Tune-scans and working point optimization for colliding beams in HL-LHC

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and
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(in conjunction with their talks at this meeting)
with the help of
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CERN-TRIUMF HL-LHC collaboration

Outline

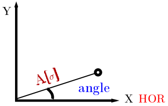
1. Tune-scan (TS) Procedure
2. Domains
3. 1D (Linear) TS
4. Resonances new: 16th order
5. 2D TS
6. New working point – a “candidate” for future studies

Tune-scan procedure: MadX+SixTrack environment

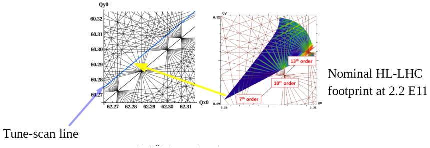
HL-HLC lattice
V1.2, V1.3
collision settings

Beam-Beam + sextupoles + <octupoles> (HL-LHC)

Initial coordinates:
amplitude $\boldsymbol{A}[\sigma]$ and
real-space angle



Note: SixTrack adjusts
tunes with beam-beam ON,
i.e. “sharp edge” $Q^{BB}_{x,y}$:
$Q^{BB}_{x,y} = Q^{0}_{x,y} - \Delta Q^{BB}_{x,y}$



Tune-scan procedure: MadX+SixTrack env.

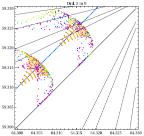
Output from Six-Track OCT. = lattice octupoles

want to place footprint on the res. mesh

NO OCT.

some SixTrack footprints:
1-12 σ; 10^4 turns; **tune=1**

(here hue prop. to slope of dist. betw twins)



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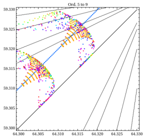
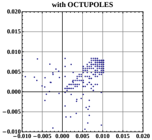


WITH OCT.

reduced size in direction $\perp$ diagonal



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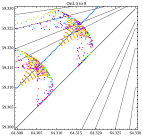
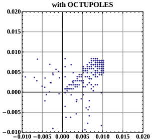
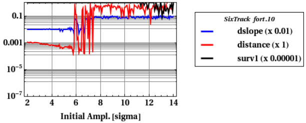


WITH OCT.

reduced size in direction $\perp$ diagonal



1) survival turns for 2 twins
2) distance between twins
3) slope of dist. etc



Tune-scan procedure: MadX+SixTrack env.

Output from Six-Track (LONG term) 10^6 turns BOINC or HTCondor

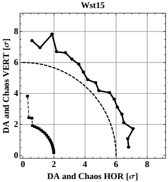
dynamic apert. (DA)
= last surv part. =
= Min[surv1,surv2]

also chaotic border,
but not reported here

Tune-scans (TS):

1D TS: DA-by-angle dep. on tune

2D TS: MIN DA over 20 angles dep. on tune



Old (<2010) studies – LHC

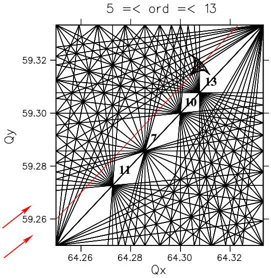
along Line || diag., +0.01, OCT=0, low chrom.=2

losses =dips mostly in HOR. plane max. res. ord. = 13

tunescan lines (step 0.001)

split 0.02

split 0.01



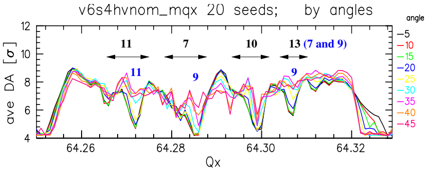
Average Dyn. Aperture (DA), 10^6 turns

20 seeds triplet errors and corr. nominal bunch hor.–vert. crossing IP1 and 5

shown angles 0 – 45 deg

split 0.01

HV Nom

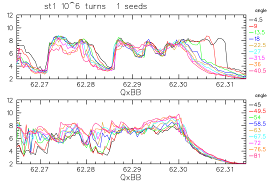


unperturbed (by bb) tune

Tune-scan procedure: HL-LHC Steps

1) Contour DA-by-angle. 2) Extend in 2D. 3) add octupoles + high. chr.

