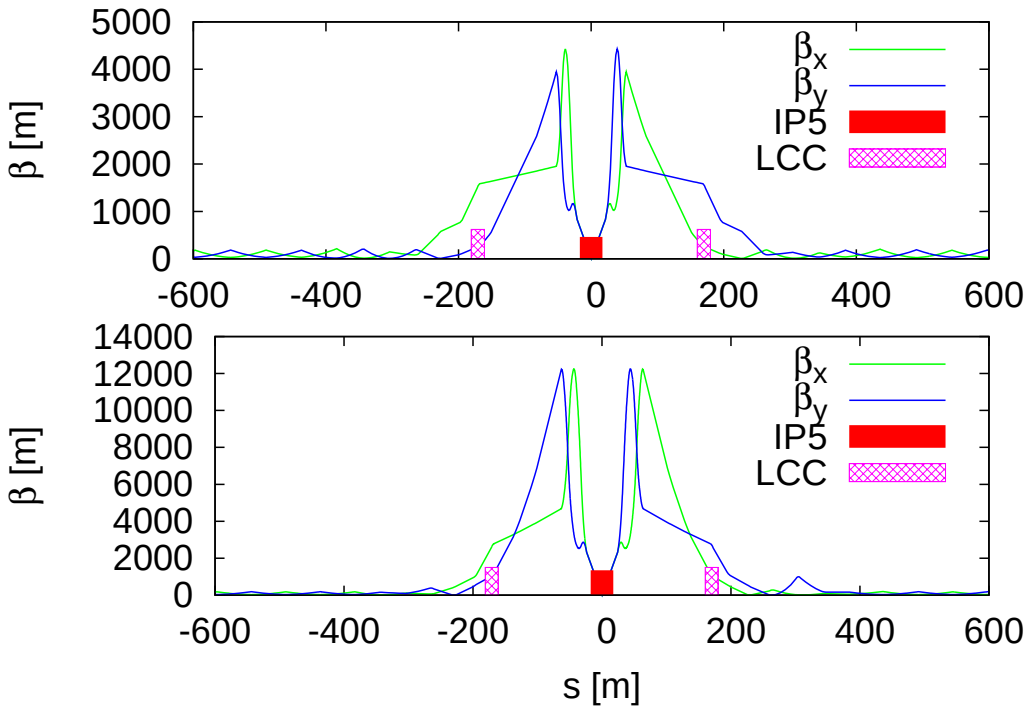


$$V = \frac{c^2 \cdot p_s \cdot \tan(\frac{\theta}{2})}{q \cdot \omega \cdot \sqrt{\beta^* \cdot \beta_{crab}}} \cdot \left| \frac{2\sin(\pi Q)}{\cos(\Delta\varphi_0 - \pi Q)} \right| .$$

Two LHC optics

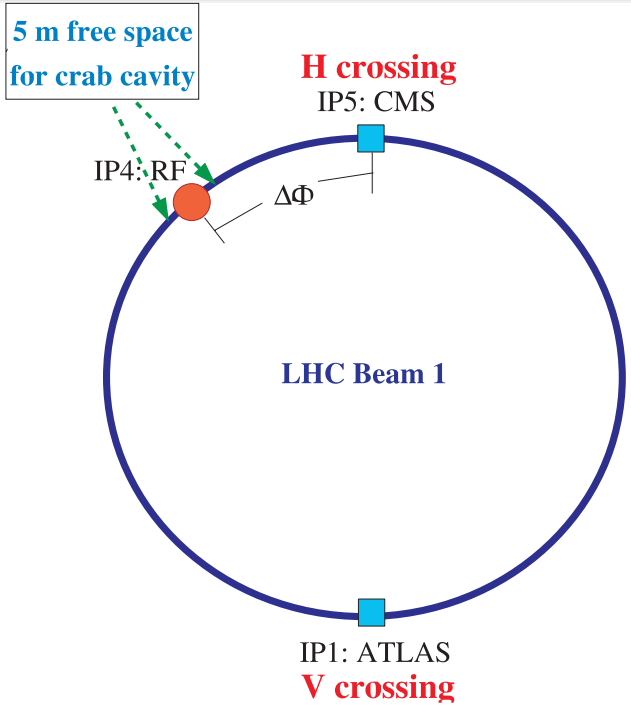
parameter	symbol	nominal LHC	upgrade SLHC
p per bunch	$N_b[10^{11}]$	1.15	1.15
n of bunches	n	2808	2808
rms bunch length	σ_z [cm]	7.55	7.55
rms energy spread	$\sigma_e[10^{-4}]$	1.1	1.1
β at IP1 & IP5	β^* [m]	0.55	0.25
emittance	ϵ [10^{-6} m $\cdot$ rad]	3.75	3.75
full crossing angle	θ [μ rad]	285	381

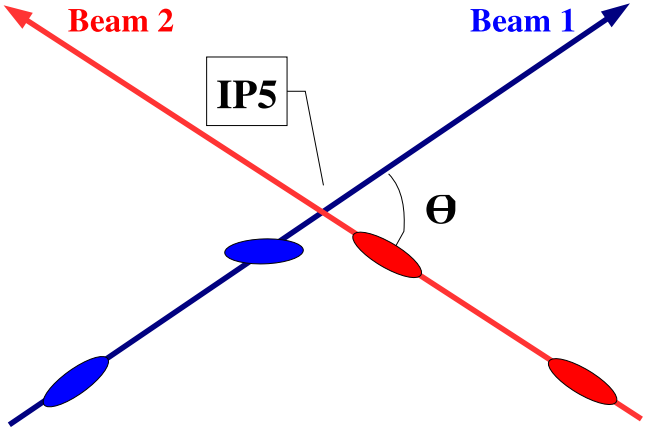
Local scenario



	V_{cc1} [MV]	V_{cc2}	β_{cc1}	β_{cc2}	$\varphi_{IP} - \varphi_{cc1}$	$\varphi_{cc2} - \varphi_{IP}$
nominal	3.5	0.7	1541	665	0.259	0.259
upgrade	4.9	3.1	2616	1023	0.254	0.254

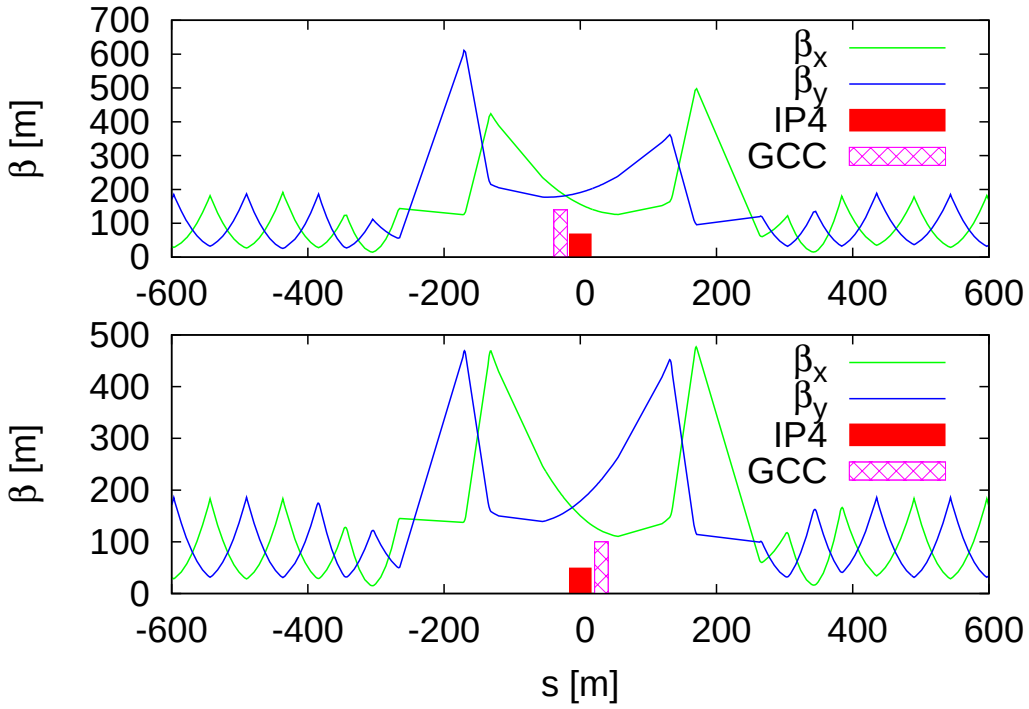
Single global scenario





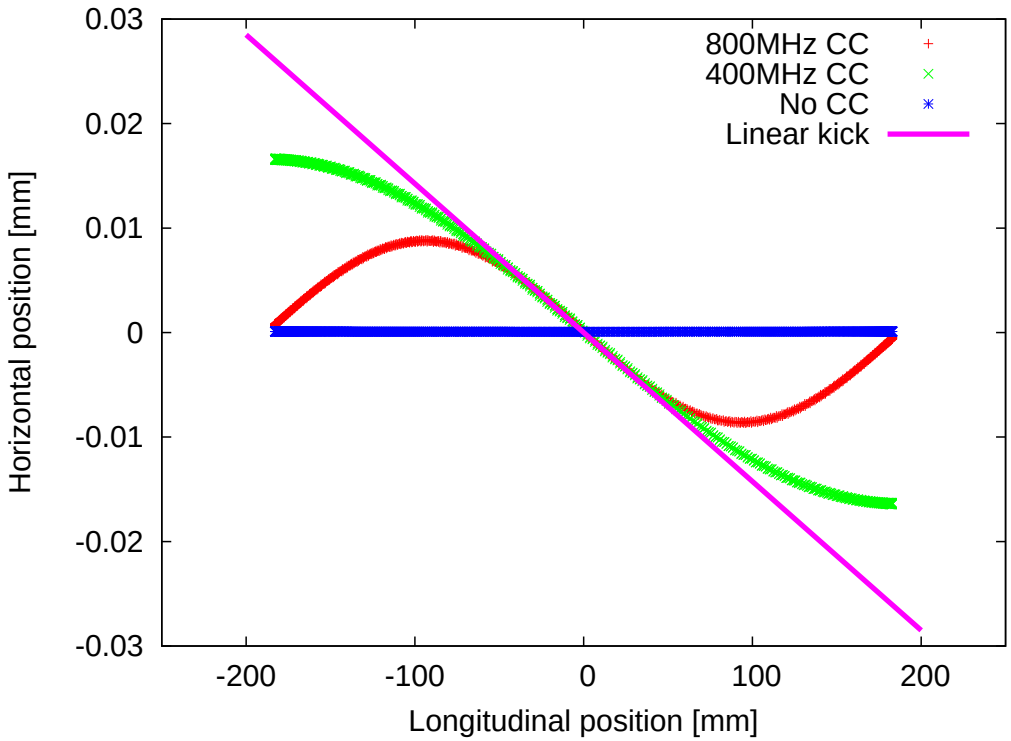
- Only one global crab cavity (800 MHz) at IR4, to test the crab cavity in hadron colliders
- Aim for 10% (max 25%) luminosity gain

Single global scenario, optics



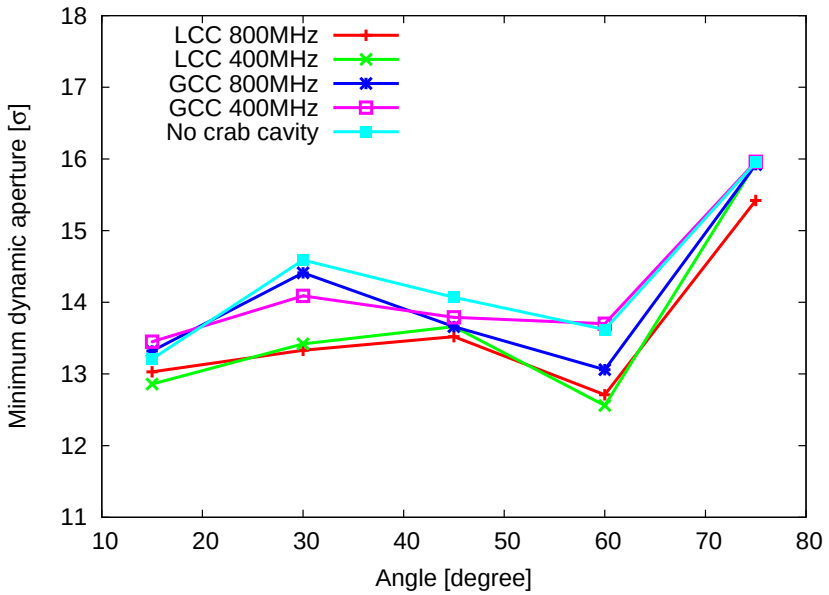
- 2.3 MV for nominal LHC, $\beta_{x,CC}$ increased up to 3 km
- 1.3 MV for *lowbetamax*, $\beta_{x,CC}$=3 km + Move Q_x near int. (factor 3 reduction for $Q_x = 0.1$)

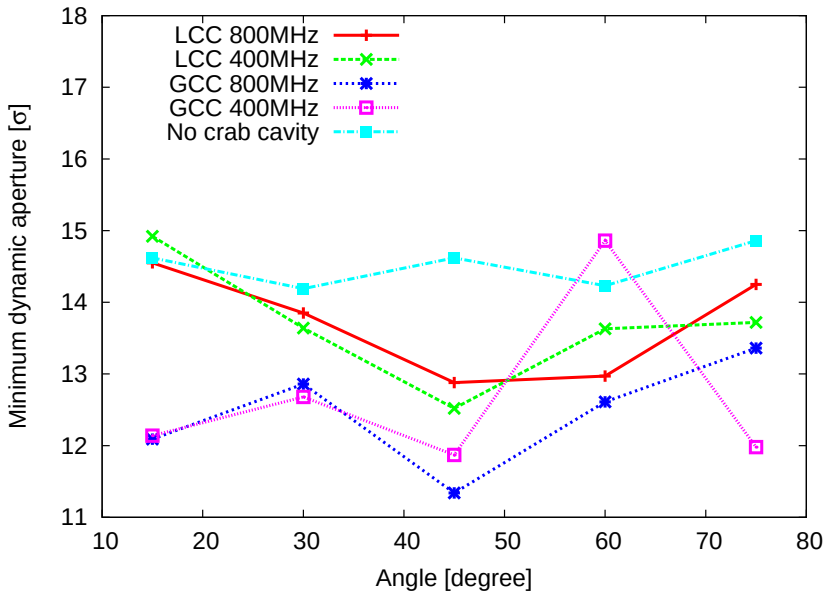
CC works at IP5



Turn-by-turn x-z correlation, $2.5\sigma_p$, IP5 with 400-MHz and 800-MHz global CC, nominal LHC with rms bunch length $\sigma_z = 75.5$ mm.

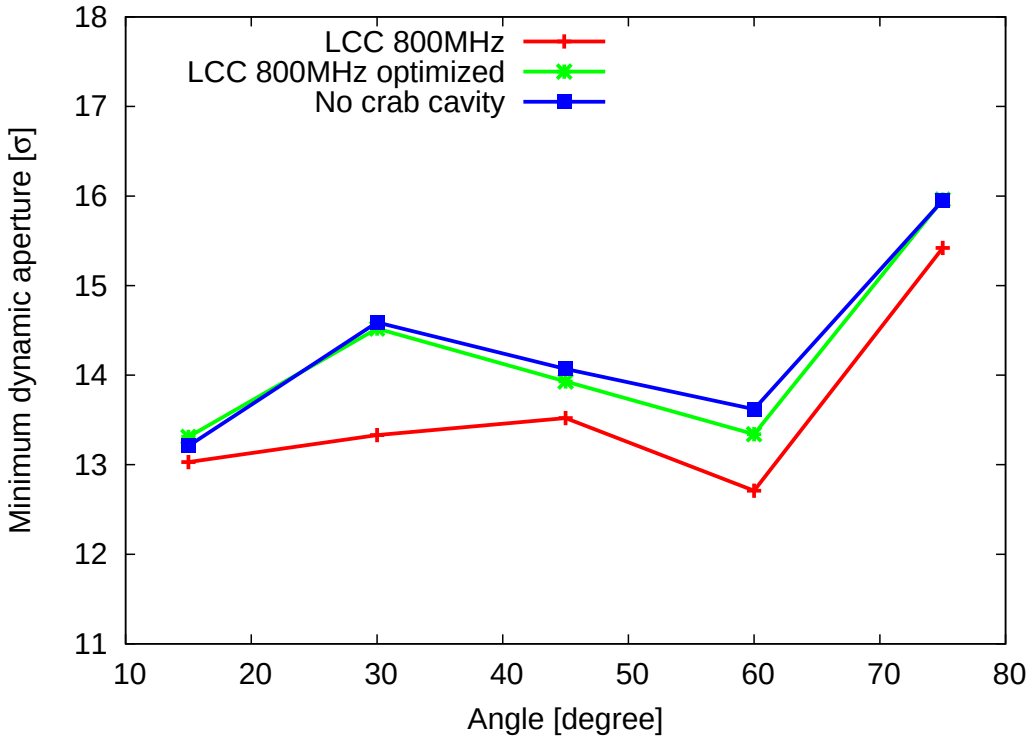
Dynamic Aperture





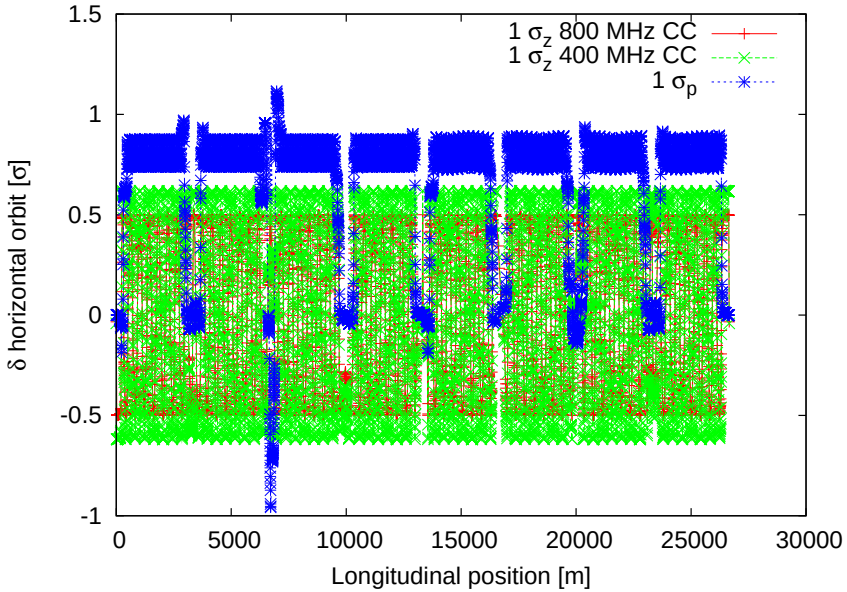
Min dynamic aperture (DA) over 60 error seeds
Primary collimator half opening 6σ –> DA larger than 12σ more than sufficient for LHC

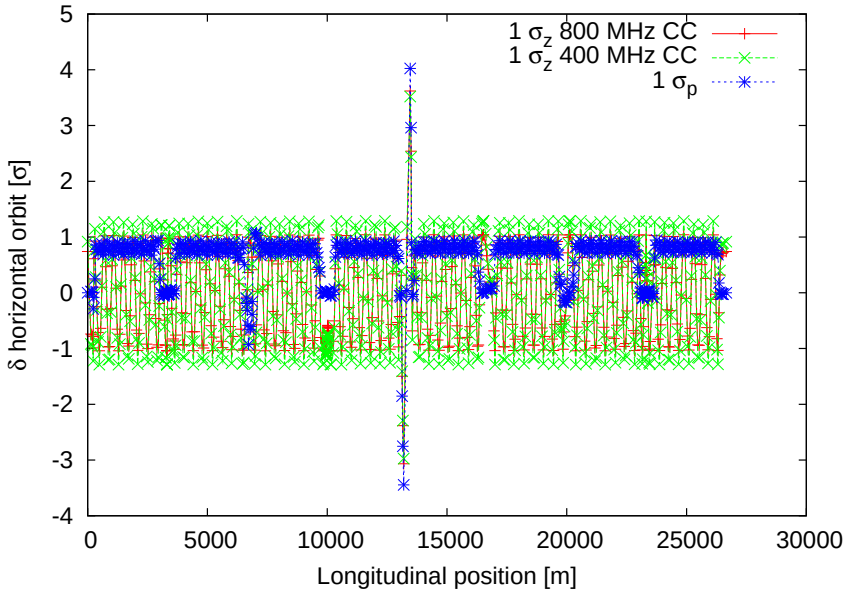
To recover dynamic aperture in the local scheme



DA recovered by optimizing the phase advance (in the crossing plane) between the two local CCs to be much closer to 0.5 (in units of 2π).