HL-LHC old-style plot: DA [sigma] by initial angle (angle=0 means part. launched in HOR plane)

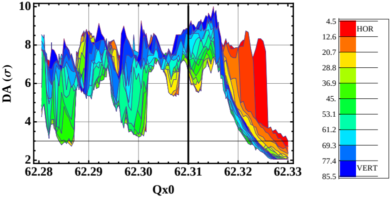


old style plot
< 2010

18 azimuthal angles

split into two plots

New-style "DA by angle" with contours



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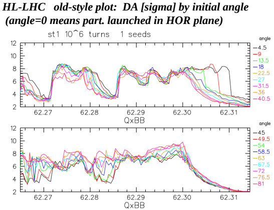

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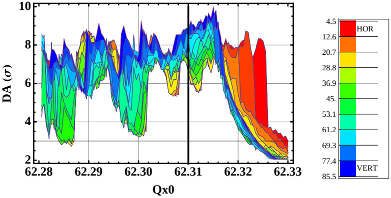
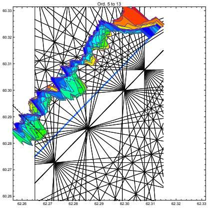


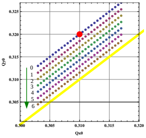
Correlate DA Maxima and Dips

with Resonances



Extend in 2D towards diag.(yellow)

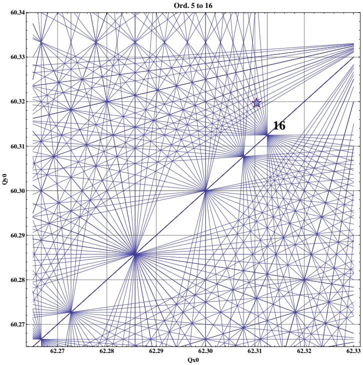
$\Delta Q^{\|\text{diag.}} \geq 5\ 10^{-4}$, $\Delta Q^{\perp\text{diag.}} \geq \sqrt{2}\ 10^{-3}$



Tune-scan procedure: Domains

resonances 5-16 ord

clusters right to left: **16**,13,10,7+14,11



Tune-scan procedure: Domains

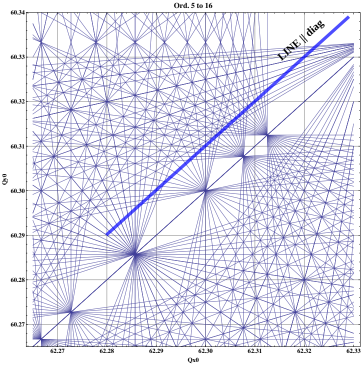
resonances 5-16 ord

clusters right to left: **16**,13,10,7+14,11

1) Linear TS (no oct)

along +0.01 line: $\Delta Q^{||} = 5\ 10^{-4}$

HL-LHC V1.2 and LHC



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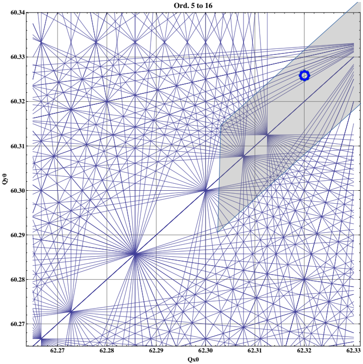
HL-LHC V1.2 and LHC

2) 2D (oct., chr=15) near 1/3

base-line WP (Yannis,Dario,Nikos)

HL-LHC V1.2 and V1.3

$\Delta Q^{\|} = 2\ 10^{-3}$, $\Delta Q^{\perp} = 2.3\ 10^{-3}$



Tune-scan procedure: Domains

resonances 5-16 ord

clusters right to left: **16**,13,10,7+14,11

1) **Linear TS (no oct)**

along +0.01 line: $\Delta Q^{\|} = 5\ 10^{-4}$

HL-LHC V1.2 and LHC

2) 2D (oct., chr=15) near 1/3

base-line WP (Yannis,Dario,Nikos)