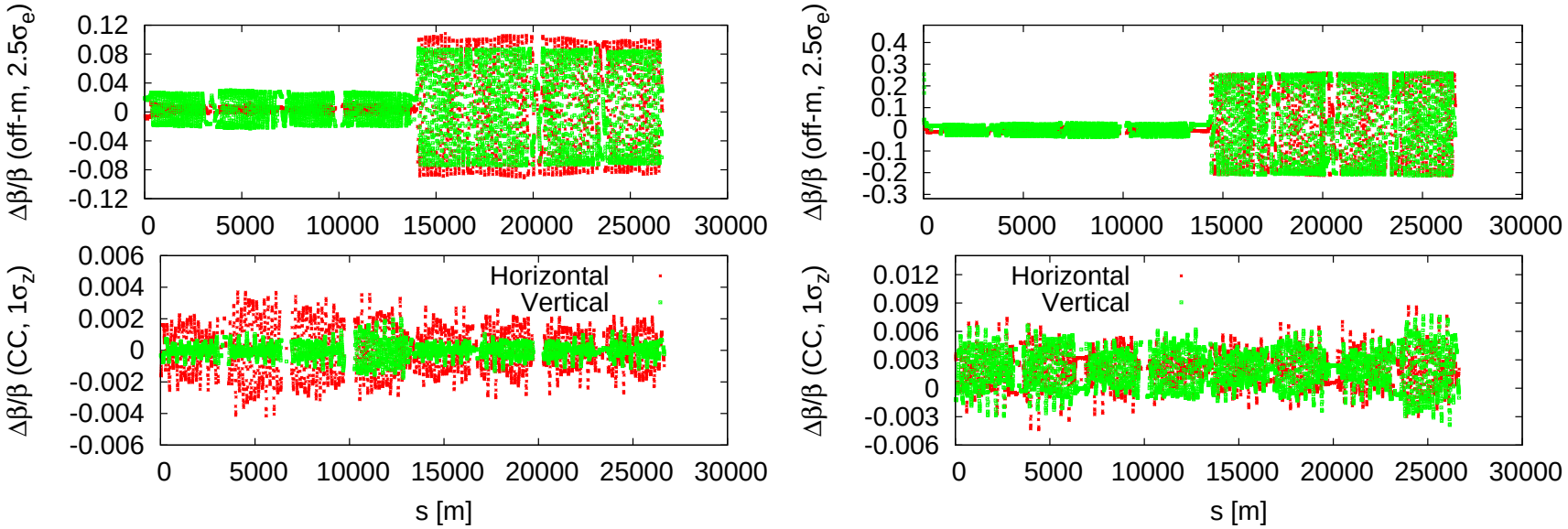
Aperture





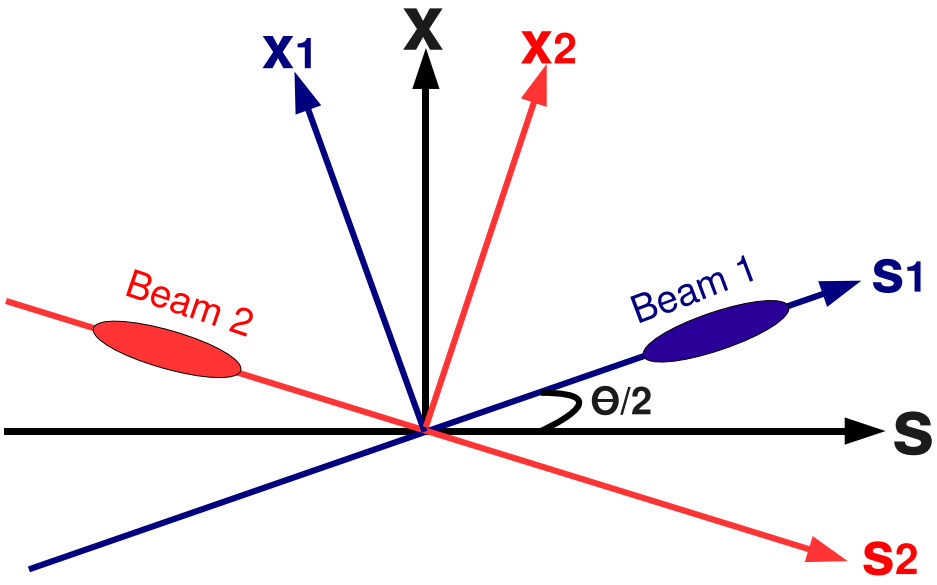
Global scheme, nominal LHC, beams occupy an additional 0.5σ aperture (*lowbetamax* about 1σ).

z-dependent 'beta beating'



Off-momentum β-beat, nominal LHC, momentum offset 0.00027 (top); z-dependent 'β-beat' due to the global CC (bottom), much smaller
Nominal LHC optics (left) & *lowbetamax* (right).

Coordinates system for the two colliding beams



$x_{1,2}$ and $s_{1,2}$ are the coordinates of an arbitrary particle in beam 1 (2).

Analytical treatment (1)

Gaussian distribution

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

x-z correlation from the crab cavity

$$V_1 = \frac{c^2 \cdot p_s \cdot \tan(\frac{\theta}{2})}{q \cdot \omega_{crab} \cdot R_{12}}$$
$$\Delta x_{1,2} = \pm R_{12} \cdot \frac{qV_1}{c \cdot p_s} \cdot sin\left(\frac{2\pi f_{crab}(s \mp ct)}{c}\right)$$

coordinates

$$x_1 = x\cos\frac{\theta}{2} - s\sin\frac{\theta}{2} + \frac{1}{k_{cr}}\sin[k_{cr}(s-ct)]\sin\frac{\theta}{2}$$
$$x_2 = x\cos\frac{\theta}{2} + s\sin\frac{\theta}{2} - \frac{1}{k_{cr}}\sin[k_{cr}(s+ct)]\sin\frac{\theta}{2}$$
$$s_1 = s\cos\frac{\theta}{2} + x\sin\frac{\theta}{2} \text{ and } s_2 = s\cos\frac{\theta}{2} - x\sin\frac{\theta}{2}$$

Analytical treatment (2): lumi. reduction factor

Integration

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

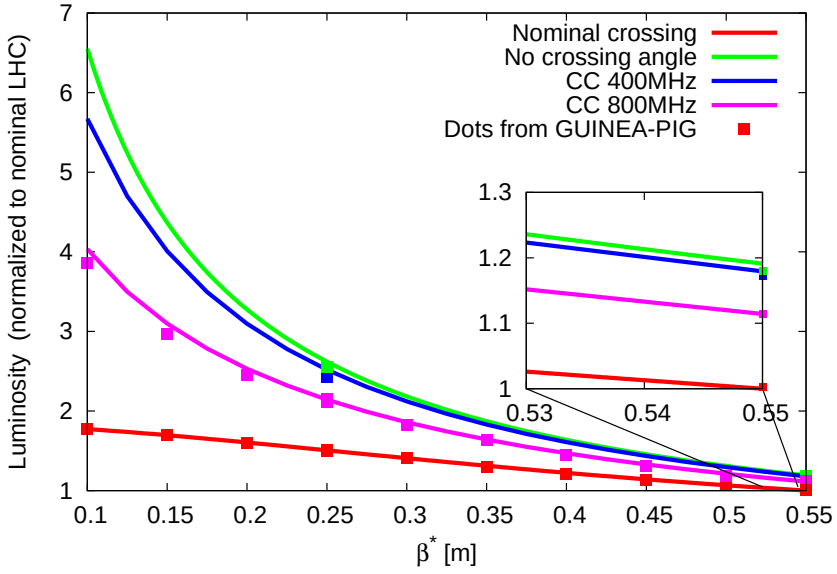
Two beams crab crossing

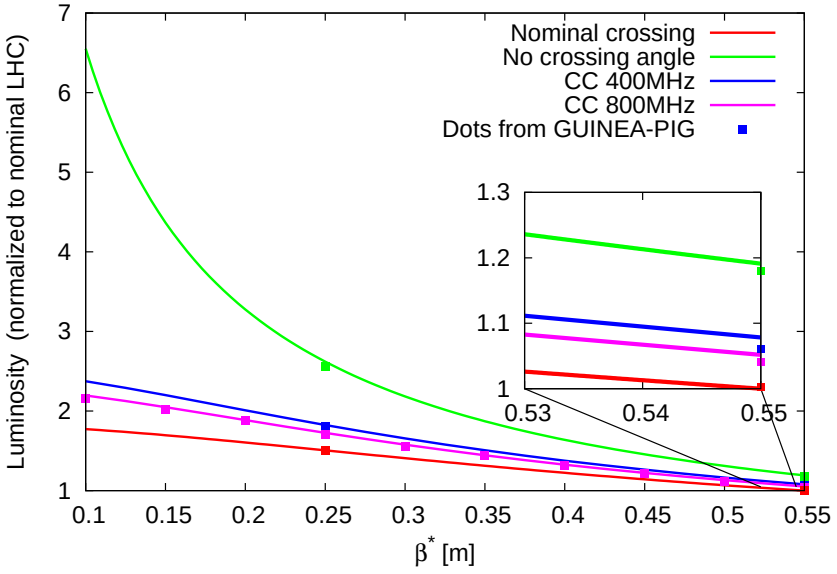
$$R = \frac{\cos(\theta/2)\cdot c}{\pi\cdot\sigma_z^2} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \exp\left[-\frac{c^2t^2}{\sigma_z^2} - \frac{s^2\cos^2(\theta/2)}{\sigma_z^2} - \frac{\sin^2(\theta/2)}{4k_{cr}^2\sigma_x^2}\cdot(2 + 4k_{cr}^2\cdot s^2 - \cos(2k_{cr}(s - c\cdot t)) - \cos(2k_{cr}(s + c\cdot t)) - 8k_{cr}\cdot s\cdot\cos(k_c\cdot c\cdot t)\sin(k_c\cdot s) - 4\cos^2(k_c\cdot s)\cdot\sin^2(k_c\cdot c\cdot t))\right] dtds$$

Single global, only one beam crabbed

$$R = \frac{\cos(\theta/2)\cdot c}{\pi\cdot\sigma_z^2} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \exp\left[-\frac{c^2t^2}{\sigma_z^2} - \frac{s^2\cos^2(\theta/2)}{\sigma_z^2} - \frac{\sin^2(\theta/2)(-2k_{cr}s+\sin(k_{cr}(s-c\cdot t)))^2}{4k_{cr}^2\sigma_x^2}\right] dtds$$

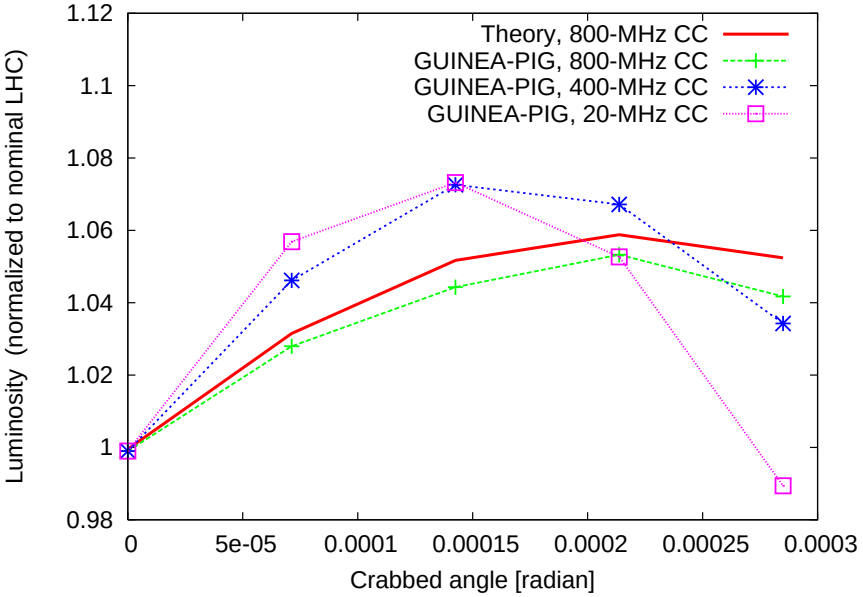
Comparison with GUINEA-PIG Simulation

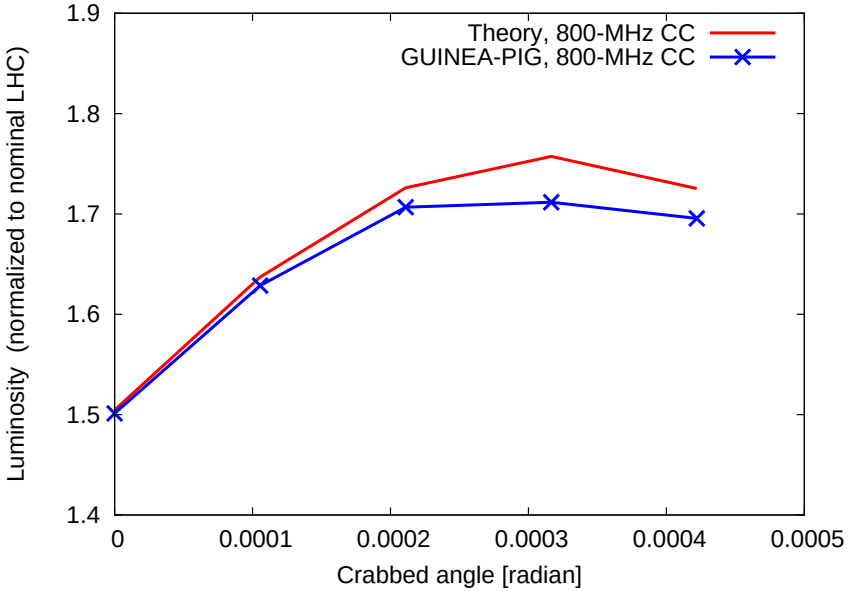




- analytical formulae (curves) and GUINEA-PIG simulations (dots), two h-crabbed beams (crabbing angle of $\theta/2$) at IP5 (left)
- only one h-crabbed beam ($\theta/2$) at IP5 (right).

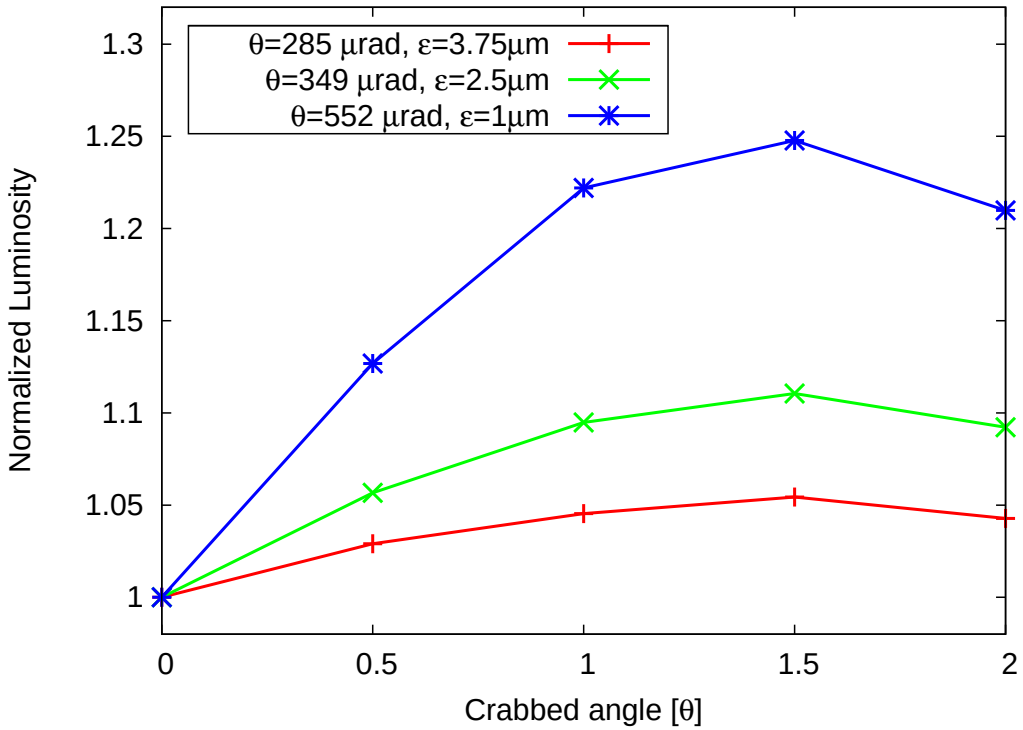
Relative luminosity gain vs crabbing angle





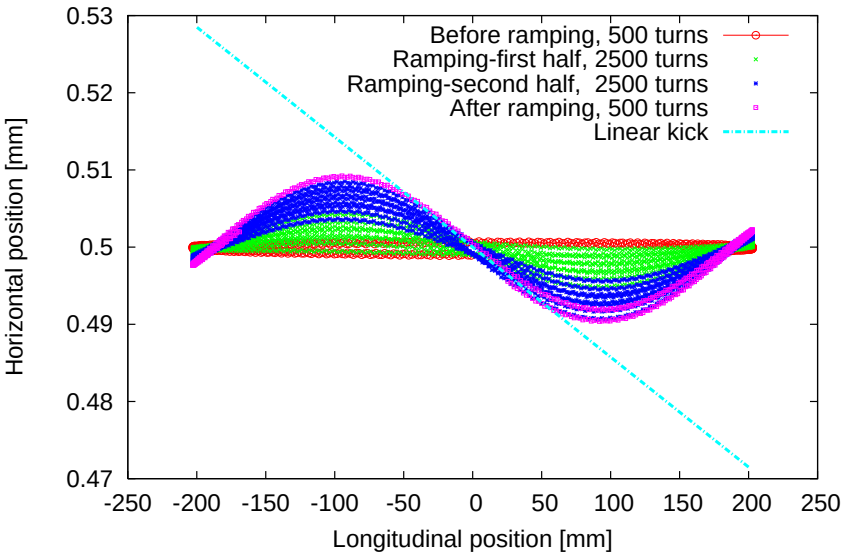
- nominal LHC collision optics (left) and *lowbetamax* (right) with single global CC. Luminosity gain of 7% or 25%
- 20 MHz, optimum crab angle = half crossing angle; higher crab frequencies –> rf curvature.

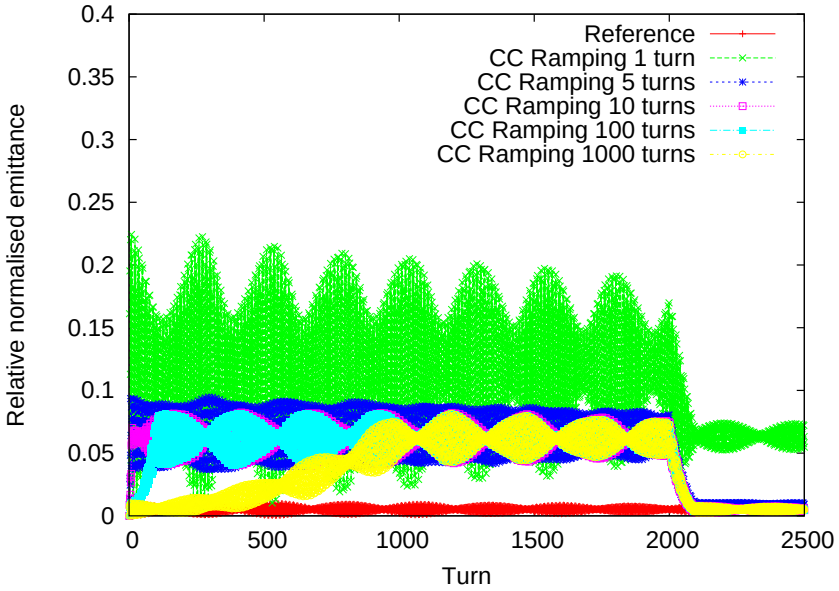
Luminosity gain for the CC prototype test



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

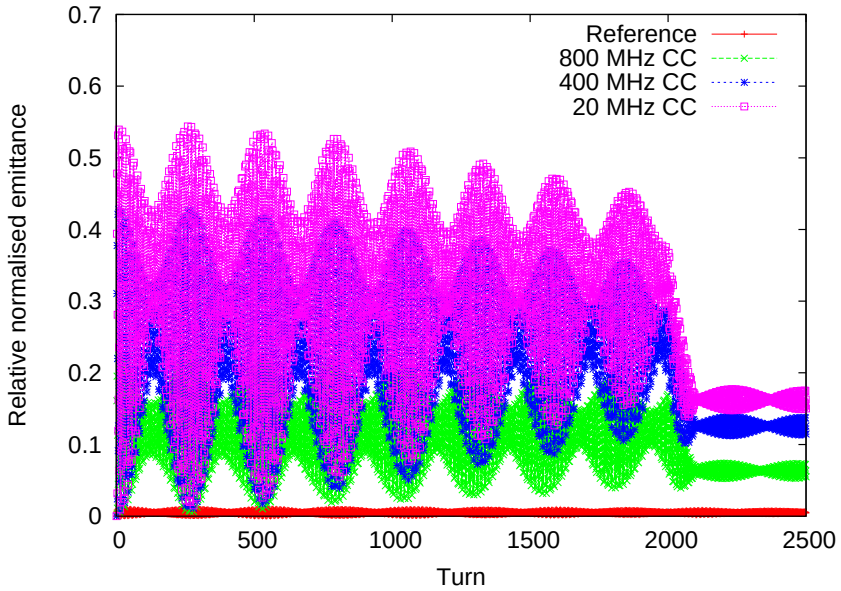
Emittance growth (1)

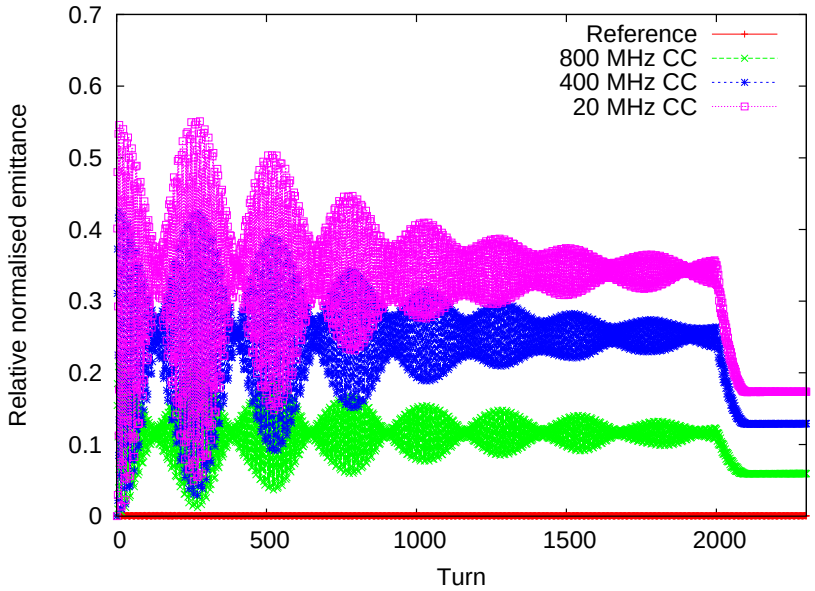




- Left: check of crab cavity ramping
- Right: relative horizontal emittance growth indicateds ramping time $>$ 10 turns

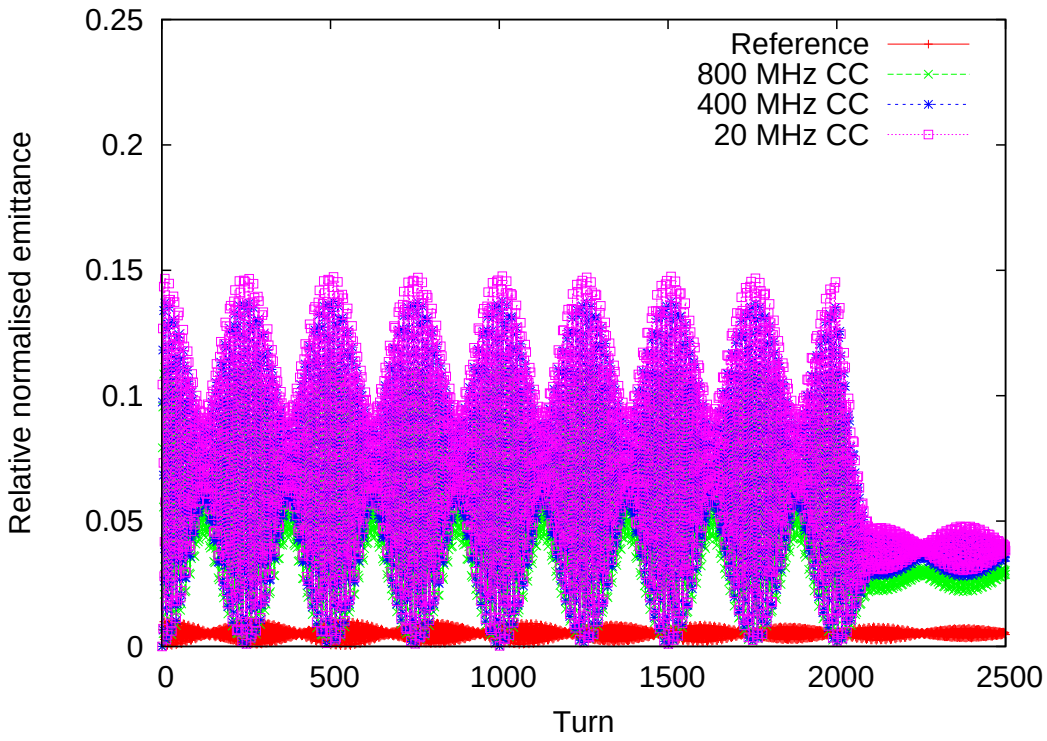
Emittance growth (2)





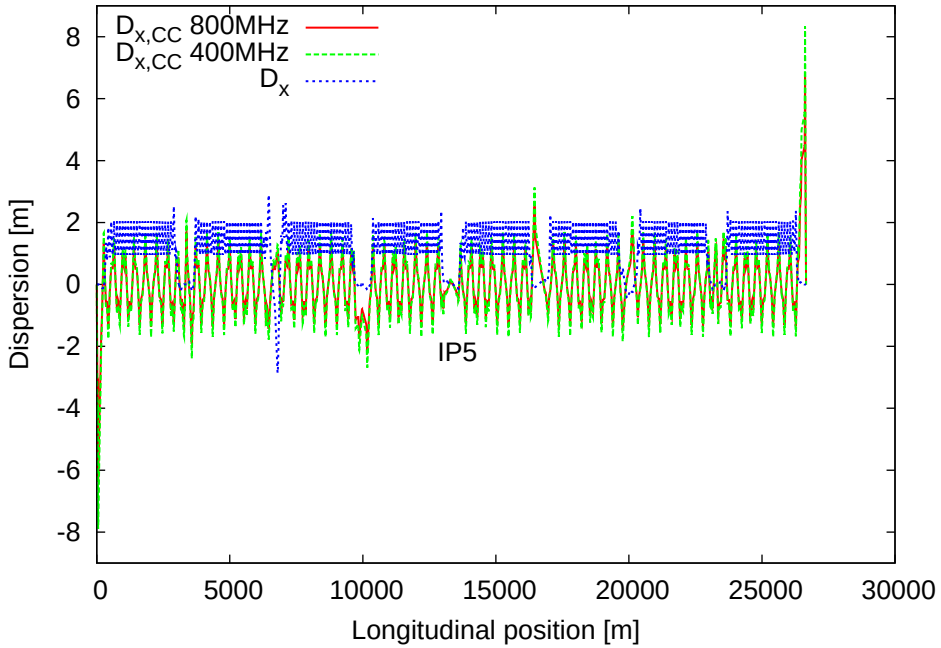
- CC ramping with different frequency 20 MHz, 400 MHz and 800 MHz, without (left) and with (right) Landau octupoles
- 1 turn ramping speed. Lower the frequency –> larger the emittance growth

Emittance growth (3)



CC ramping with different frequency 20 MHz, 400 MHz and 800 MHz, longitudinal cut at 1σ. 1 turn ramping speed. Emittance growth due to particles in the longitudinal tails.

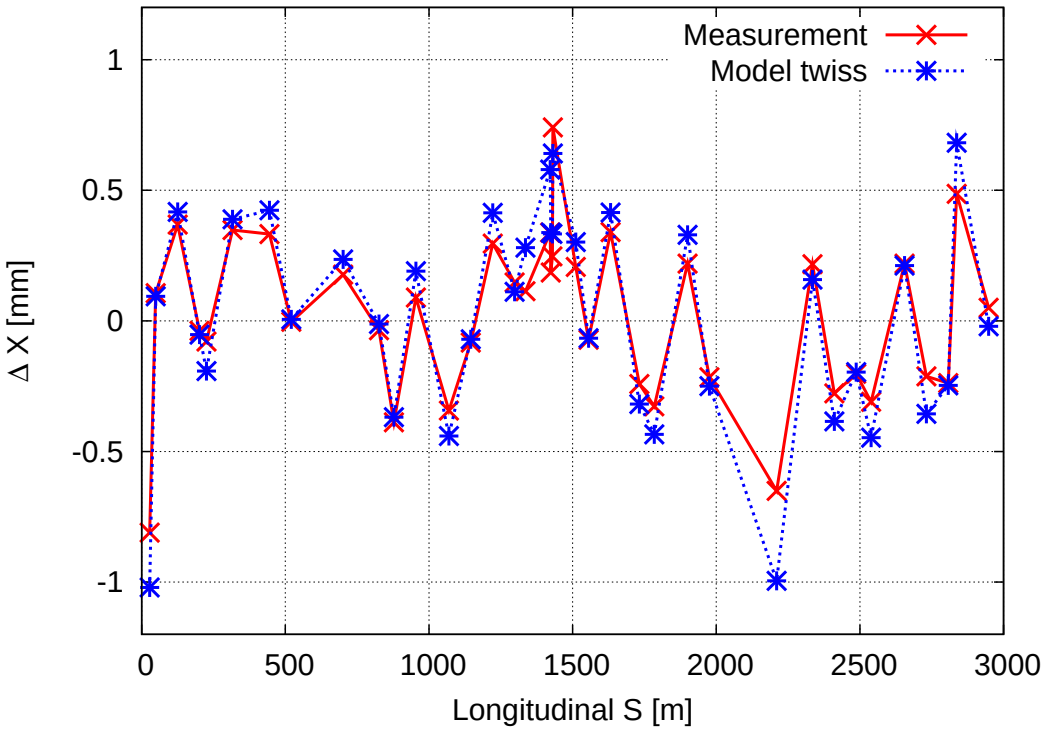
Crab dispersion



$$x_{D_{cc}}(z,s) = \sqrt{\frac{\beta(s)}{\beta^*}} \cdot \frac{q \cdot c \cdot \tan(\frac{\theta}{2})}{\omega} \cdot \sin\left(\frac{\omega z}{c}\right) \cdot \frac{\cos(\Delta\varphi_1 - \pi Q)}{\cos(\Delta\varphi_0 - \pi Q)}$$

Crab dispersion one 800-MHz global CC (red) and one 400-MHz global CC (green); normal dispersion (blue).

Crab dispersion, KEKB measurement



Measurement (L+H kick) R. Tomas et al. Dec. 2008. Analytical prediction agrees with measurement.

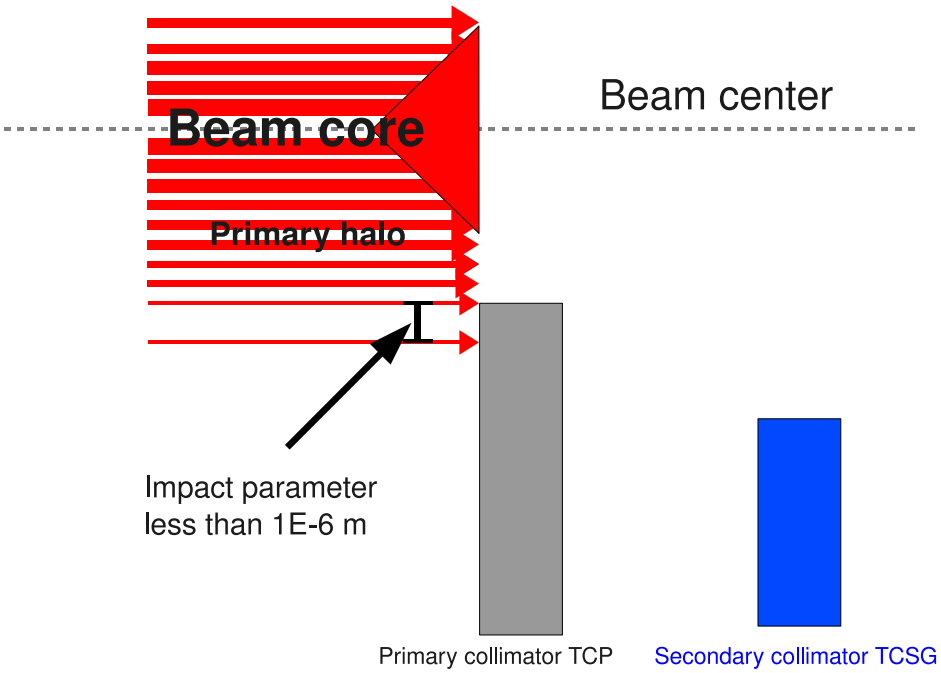
Collimation overview

The half gap of the different group of LHC collimators

	IR7 (β cleaning)	IR3 (δ_p cleaning)
TCP	6	15
TCSG	7	18
TCLA	10	20
TCTH (IR1&2&5&8)	8.3	8.3
TCDQ (IR6)	8	8

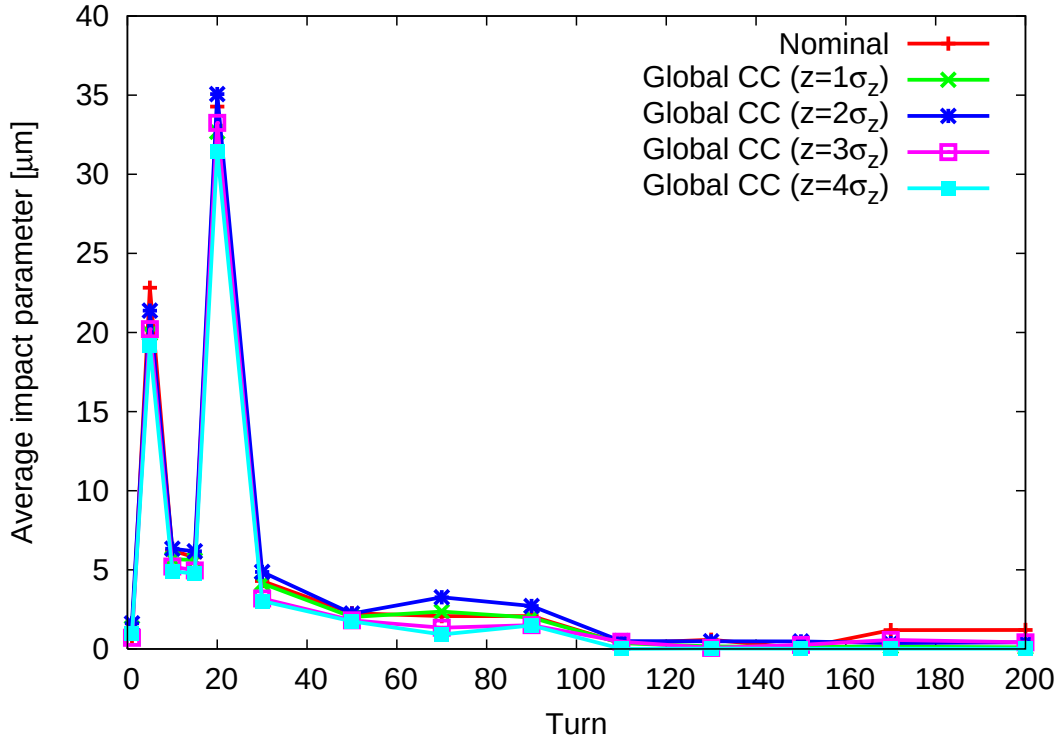
- Collimation: absorb the beam halo and protect the super-conducting ring
- Impact parameter
- Local loss map
- Collimators hierarchy & available phase space

Impact parameter (1)



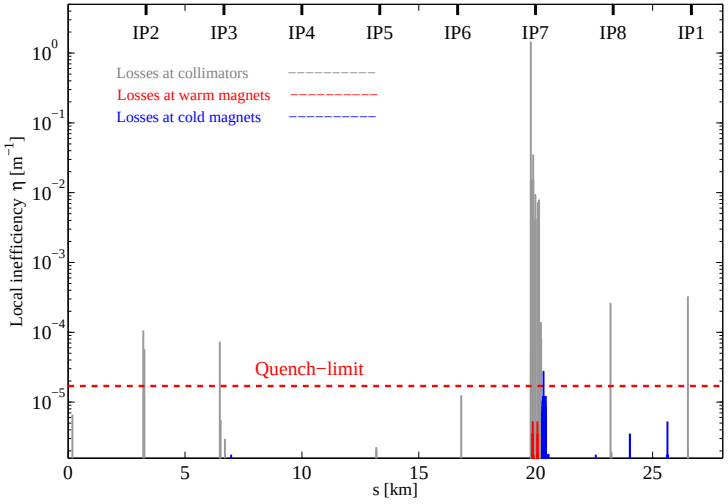
Sketch & 1×10^{-6}m requirement on impact parameter