HL-LHC V1.2 and V1.3

$\Delta Q^{\|} = 2\ 10^{-3}$, $\Delta Q^{\perp} = 2.3\ 10^{-3}$

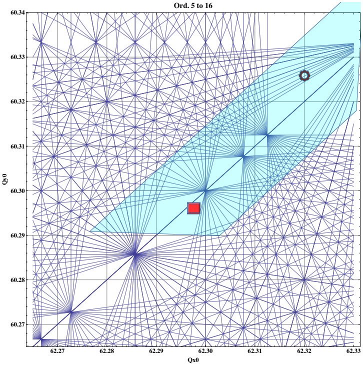
3) 2D (oct., chr=15) extended

with params at end of level.

new candidate WP **near 10th ord cl.**

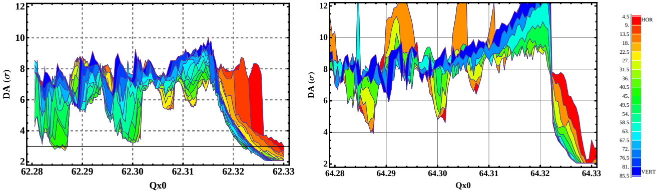
HL-LHC V1.3

$\Delta Q^{\|} = 5\ 10^{-4}$, $\Delta Q^{\perp} = 2.8\ 10^{-3}$



Linear TS (no oct) : DA by-angle “HL-LHC case 0”

HL-LHC BB + Sext $N_b = 1.1\ 10^{11}$ **LHC as-built** BB + Sext + corr. tripl. err. seed 1



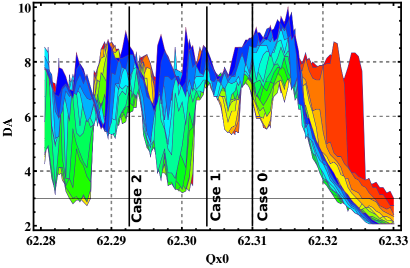
Shown contours of constant dynamic aperture with color hue proportional to the angle (angle=0 part. launched in HOR plane) every second angle plotted

HL-LHC parameters (**call this case 0**):

- HLLHCV1.2; intensity: 1.1×10^{11}; single HO replaces full crabs chr=3
- IR1,5 Xing half-ang = 295 μrad, $\beta^{\star}$= 15 cm
- IR8 $\beta^{\star} =$ 1m, Xing half-ang =-135+250=-115 μrad (LHCb spect. pol.=+1)
- IR2 $\beta^{\star} =$ 10m, hor. sep.„ Xing = 170 μrad
- emit$_n$= 2.5 μm, bunch length = 7.5 cm, $\frac{\Delta p}{p}$=2.7×10^{-4}, bunch spacing 25 ns, chrom=3

HL-LHC cases with $\Delta Q_x^{BB} \sim 0.02$ and 0.03

are predicted to be already at optimum Vert. axis is only valid for **case 0**.



case	*comment*	*tune shift*	*Qx0*
0	*as scan made* $N_b = 1.1\ 10^{11}$	*0.0155*	*62.31*
1	$N_b = 2.2\ 10^{11}$ *, no BB in IP8*	*0.022*	*62.3035*
2	$N_b = 2.2\ 10^{11}$ *, with BB in IP8*	*0.033*	*62.2925*

E.g. for Case 1: the predicted Qx0=62.31 - (0.022 - 0.0155)= 62.3035.
It is seen to be exactly at optimum loc.!

“Delta-function" head (footprint shape → symmetries)

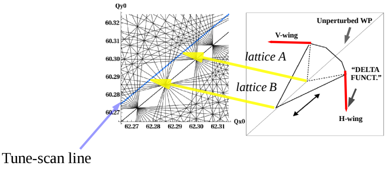
Linear TS (no oct) :
If only interested in optimum loc., then one scan is enough.
A TS made with setup A can predict optimum tunes for setup B of different ΔQ_x^{BB} since the head scans the **same resonances** at a distance = difference between the tune-shifts of B and A.

1) losses occur mostly near the high-σ head

2) head’s projection on the hor. axis is very close to unperturbed tune point

naive table: octupoles OFF ($H \leftrightarrow V$)

DA-loss in setup A	Active point on	escape dir	TS transl. symmetry
H plane	H wing	V	H



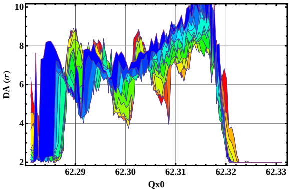
Linear TS (no oct) – HOR plane dominates –
H-wing scans resonances as “δ – function”
1D model is enough to predict dips

Check the prediction

Perform TS with true setups of cases 1 and 2.

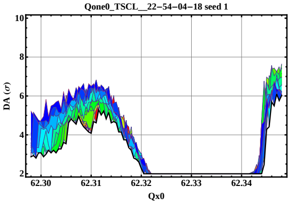
Min DA contours near 62.31 should (locally) look the same as on slide 10, and they do

case 1 $N_b = 2.2\ 10^{11}$ BB in IR2,8 ON, CC ON (full), $\beta^\star_{\rm IP8} = 3$m with neg. polarity, Hirata ON.



CHECK: .31 falls at optimum

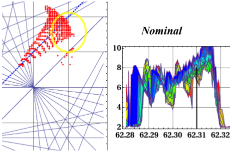
case 2 $N_b = 2.2\ 10^{11}$ (ΔQ_x^{BB} =0.033).



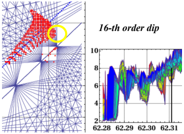
CHECK: .31 falls near optimum (+ 0.002)

Linear TS (no oct) – HL-LHC Footprint Slider

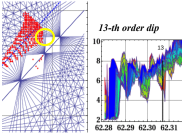
Near nominal WP one sees 16th ord (neglected before). Valid for LHC too, only DA scaled.



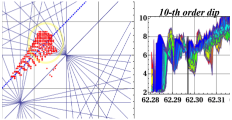
(a) HOR, 16th order



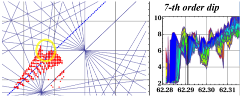
(b) HOR, 16th order



(c) HOR, 13th order



(d) HOR+VERT, 10th ord



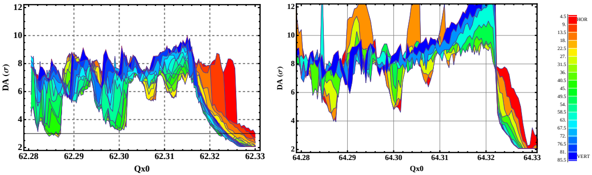
(e) VERT, 7(14) ord

For plots on the right, vert. black line shows Q_x^0.

Animations: t1 t2, t3 local: t1 t2 t3

Linear TS (no oct) Resonance dips via distorted ellipse

3 or 2-IP HO Lie (CS) invariant in H plane agrees (wherever HOR plane dominates) Left: HL-LHC, 1.1×10^{11}; Right: LHC as-built:



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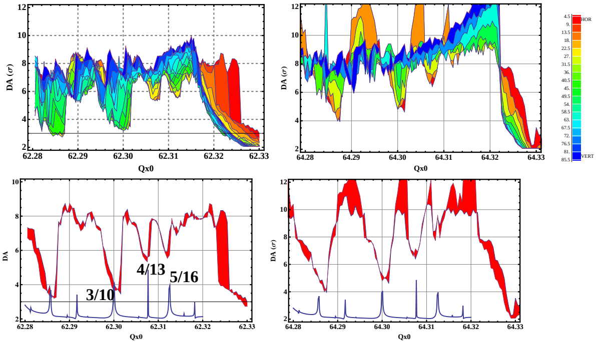
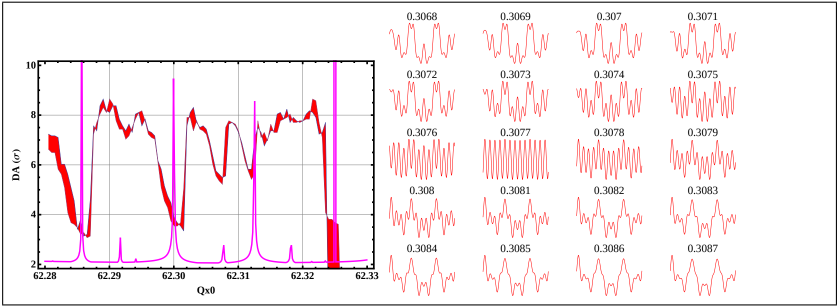


Bottom two: Red curve – only near HOR plane.

Blue peaks: high-order-harmonic amplitude of the **1D** Lie-inv.

The 4/13 peak depends on $\Delta\nu_{\mathrm{IP5-IP1}}$ (=0 for $0.25\times$ integer).

Two Head-On IPs Lie (Courant-Sn.) invariant continued



- Magenta (left) = $\mathrm{Max}_{n=1}^{n=40}$, red curves (right) = $\sum_{n=1}^{n=40}$ of:

$$\frac{2\ n\ c_n(A)}{\sin(n\ \mu_x/2)} \cos\left[n(\phi+\mu_x/2+\Delta\mu_{51}/2)\right] \cos\left(n\ \Delta\mu_{51}/2\right)$$

$c_n(A)$ = res coef (dr. terms), A=10 σ_x, $\mu_x \equiv 2\pi\ \mathrm{Qx0}$, $\Delta\mu_{51} \equiv 2\pi\Delta\nu_{\mathrm{IP5-IP1}}$,

$\phi = 0.1(\textbf{arb}.)$, $\Delta\nu_{\mathrm{IP5-IP1}}$=31.2104

- Same finding: of 2 peaks near nominal 62.31, the 4/13 depends on $\Delta\nu_{\mathrm{IP5-IP1}}$, the one above nom. does not.

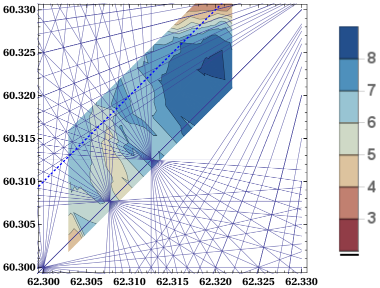
Summary of Linear TS (no oct) along line || diag

- **HL-LHC lattices w/o octupoles are already at optimum tunes for (these three) more-important scenarios (and for LHC)**
- **The role of 16-th ord resonances in HOR plane near nom WP (no octupoles, chr $\sim$ 3)**
- **Need of 2D Tune-scans (HL-LHC, with octupoles, chr = 15)**

2D TS (Min DA of 20 ang); near 1/3

still Q'= 3, I_{MO}=0, $\beta^\star$=15 cm stays constant (NOT a leveling scenario)

1) $N_b = 1.1 \times 10^{11}$



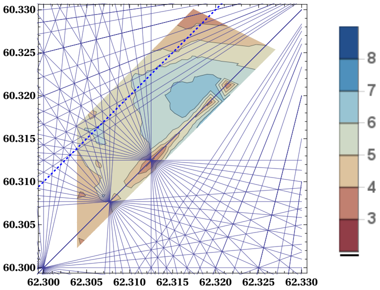
- HL-LHC V1.2
- fraction_crab=1
- IR1,5 Xing half-ang = 295 μrad

2D TS (Min DA of 20 ang); near 1/3

still $Q' = 3$, $I_{MO}=0$, $\beta^{\star}=15$ cm stays constant (NOT a leveling scenario)