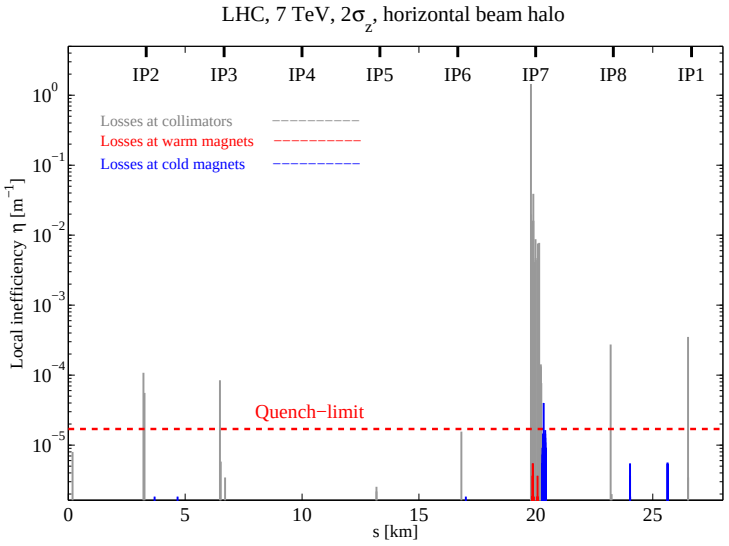
Impact parameter (2)



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

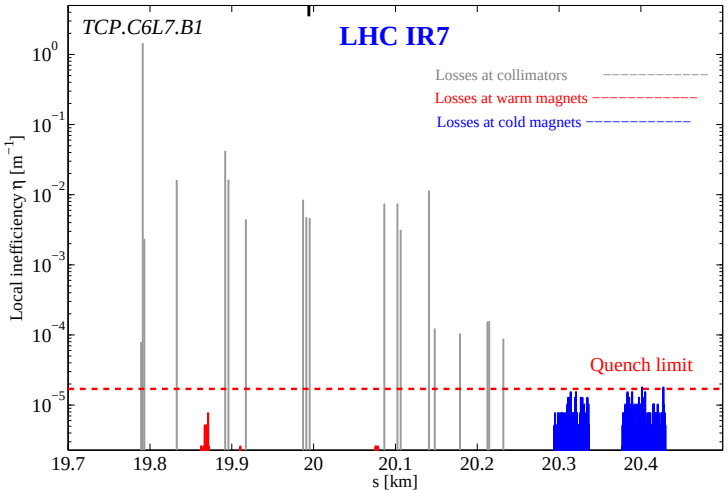
Local loss map, similar with no CC

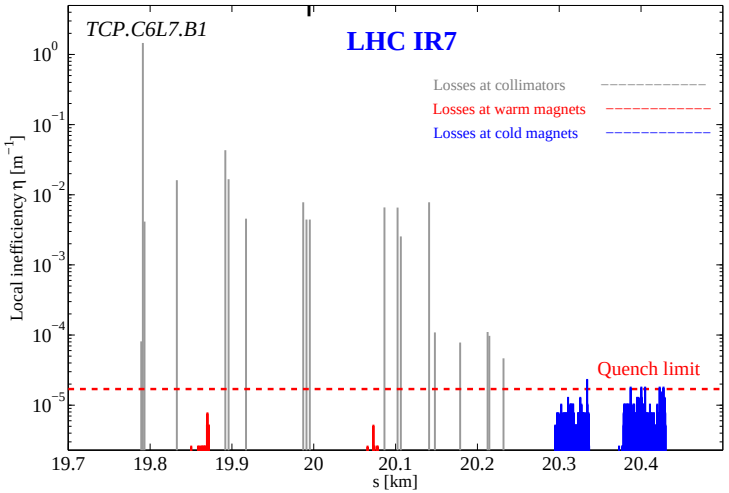




- Left: without crab cavity
- Right: z= $1\sigma_z$, with crab cavity
- Quench limit: full nominal LHC beam & 0.2 hour lifetime

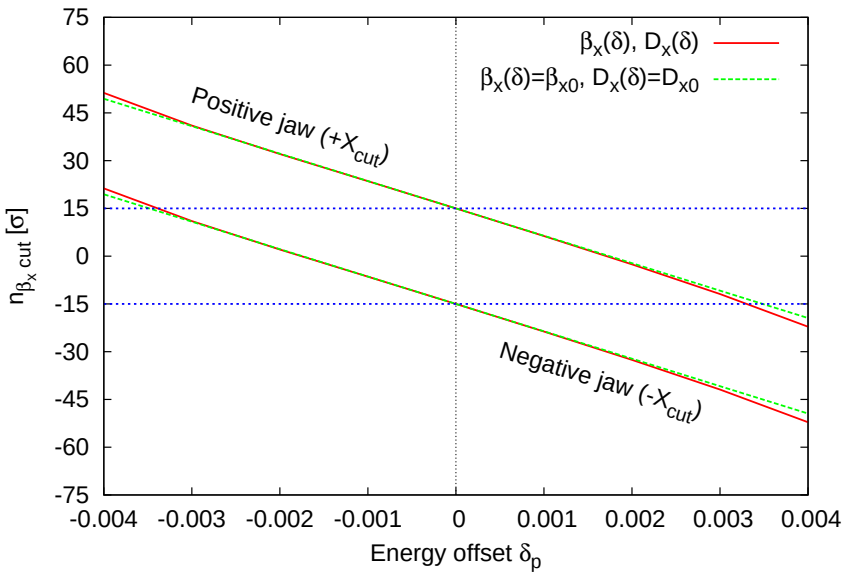
Local loss map (IR7), similar with no CC

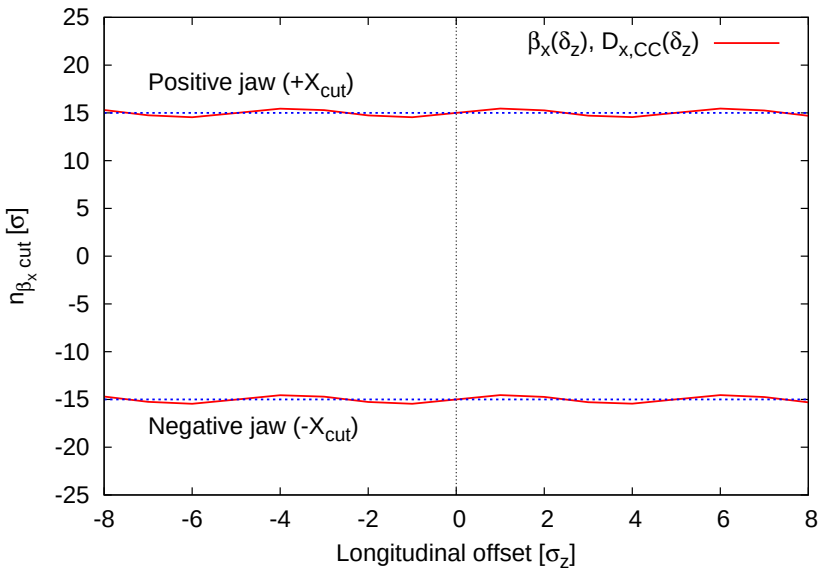




- Left: without crab cavity
- Right: z= $1\sigma_z$, with crab cavity
- Quench limit: full nominal LHC beam & 0.2 hour lifetime

Collimator hierarchy: TCP.6L3.B1

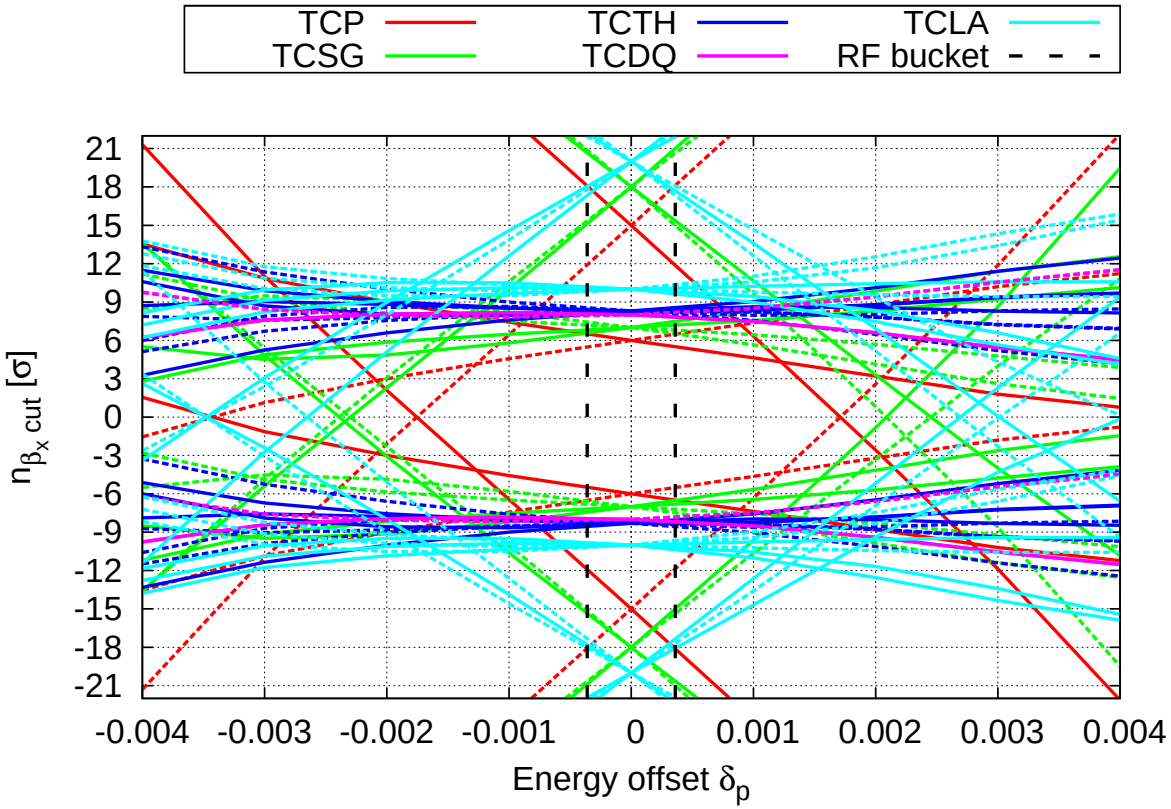




$$n_{\beta,cut}(i_{coll},\delta,z) = \frac{1}{\sqrt{\epsilon_r \beta_r(i_{coll},\delta)}} \cdot (\pm r_{cut}(i_{coll}) - D_r(i_{coll},\delta)\cdot\delta - x_{D_{cc}}(z,s))$$

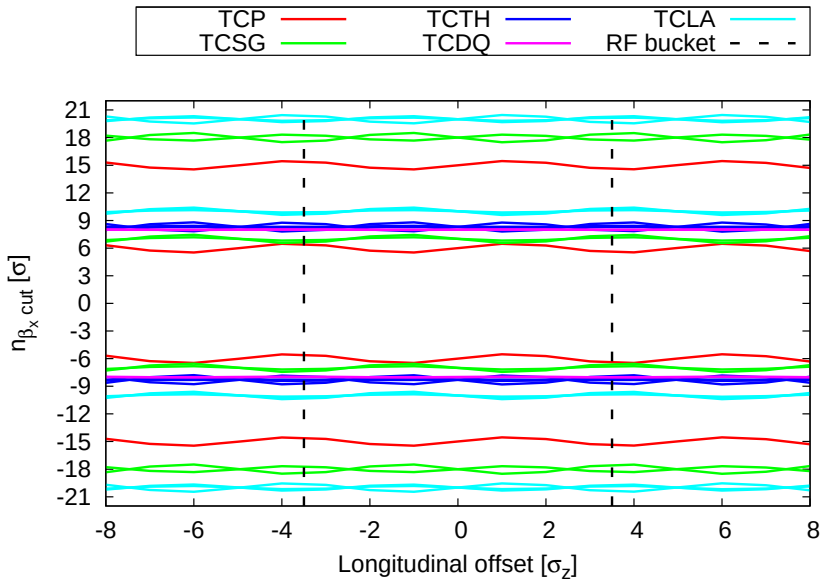
- L:Off-momentum beat (δ_p-dependent D_x and β)
- R:Crab beat (z-dependent dispersion D_{cc} and β)

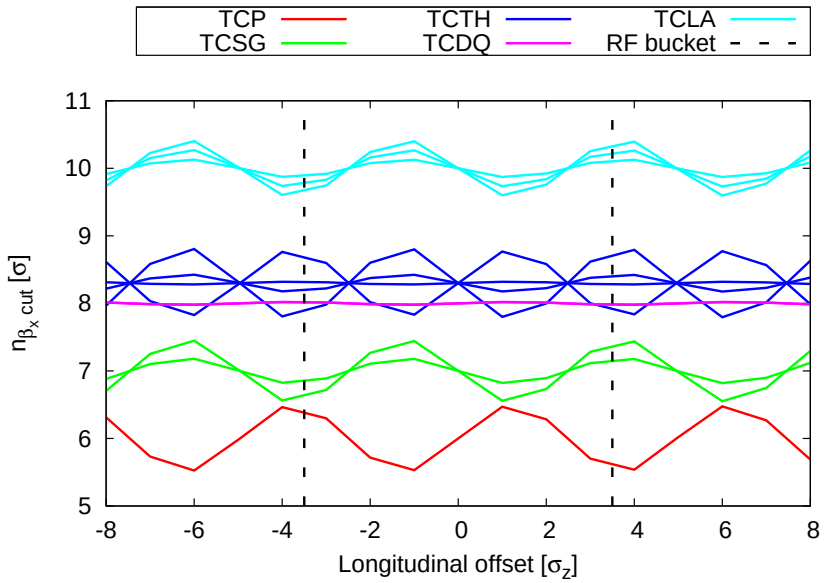
Collimator hierarchy (D_x): no crab



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

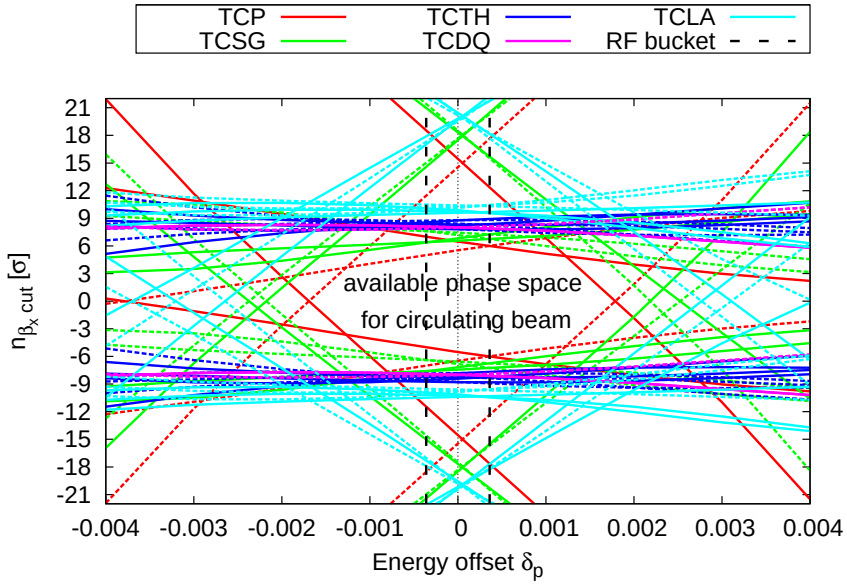
Collimator hierarchy: pure crab dispersion

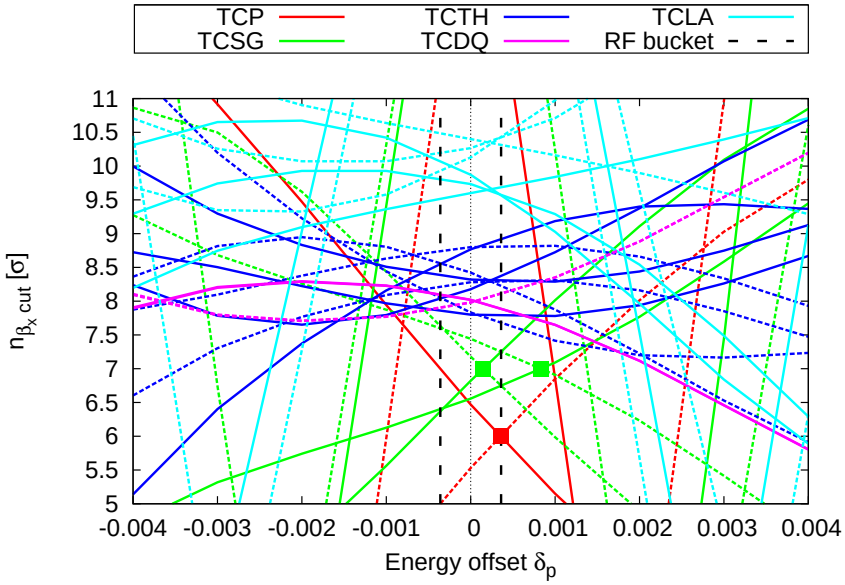




- Worst case @ $1\sigma_z$
- Crab beat (z-dependent dispersion D_{cc} and β)
- $D_r(i_{coll}, \delta) = 0$. Right: zoom.