1) $N_b = 1.1 \times 10^{11}$

2) $N_b = 2.2 \times 10^{11}$
shift of opt WP = VERT
no oct.
DA $\sim$ 6 σ

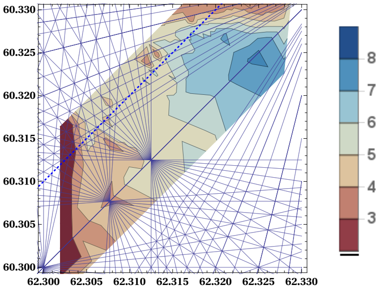


- HL-LHC V1.2
- fraction_crab=1
- IR1,5 Xing half-ang = 295 μrad

2D TS (Min DA of 20 ang); near 1/3

now with Q' = 15, I_{MO}=-570, $\beta^{\star}$=20 cm stays constant (NOT a leveling scenario)

1) $N_b = 1.1 \times 10^{11}$

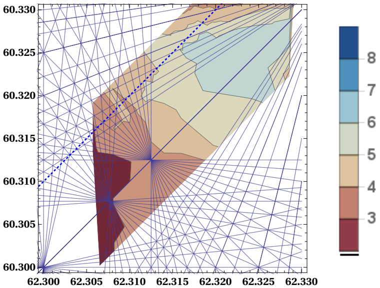


- HL-LHC V1.2
- fraction_crab=.75
- IR1,5 Xing half-ang = 295 μrad

2D TS (Min DA of 20 ang); near 1/3

now with $Q' = 15$, I_{MO}=-570, $\beta^{\star}$=20 cm stays constant (NOT a leveling scenario)

1) $N_b = 1.1 \times 10^{11}$
2) $N_b = 2.2 \times 10^{11}$
shift of opt WP = $||$ diag
(octupoles)

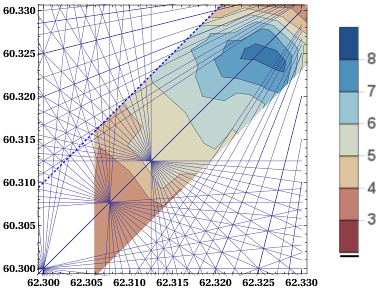


- HL-LHC V1.2
- fraction_crab=.75
- IR1,5 Xing half-ang = 295 μrad

2D TS (Min DA of 20 ang); near 1/3

Q'= 15, I_{MO}=-570 Beg. and End of leveling

Beg: $\beta^{\star}$=46cm, $N_b = 2.2\ 10^{11}$



- HL-LHC V1.3 fraction_crab=0.75 (190)
- IR1,5 Xing half-ang = 250 μrad
- IR8 $\beta^{\star} = 3$m, Xing half-ang =-135+250=-115 μrad
- IR2 $\beta^{\star} = 10$m, hor. sep., Xing = 240 μrad

2D TS (Min DA of 20 ang); near 1/3

$Q' = 15$, I_{MO}=-570 Beg. and End of leveling

Beg: $\beta^\star$=46cm, $N_b = 2.2\ 10^{11}$

End: $\beta^\star$=15cm, $N_b = 1.2\ 10^{11}$

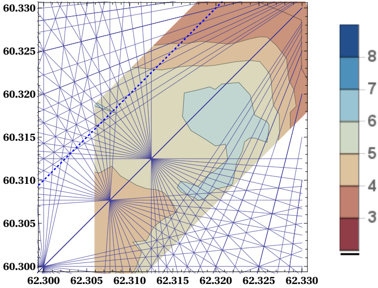
shift || diag.

agrees with N. Karastathis:

Beg: (62.32,60.325)

End: (62.315, 60.32)

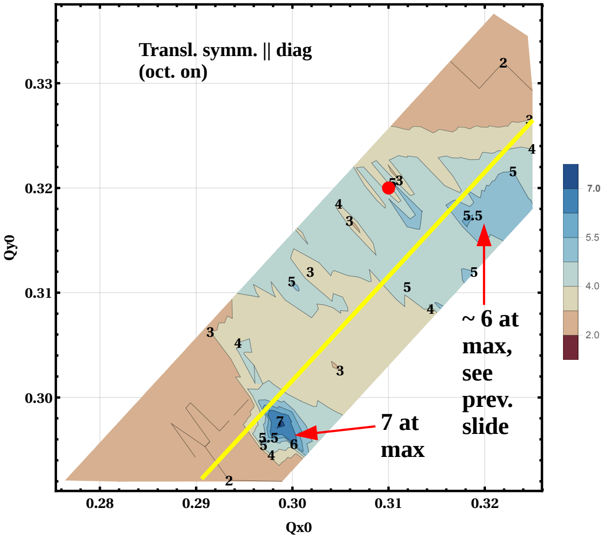
(for I_{MO}=**-300**)



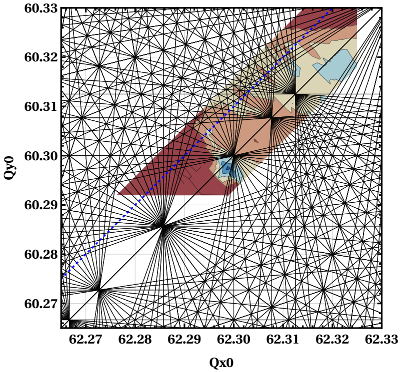
- HL-LHC V1.3 fraction_crab=0.75 (190)
- IR1,5 Xing half-ang = 250 μrad
- IR8 $\beta^\star = 3$m, Xing half-ang =-135+250=-115 μrad
- IR2 $\beta^\star = 10$m, hor. sep., Xing = 240 μrad

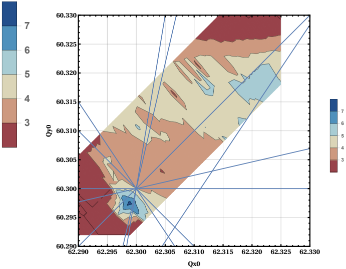
2D TS, End Fill, Min DA 20 ang   new WP candidate

Near 10th order res. cluster;   Higher maximum by 1 – 1.5 σ,   but good region smaller



2D TS (Min DA, 20 ang) – a new WP candidate





Left: Resonances of orders from 5 to 16 and the new possibly interesting region near the 10th-order res. cluster. **Right:** some resonance lines nearby:

$$Qx - Qy = 2$$
$$13Qx - 3Qy = 629$$
$$12Qx - 2Qy = 627$$
$$2Qx - 12Qy = 627$$
$$3Qx - 13Qy = -597$$

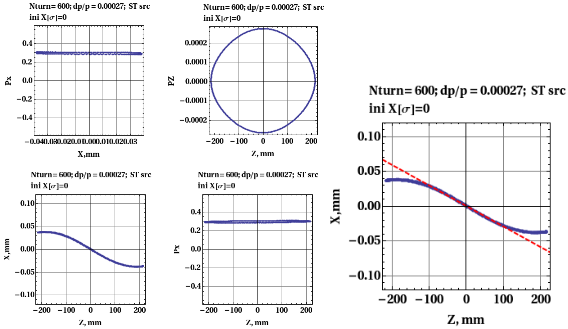
$$9Qx - 6Qy = 199$$
$$10Qy = 603$$
$$6Qx + 4Qy = 615$$
$$5Qx + 5Qy = 613$$

Thank You

spare slides

SixTrack test: Crab Cav. in IP5 and IR1

want to see rotated bunch



ST tracking for about one synchr. oscillation: phase spaces at IP5 of HL-LHC for Xing ang=295, CC=ON, BB=ON with CO added. Plots remain the same if IP5 → IP1, changing also the axes X → Y, PX → PY. Red dashed line on the right plot shows the action of an ideal CC kick; Xini = 0, Yini=0.

SixTrack Test: Hirata kicks

for BB ON in IR1,5 and 8 (look as expected)

Top: X and Y (m) after each of the 5 slices in IP5, 8 and 1, at the first turn of a particle starting at zero betatron amplitude. It has momentum offset 0.00027.

Bottom: accumulated PX and PY (rad) after each slice.