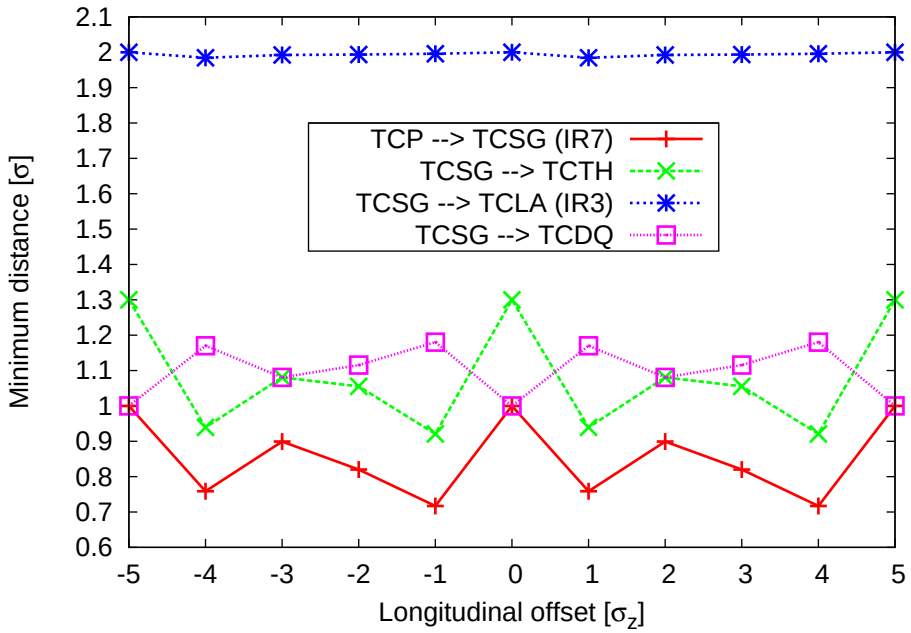
Collimator hierarchy: combine crab and off-m dispersion





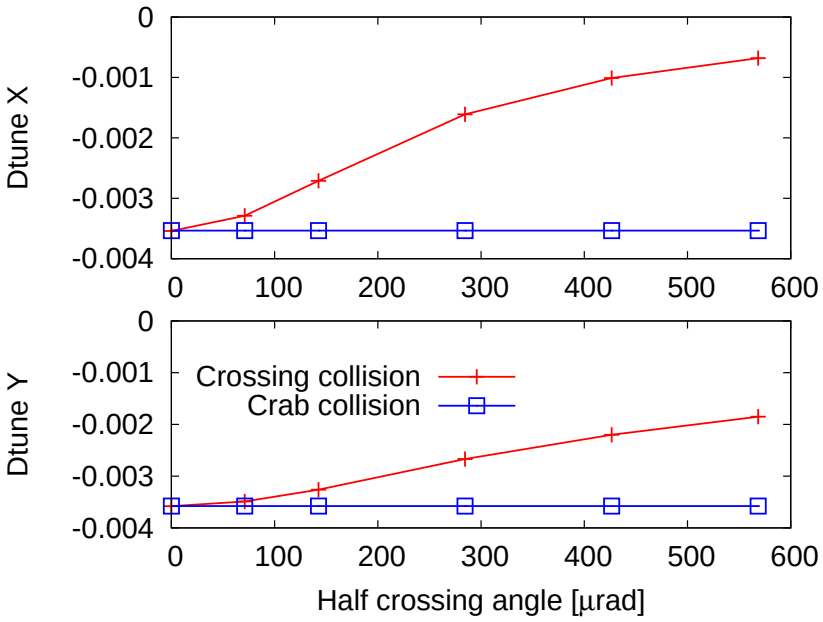
- Crab beat @1σ_z + Off-momentum beat
- **Small change**

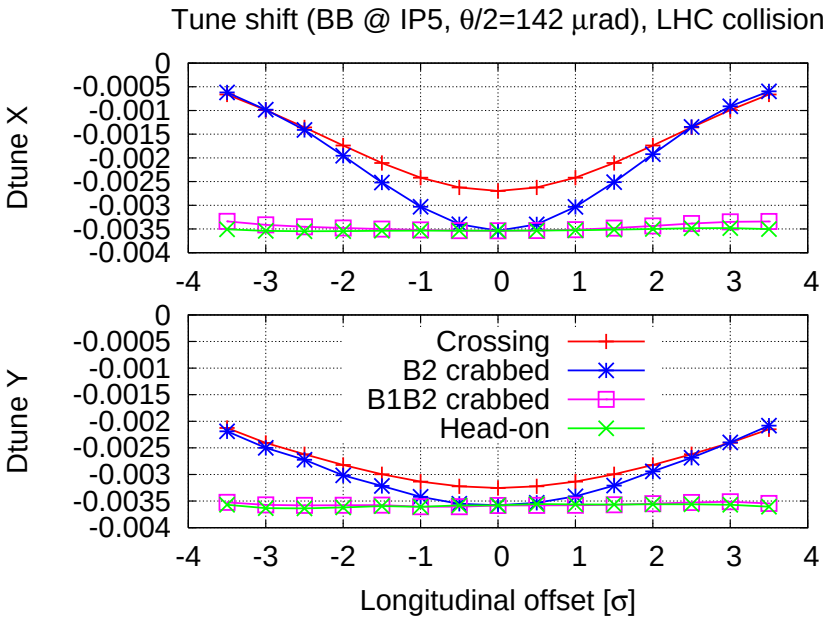
Min. P-S distance between collimators



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

Crab crossing BB tune shift, H-crossing at IP5



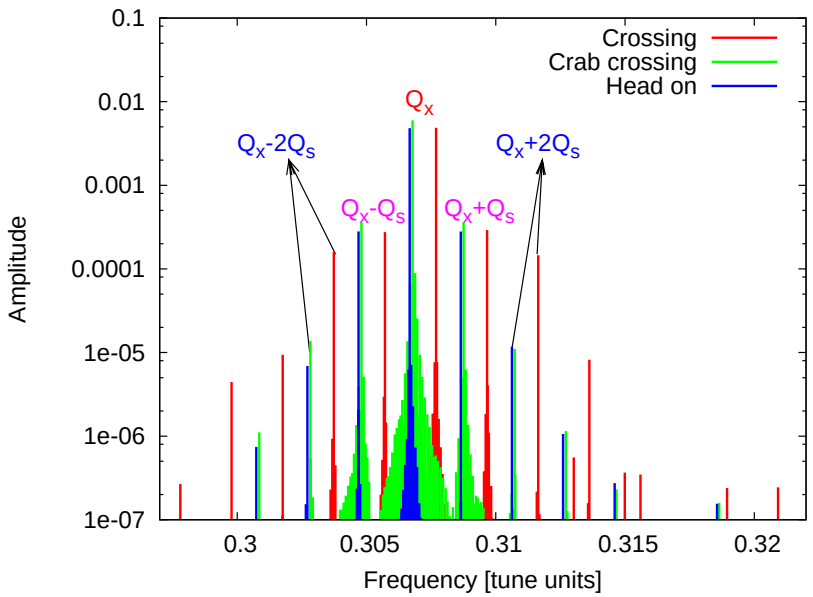


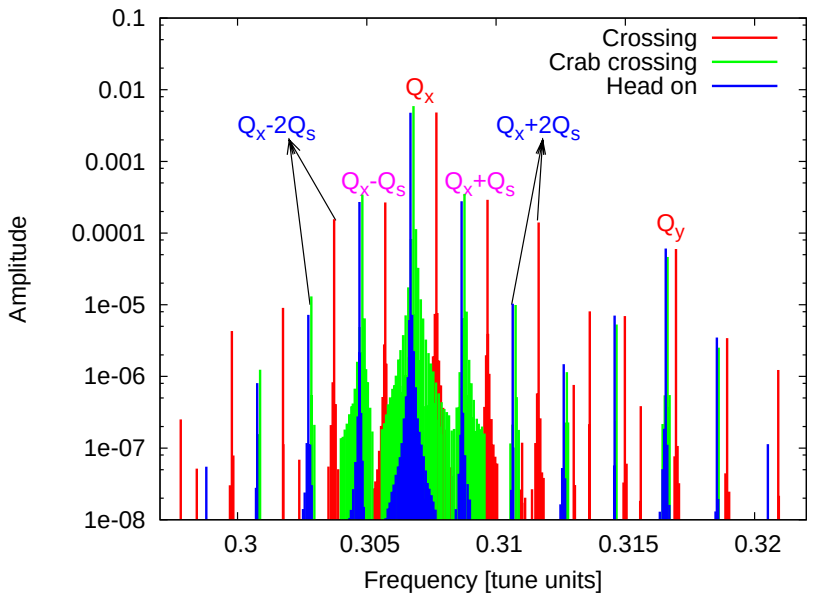
- Left: Hori. (top) and ver. tune shift (bottom);

Crab crossing tune shift = head-on collision case

- Right: Hori. (top) and ver. detuning (bottom) at different longitudinal position inside the bunch

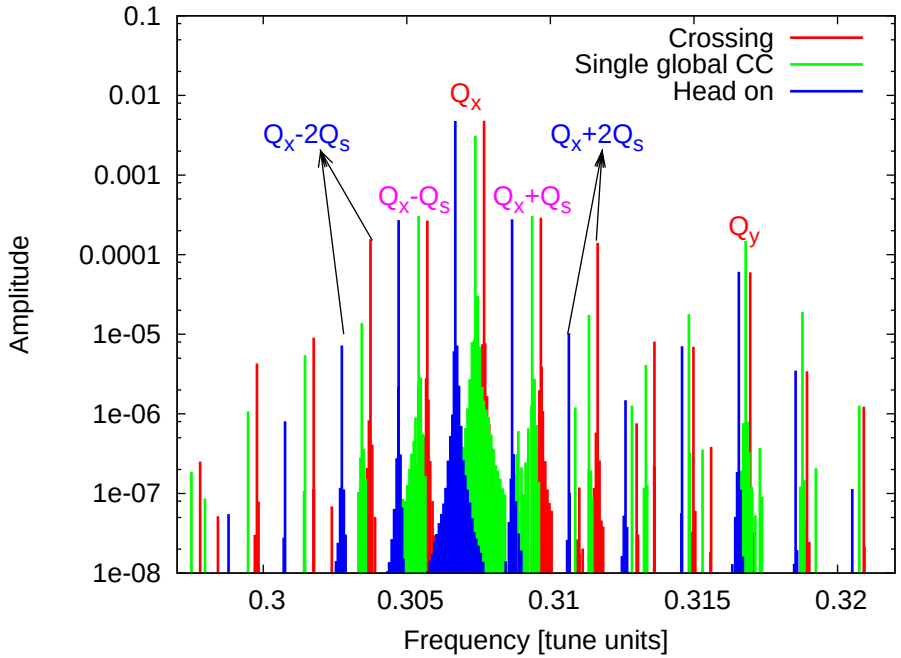
Synchro-betatron resonances: two beams crabbed





Frequency spectrum. For a particle launched with 1σ offset. The second sideband fully suppressed by the crab cavities (synchrotron tune $Q_s = 0.00197$, and chromaticity $Q'_{x,y} = 2$).

Synchro-betatron resonances: only one beam crabbed



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

Long-range + head-on effects: crab efficiency

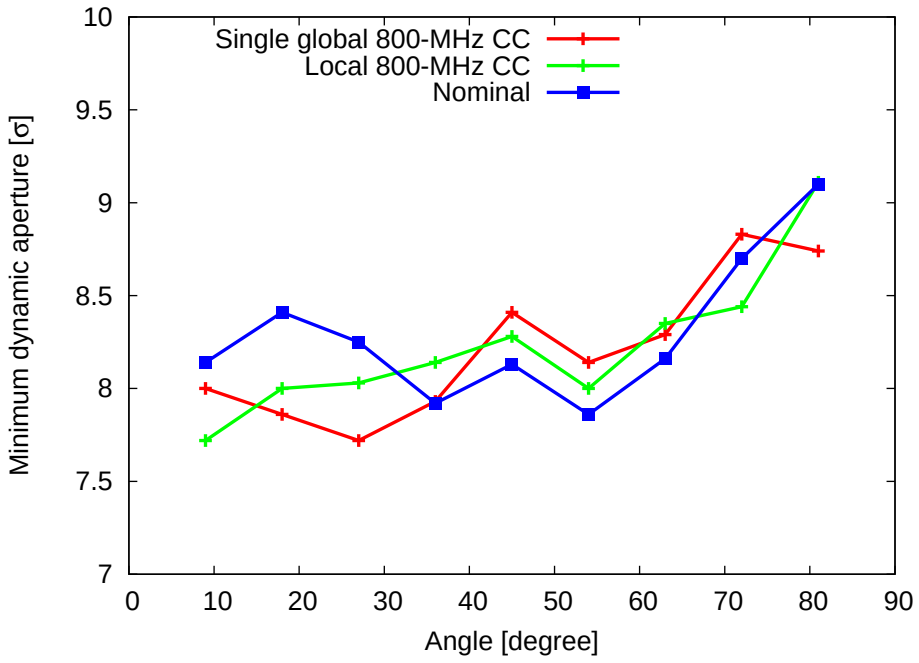
Long-range

Maximum difference in phase advance between the GCC (IR4) and IP5 for normal and PACMAN bunches smaller than 5×10^{-4} (in units of 2π). $\beta_{x,cc}$ and β^* almost unchanged by the missing long-range beam-beam collisions.

Head-on

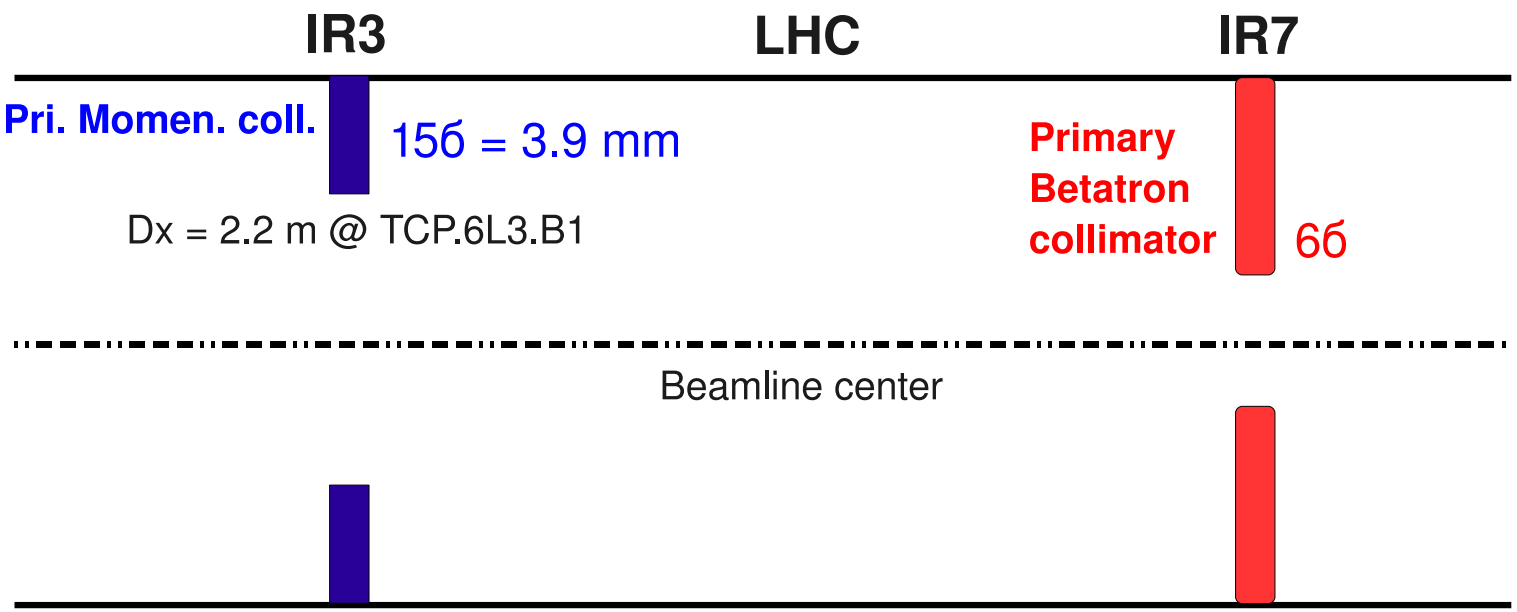
Local crabbing scheme at the nominal LHC, the beam-beam head-on collisions at IP5 and IP1 (plus all long-range collisions) change the horizontal phase advance between the two local crab cavities from 0.517 to 0.510 (in units of 2π), which will improve the locality of the crab-cavity pi bump.

Long-range effects: dynamic aperture



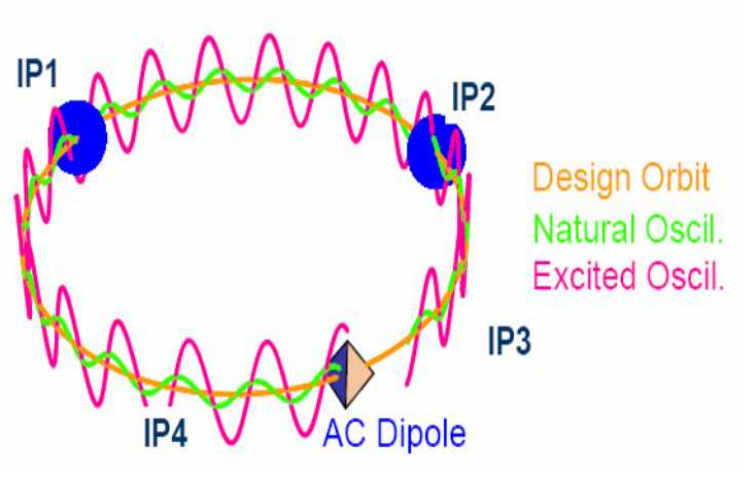
Minimum dynamic aperture over 60 error seeds for nominal LHC optics with or without crab cavity; with all the head-on and long-range beam-beam interactions at IP1, IP2, IP5 and IP8. The dynamic aperture tracking is performed for **100,000 turns**.

LHC momentum cleaning

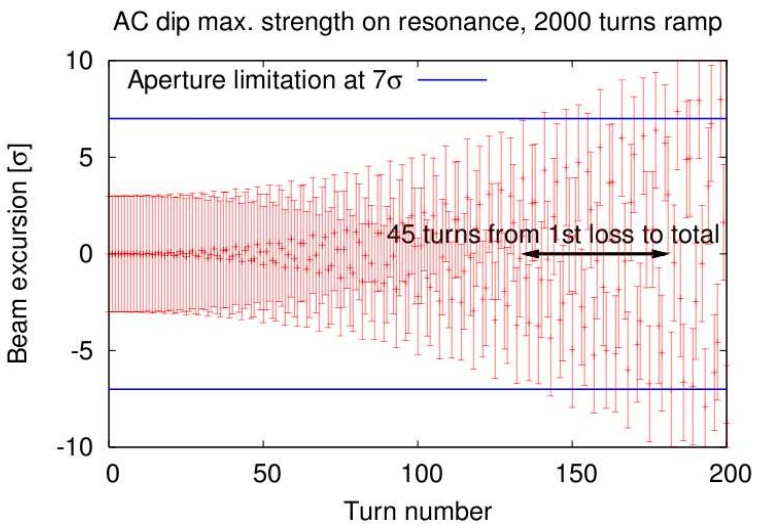


Primary momentum collimator, clean δp > -1.5 $-$ 1.8 $\times$ 10^{-3}

AC dipole



M. Bai



R. Tomas

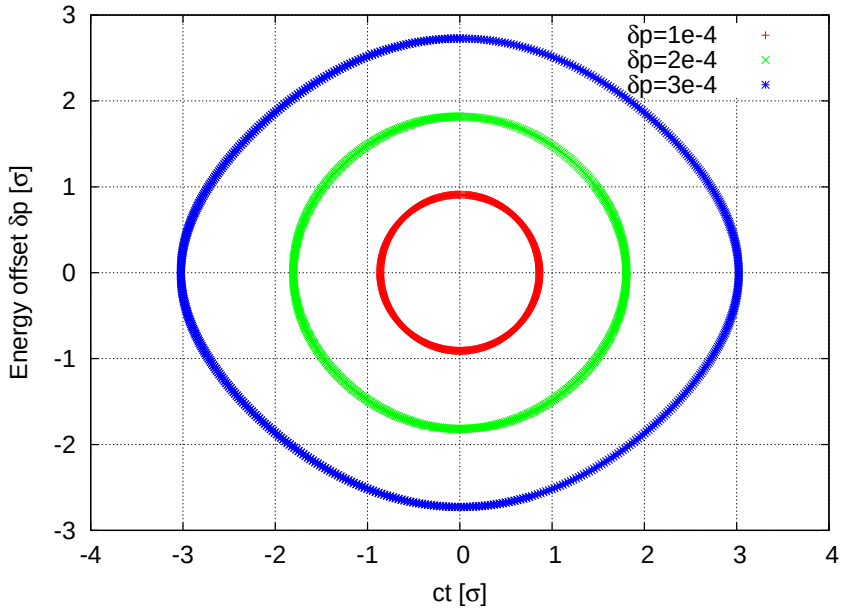
LHC IR3. $Q_{AC} = \frac{\omega_{AC}}{\omega_0}$

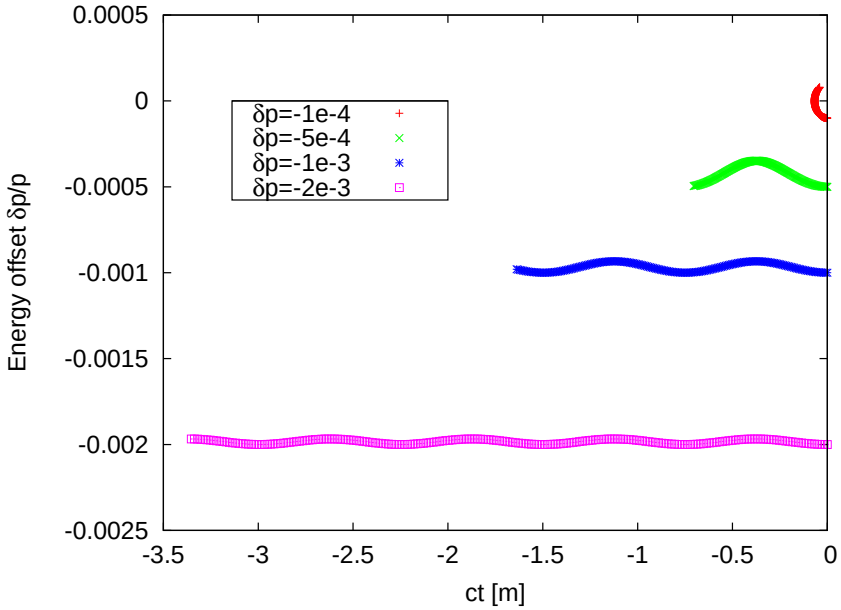
1) overcome spin resonance

2) excite coherent oscillations to measure linear & nonlinear beam parameters.

Slow adiabatical ramping –> no emittance growth

Longitudinal motion, LHC 7 TeV (16 MV)





- Left: in-bucket particles, 1000 turns
- Right: off-bucket particles, 200 turns

S. Fartoukh' proposal

Derivation

$\frac{dt}{T_0} = \frac{dC}{C_0} = \eta \cdot \delta p$ and $\Delta p_{x,CC} = \frac{q \cdot V_{CC}}{E_s} \cdot sin(\omega_{CC} \cdot t)$
$\longrightarrow \Delta p_{x,CC} = \frac{qV_{CC}}{E_s} \cdot sin(\frac{\omega_{CC}}{\omega_0} \cdot \eta \cdot \delta p \cdot n)$

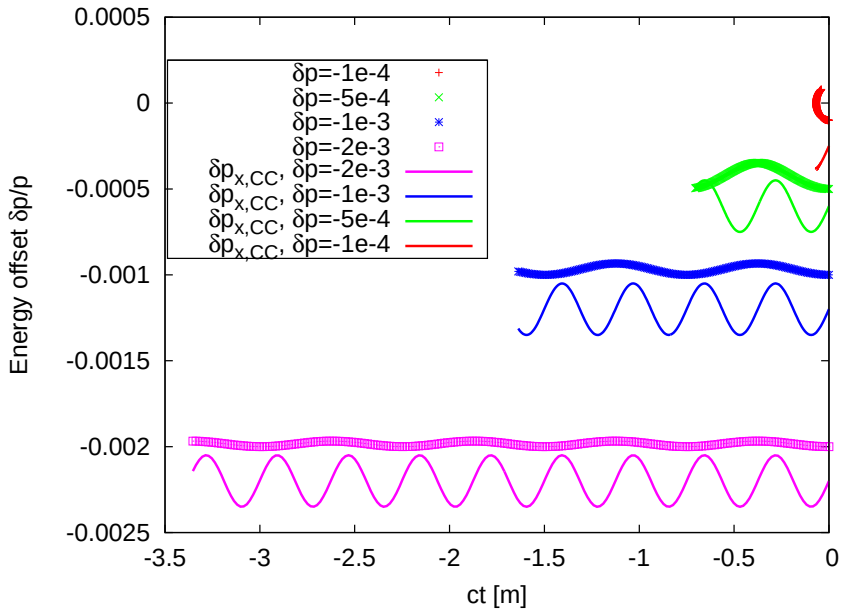
Tune of crab-AC-dipole, formula

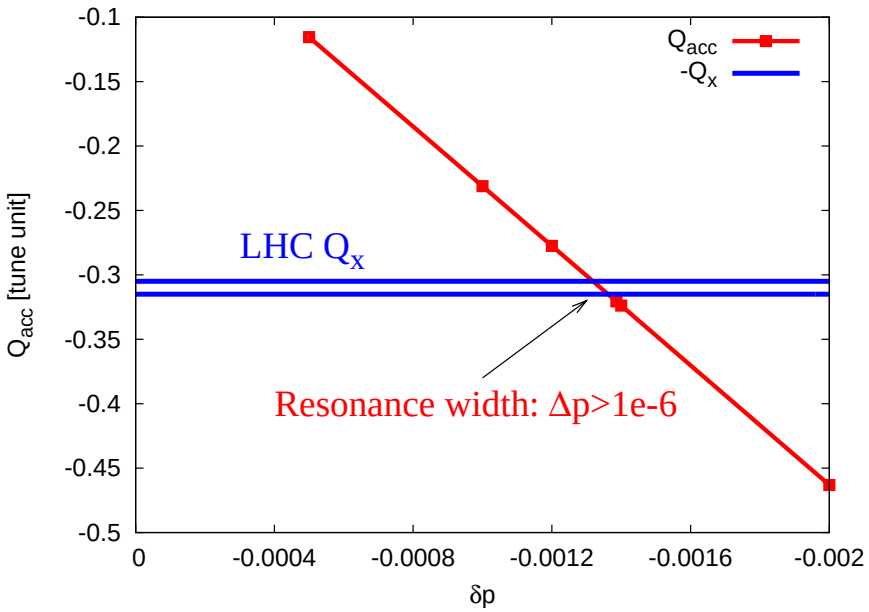
$Q_{ACC} = \frac{\omega_{CC}}{\omega_0} \cdot \eta \cdot \delta p$

Tune of crab-AC-dipole, LHC

For LHC $\eta_0 = 3.4 \times 10^{-4}$, $\omega_0 = 11$KHz
with $\omega_{CC} = 800$MHz, $Q_{ACC} = 0.025$ for $\delta p = 0.001$
with $\omega_{CC} = 8$GHz, $Q_{ACC} = 0.31$ for $\delta p = -0.001386$
$\longrightarrow\!\!\!\!\rightarrow$ $Q_{ACC} = Q_x = 0.31$, coherent oscillations

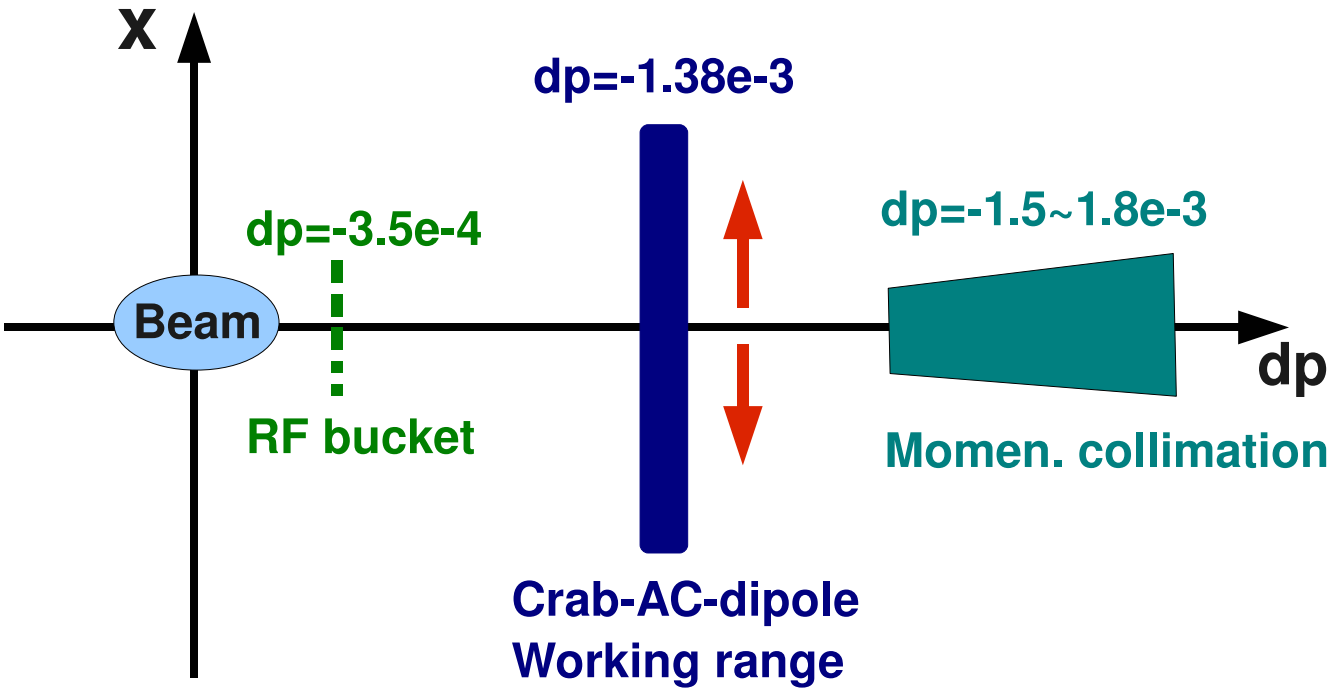
How it works





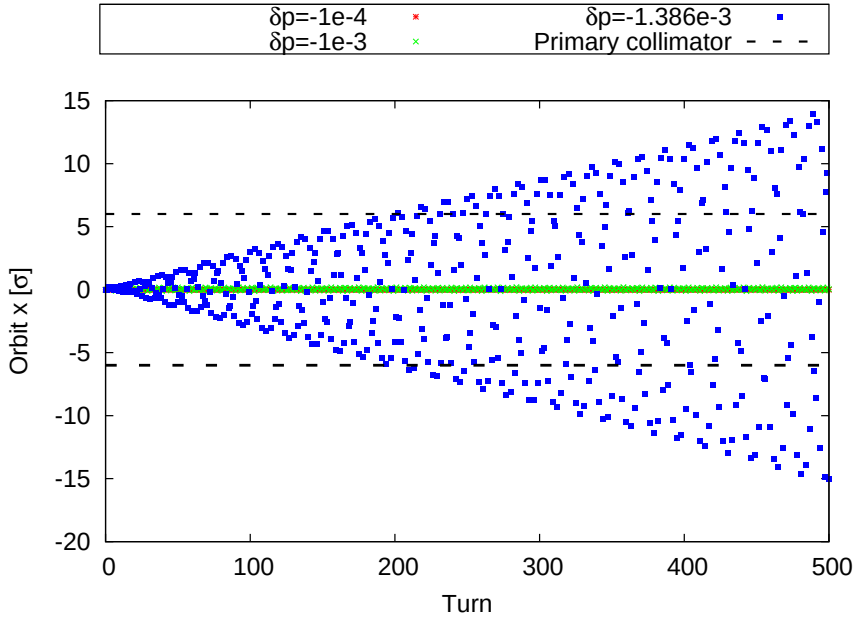
- Left: 800-MHz CC, 6 MV, for different δp in the same 200 turns
- Right: at 7 TeV, energy loss per turn: 10^{-9}, to excite in 1000 turns

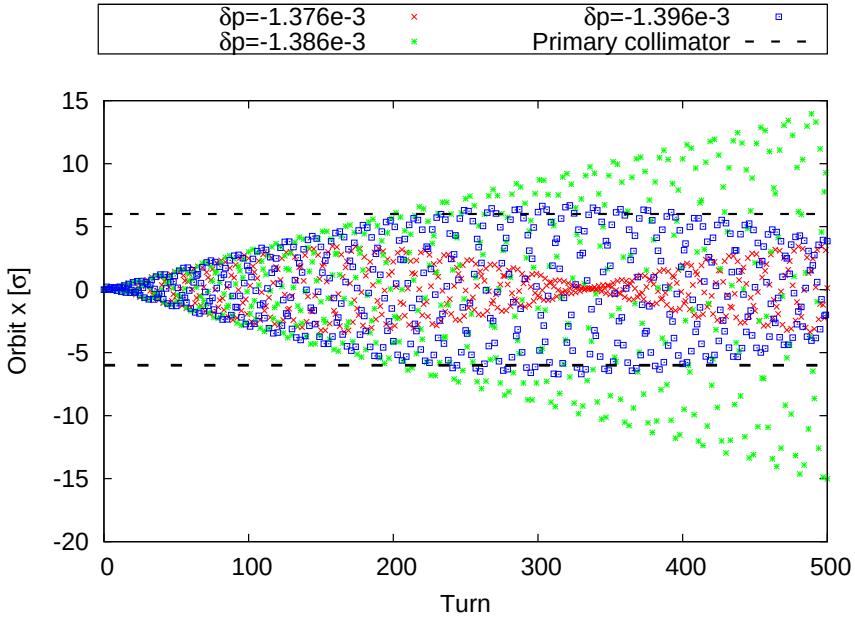
Alternative for momentum collimators



Fast enough, compared with synchrotron radiation loss

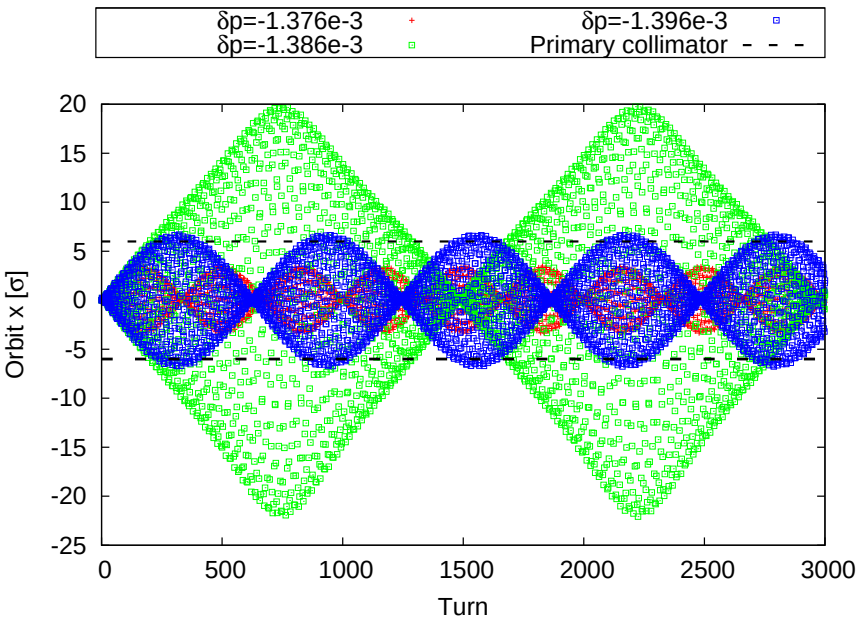
Coherent oscillation with 8-GHz CC (1)

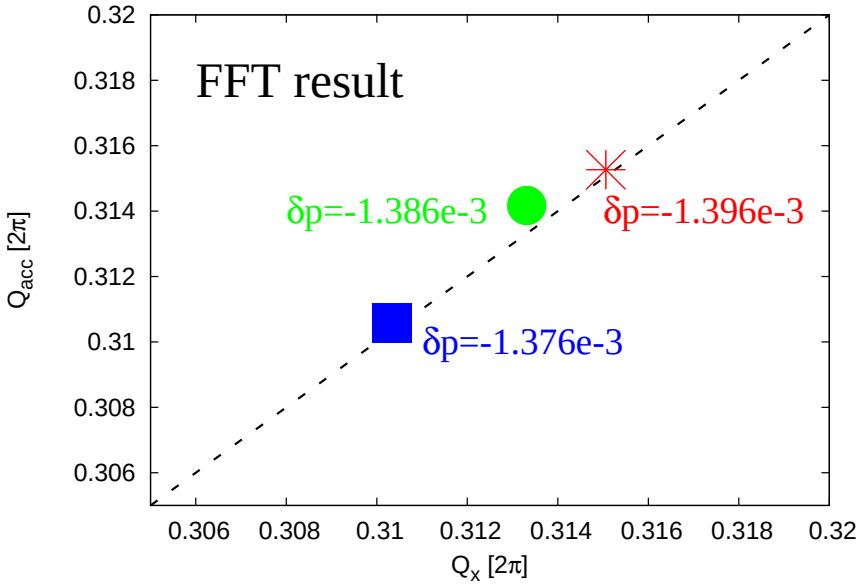




$\delta p = -0.001386$, $Q_{ACC} = Q_x = 0.31$ works with 3×10^{-6}rad, smaller than LHC AC dipole strength

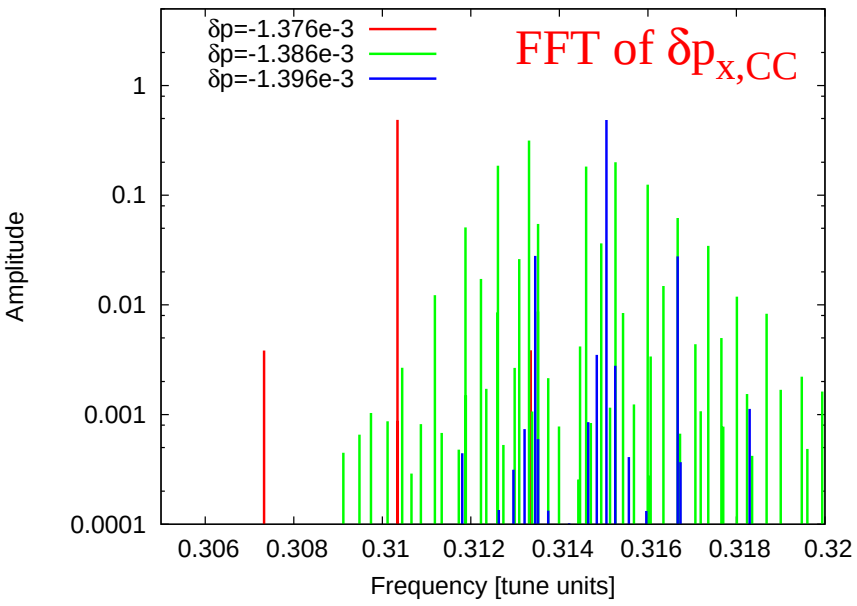
Coherent oscillation with 8-GHz CC (2)

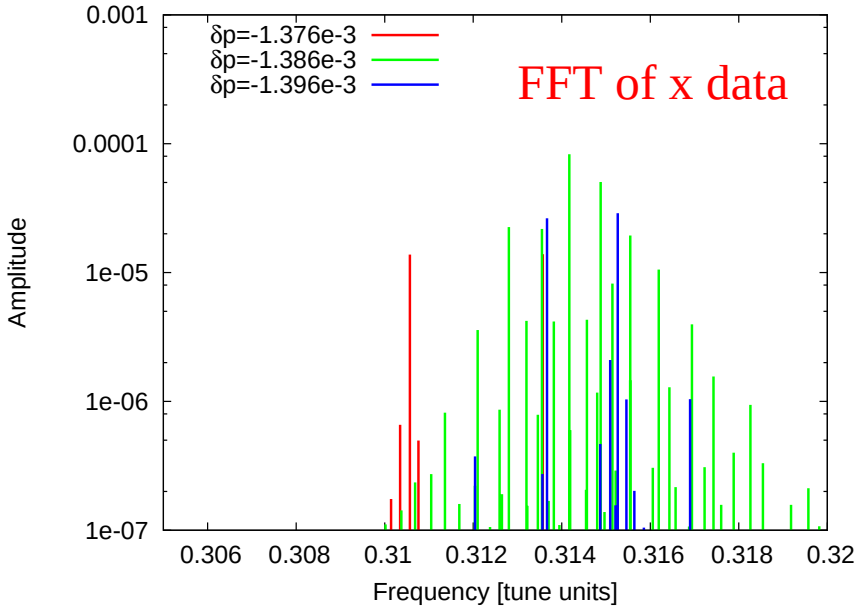




- Decoherence-recoherence, or damping effect?
- Resonance width $\Delta p = 2 \times 10^{-5}$

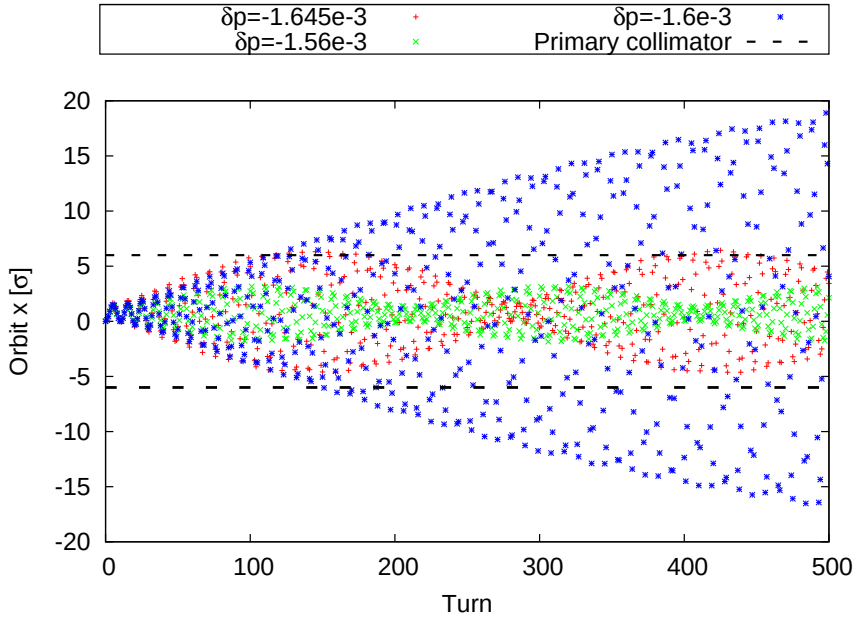
FFT spectrum

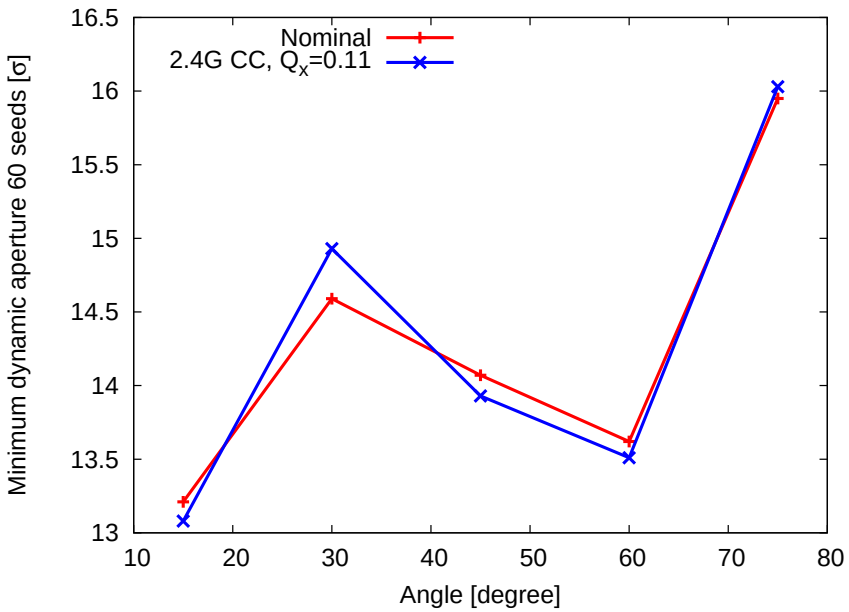




- Left: FFT of turn-by-turn crab-AC-dipole kick
- Right: FFT of turn-by-turn x data

Coherent oscillation with 2.4-GHz CC





- $\delta p = -0.0016$, $Q_{ACC} = Q_x = 0.11$
- Resonance width $\Delta p = 9 \times 10^{-5}$, voltage 1 MV for 2.4-GHz CC

Conclusion

- Crab-AC-dipole works in LHC for 8-GHz & 2.4-GHz
- Clean very early the off-bucket particles which have not yet reached the abort gap (good for background)
- Alternative to the momentum collimation insertion
- pi/2 IR phasing–> $\beta^* = 15$cm
- For 800-MHz, Q_x–> 0.04 to use linear resonance; or creat the condition for 4th-order resonance

What To do next

- **2.4-GHz possible in LHC?**
- **Crab-cleaning collimation tracking: on-going**
- **Find resonance condition for 800-MHz CC**

Conclusion (1)

- Both local and global crab schemes studied
- Various beam dynamics issues have been studied
- LHC optics can fulfill the requirements to install CC
- Min dynamic aperture over 60 magnetic errors seeds shows a maximum 1 to 2σ degradation, acceptable
- Global crabbing scheme for nominal LHC requires an additional 0.5σ aperture (*lowbetamax* 1σ)
- z-dependent 'beta beating' due to the global crab cavity much smaller than the regular off-momentum beta beating

Conclusion (2)

- Luminosity gain from crab crossing computed analytically and by GUINEA-PIG simulations shows good agreement
- Local crabbing scheme with 400-MHz crab cavities, luminosity recovered to head-on collision
- Global crabbing scheme with only one 800-MHz global CC, luminosity gain as large as 25% for reduced beam emittance
- Emittance growth study for CC voltage ramping –> ramping period of longer than 10 turns
- 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

Conclusion (3)

- 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 the same as the head-on collision tune shift
- Second-order synchro-betatron resonances introduced by the crossing collision suppressed by the crab cavities

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

MADX and SixTrack code development

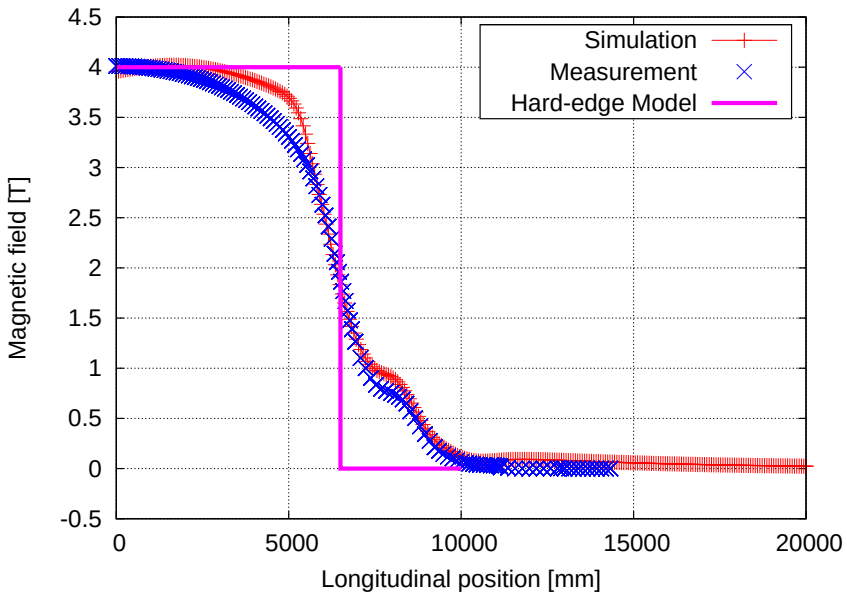
MADX

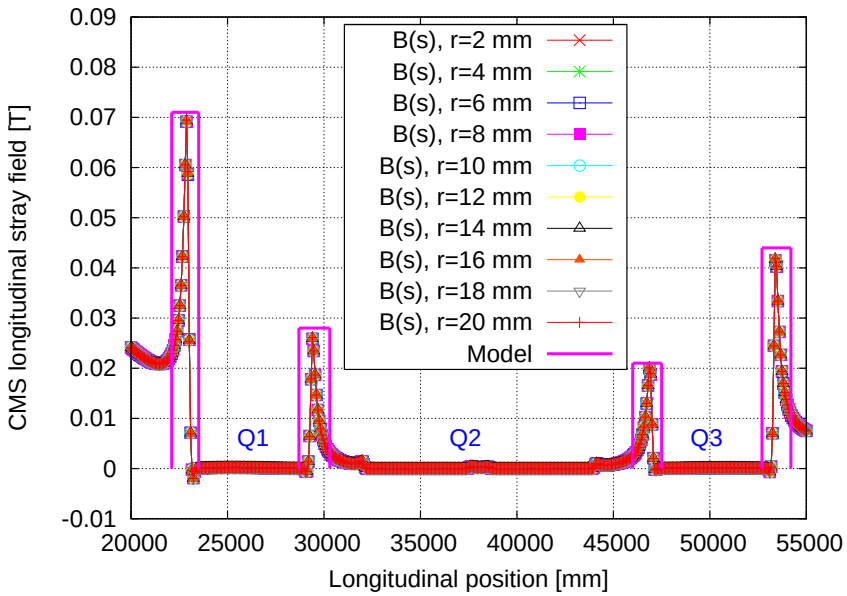
- MADX “thintrack" module keeper
- 6D closed orbit search by iteration
- New type aperture: Racetrack
- To do: AC dipole and Noise elements

SixTrack

- new element ‘solenoid’ has been added in the SixTrack code and debugged
- Small modifications on collimation part

Impact of CMS Field on LHC Beam Dynamics (1)

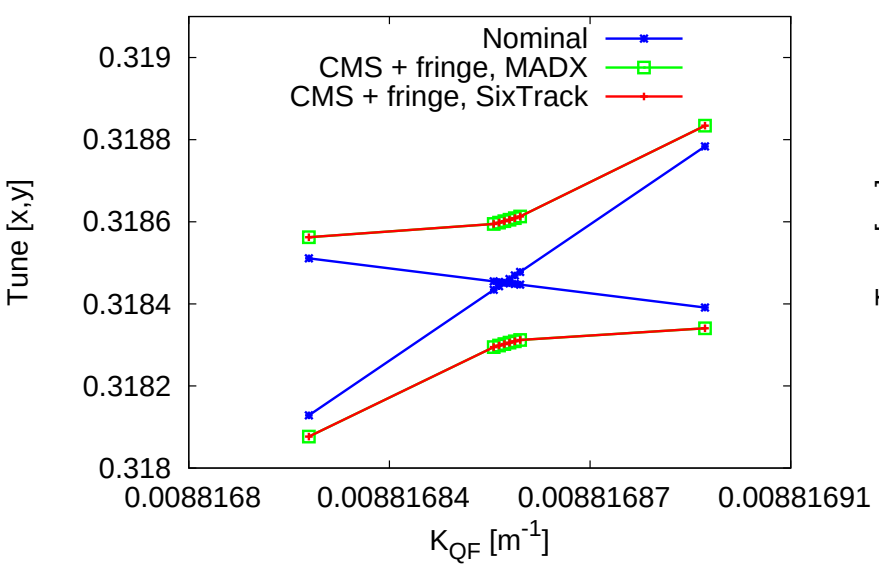


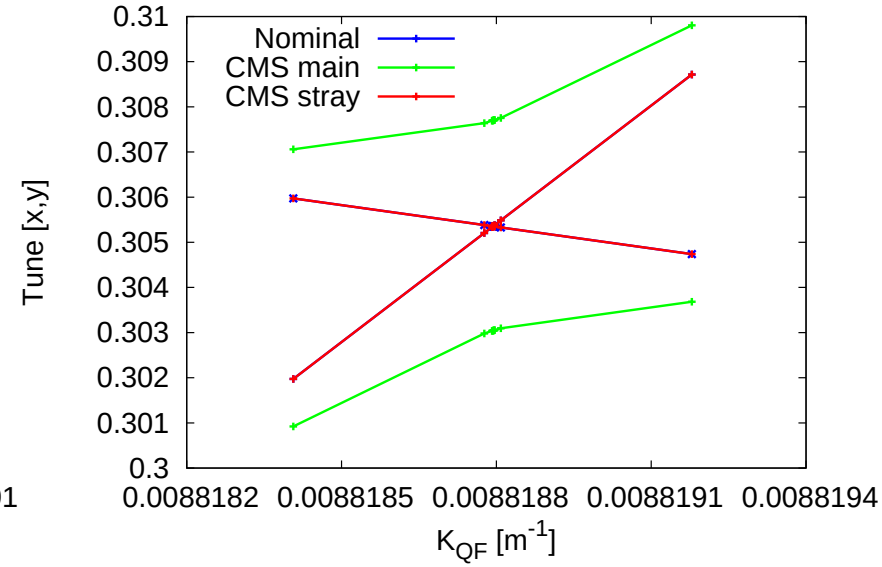


Left: comparison of CMS field between simulation and measurements. IP5 is located at the origin of the abscisse. A simple hard-edge model is used (magenta lines).

Right: Longitudinal component of the CMS solenoid stray field.

Impact of CMS Field on LHC Beam Dynamics (2)

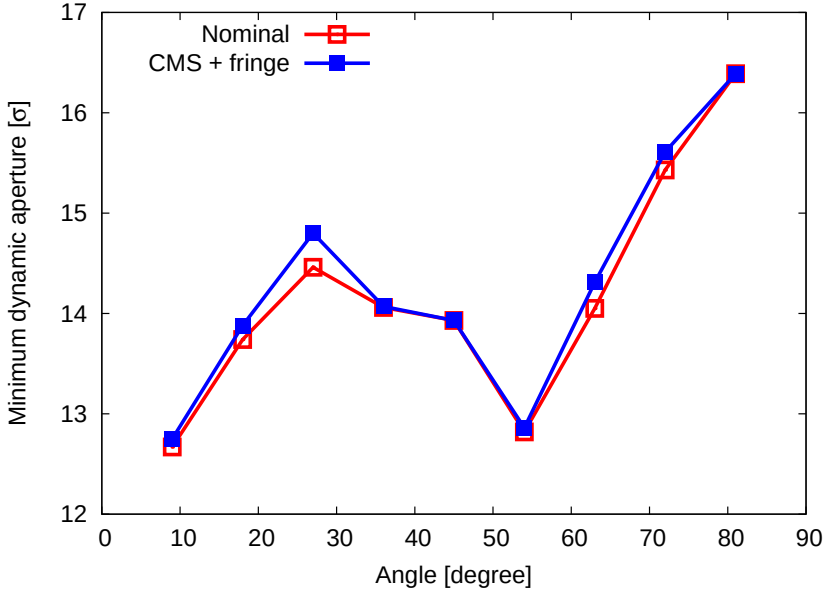


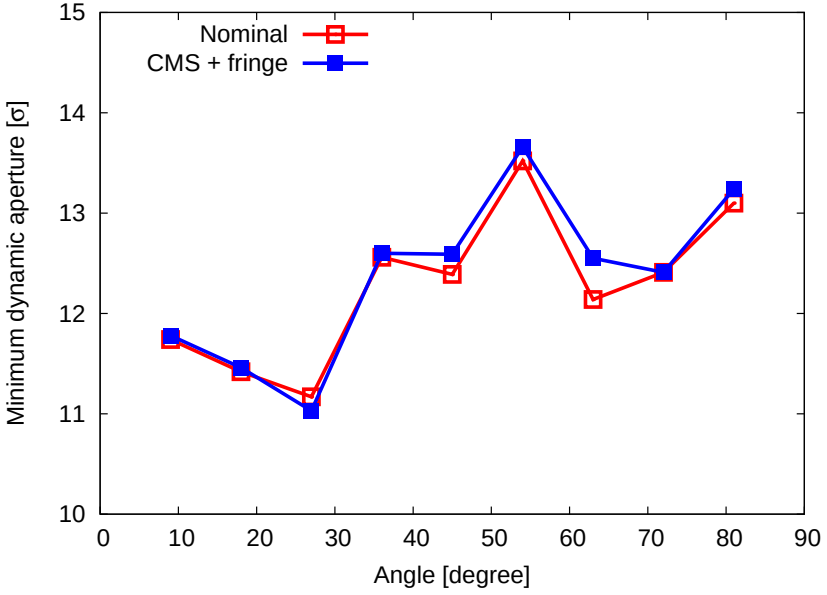


Left: Coupling 2.99×10^{-4} introduced by the CMS solenoid for the collision optics at 7 TeV.

Right: Coupling 4.65×10^{-3} introduced by the CMS solenoid for the injection optics at 450 GeV.

Impact of CMS Field on LHC Beam Dynamics (3)





Left: Minimum dynamic aperture over 60 seeds for nominal LHC optics long term (100,000 turns). LHC collision optics at 7 TeV.

Right: LHC injection optics at 450 GeV.

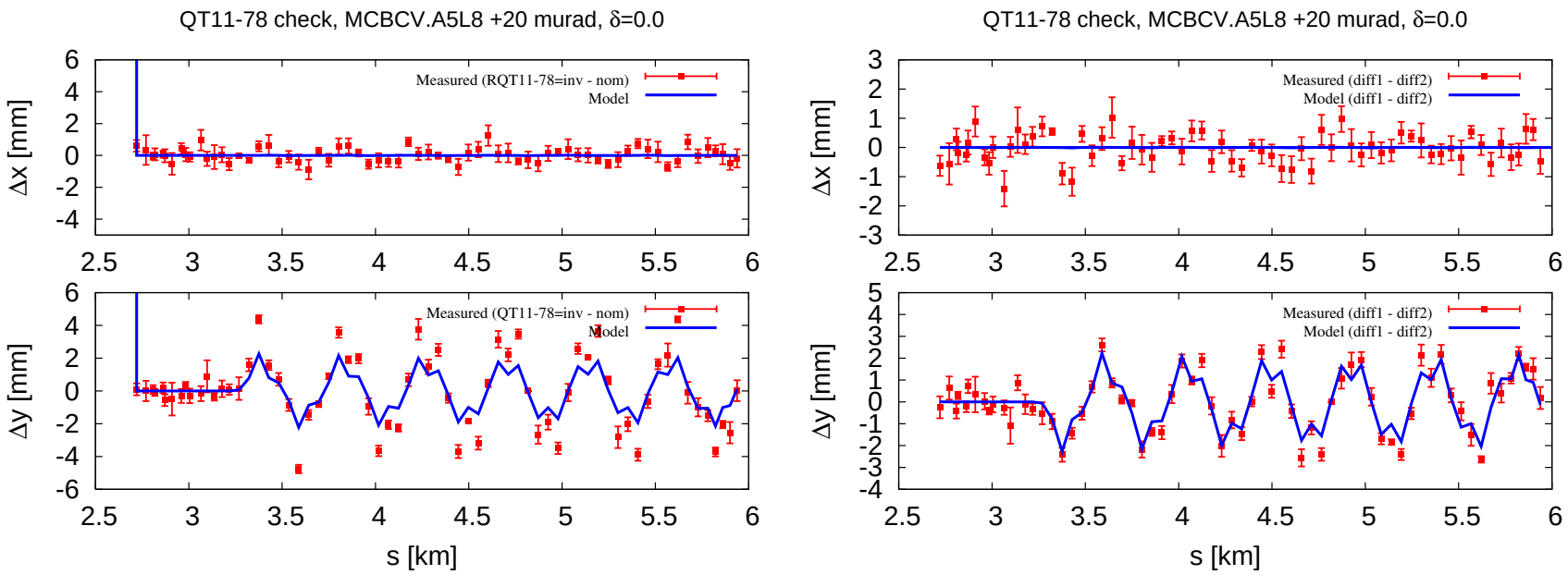
Polarity check for LHC injection test (S23 & S78)

Conclusions

Data 24 Aug 2008, for LHC sector 78

	Rama Calaga	Yipeng Sun & Frank Zimmermann
Sequence	Beam2+ '-' bv + reflect	Beam4 + flipped x YASP measured data
Questionable BPM	BPM.12R7.B2 (x-y inv); BPM.34R7.B2;	BPM.12R7.B2 (x-y inv); BPM.28R7.B2 (y) BPM.34R7.B2 (x); BPMSX.4L8.B2
Questionable correctors	BXV3;	BCH6(off-m); BXV3; BYH4(off-m)
Questionable magnets	QT11; QS; MSS; OD; QT13; SF[1] (amp)	OD; QT13; QS; MCS; MSS
Polarity OK	BCH6; BCV5; BYH4; BCH6 OF; MCS; QT12; SD[1,2]	BCH6(on-m); BCV5 OF; QT11; QT12; SD[1,2]; SF(?)
Polarity OK? (swap or?)	SD[1] <-> SD[2]	SD[2] -> SD[1,2] SF[1] -> SF[1,2]

Polarity check for LHC injection test (1)



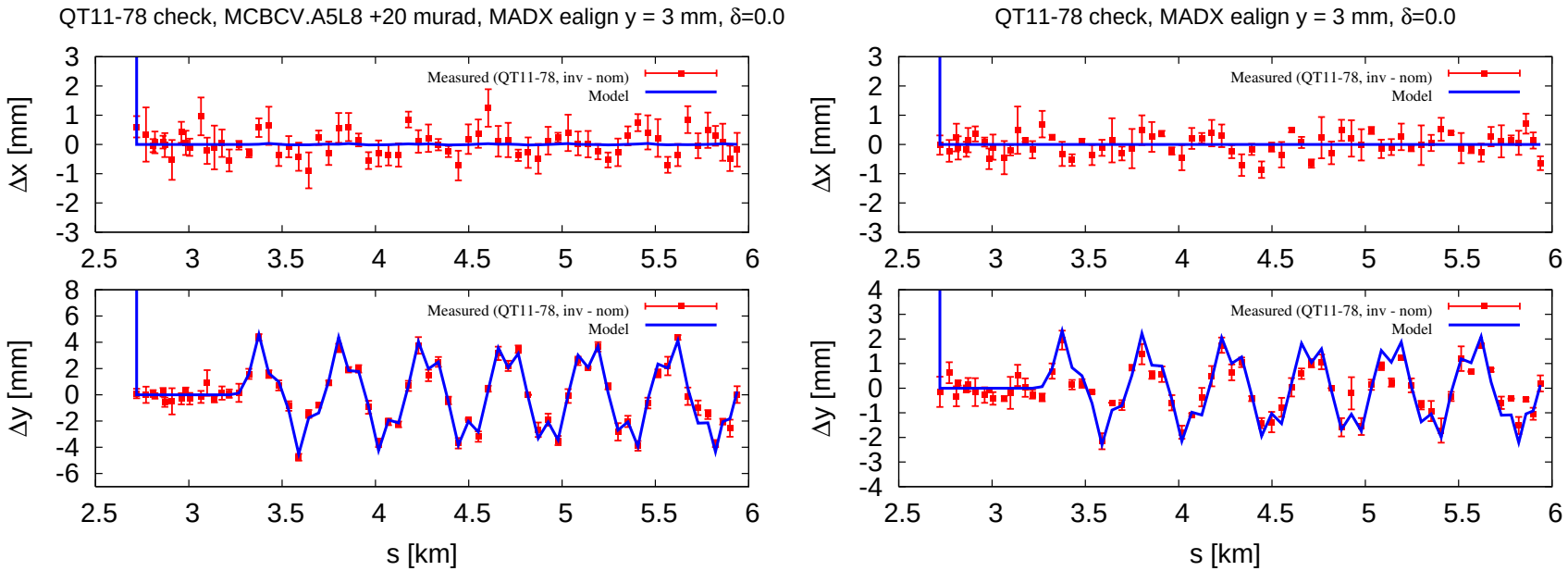
MQTLI.11L8.B2 (on-m)

Diff1(2): with(out) corrector, inv - nom (Left fig is diff1)

$\theta = 2(k_{QT11} \cdot L)\Delta y$ –> Estimated Y offset: 4.7 mm

nearby BPM.11L8.B2: -0.18 mm, BPM.10L8.B2: -1.13 mm, BPM.9L8.B2: -4 mm

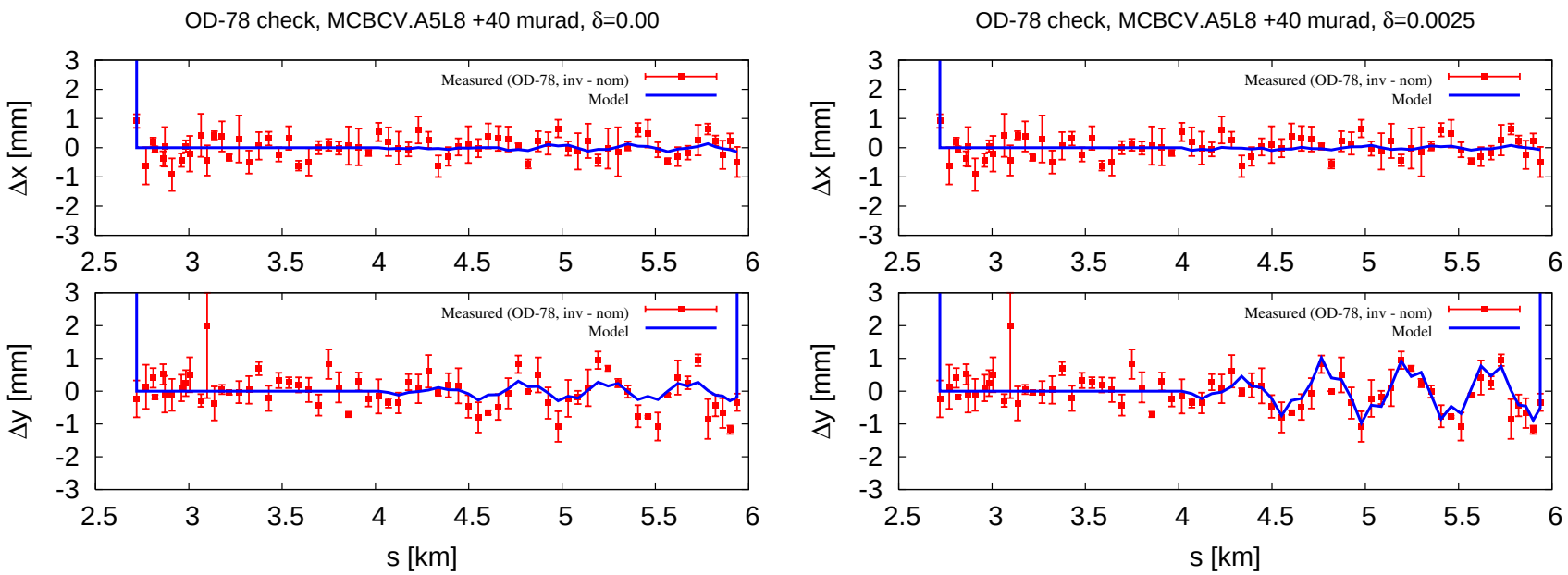
Polarity check for LHC injection test (2)



Left: with corrector, inv - nom; Right: without corrector, inv - nom

In MADX, set MQTLI.11L8.B2 misaligned error y = 3 mm

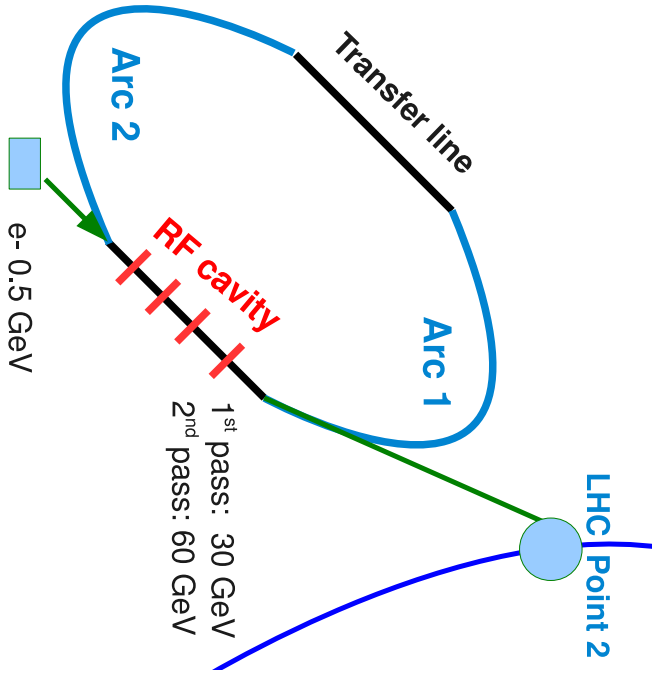
Polarity check for LHC injection test (3)

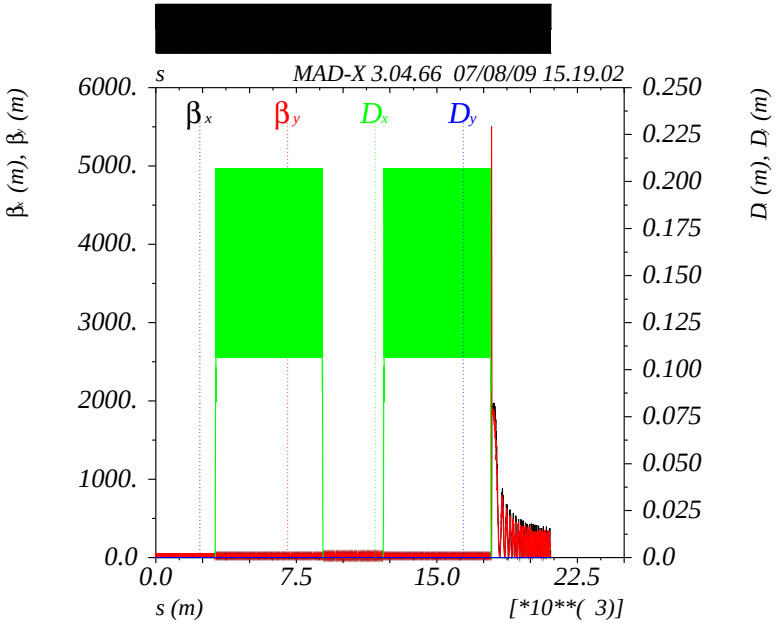


No obvious effect in MADX model (Left fig)

At Lhcinj.ti8, introduce: dy = -0.179 m (from measured BPMYB.4R8.TI8) (Right fig)

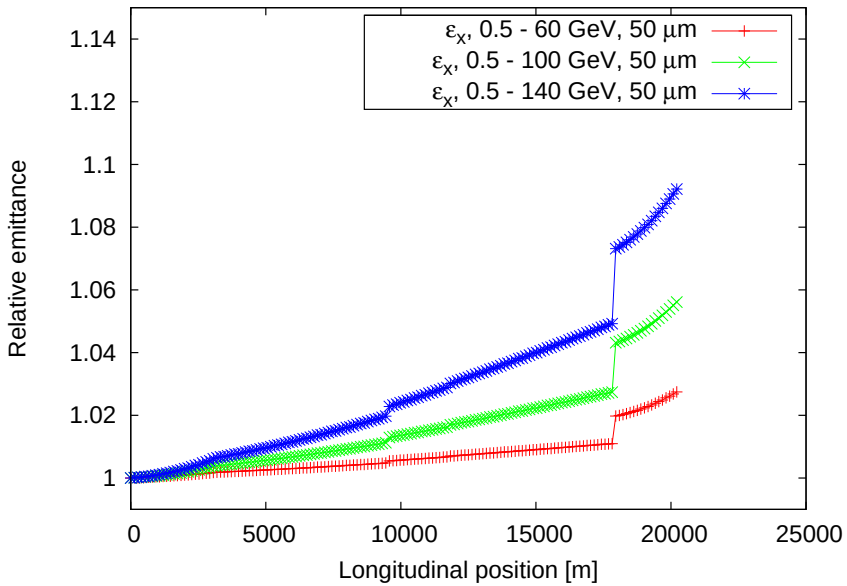
Emittance growth in the LHeC recirculating Linac (1)

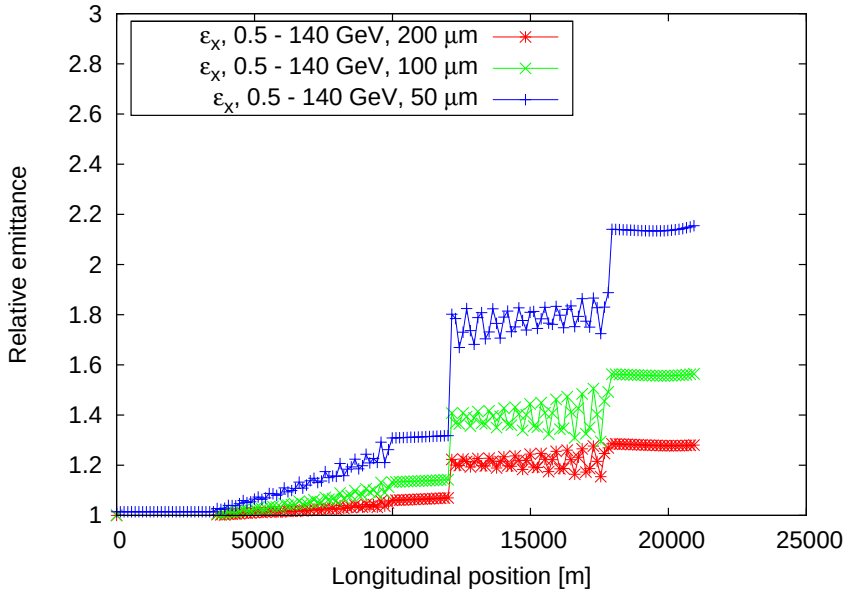




Optics designed by Anders Eide & Frank Zimmermann

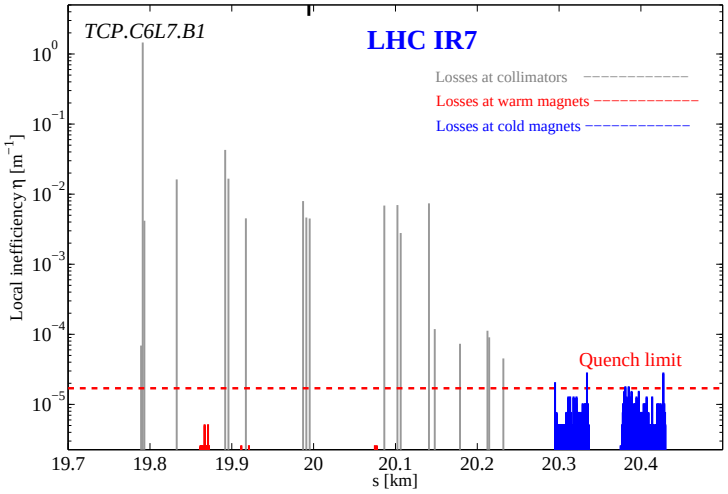
Emittance growth in the LHeC recirculating Linac (2)

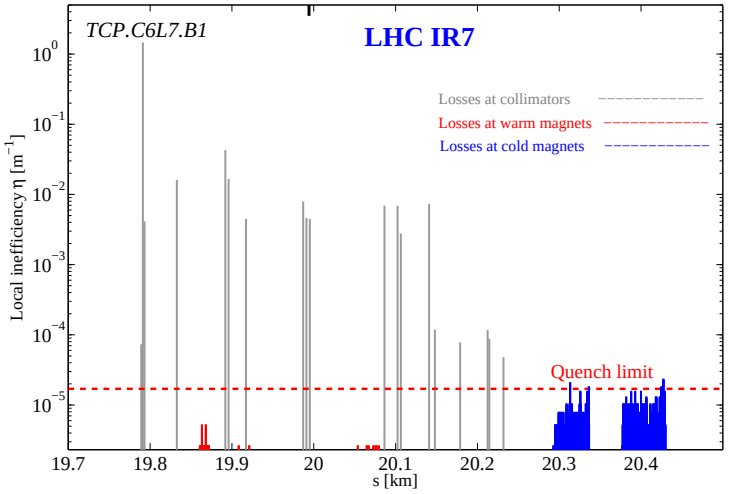




Left: Energy accelerated from 0.5 GeV to 60 (100 or 140) GeV & Energy spread and chromatic effects; Right: Synchrotron Radiation damping and quantum excitation.

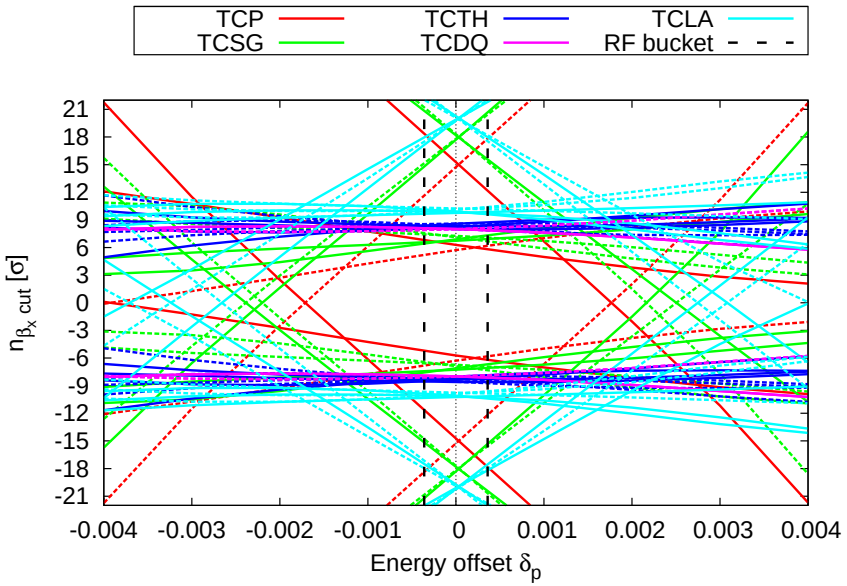
Backup: Local loss map

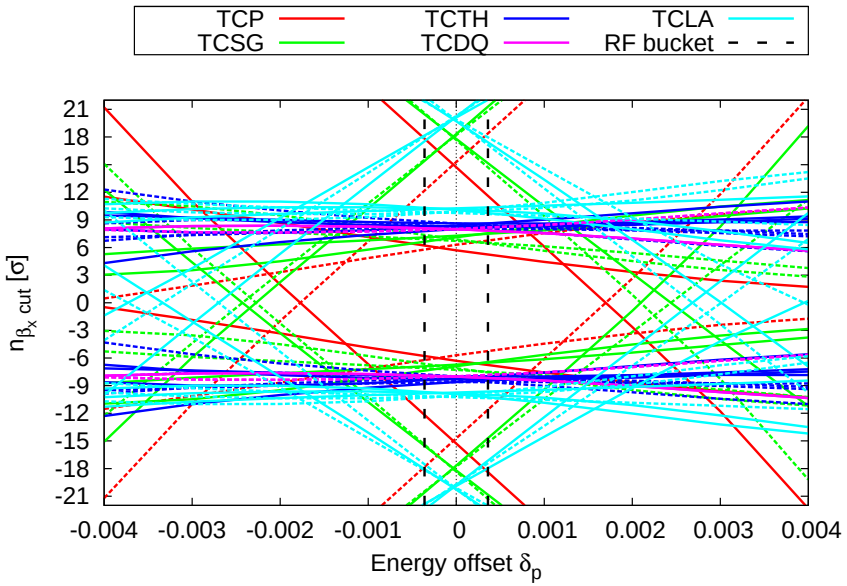




Left: with CC, **beam halo generated at** $z = 2\sigma_z$; Right: with CC, **beam halo generated at** $z = 3\sigma_z$.

Backup: collimator hierarchy





Left: with CC, **beam halo generated at $z = 2\sigma_z$**; Right: with CC, **beam halo generated at $z = 3\sigma_z$.**