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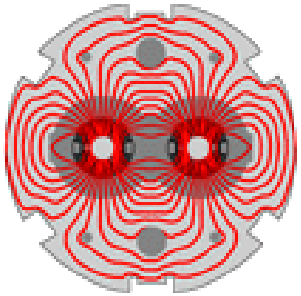

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Beam-beam Studies for HL-LHC

A.Valishev (Fermilab/US LARP) for WP2 Task 2.5

ICFA Mini-Workshop on Beam-Beam in Hadron Colliders
CERN, March 18-22, 2013

The Task: D.Banfi, A.Burov, S.Fartoukh, B.Muratori, K.Ohmi, S.Paret, T.Pieloni, J.Qiang, D.Shatilov, S.White, F.Zimmermann

The HiLumi LHC Design Study (a sub-system of HL-LHC) is co-funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404. Fermi Research Alliance, LLC operates Fermilab under Contract DE-AC02-07CH11359 with the US Department of Energy. This work was partially supported by the US LHC Accelerator Research Program (LARP).

HL-LHC Beam-Beam Study

Evaluate beam-beam for HL-LHC scenarios, identify minimum requirements – β^*, crossing scheme

- Evaluate limitations
- Luminosity leveling techniques - talk by T.Pieloni/B.Muratori
- Develop self-consistent simulations of beam-beam with other dynamical effects
  - Interplay with machine impedance - talk by S.White
  - Crab cavity, noise, offset, etc. – talks by K.Ohmi, S.Paret
- Support new ideas – talk by A.Burov

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Methods

- Analytical calculations, where possible
- Weak-strong
  - Tune footprint (very fast)
  - Dynamic Aperture (fast)
  - Full-scale multi-particle simulation of intensity and emittance life time (slow)
- Strong-strong
  - Self-consistent multi-effect simulation (short reach as far as the number of turns, slowest)

Simulation Tools

- Weak-strong
  - SixTrack. Well-tested code, the backbone of tracking studies for LHC design.
  - Lifetrac. Many years of use for electron machines and Tevatron. Well-tested 6D beam-beam with crossing angle and crab cavity.
- Strong-Strong
  - BeamBeam3D. Many users – LBNL, FNAL, BNL
  - COMBI. Good for multi-bunch simulations

Study Topics

- Evaluate the options for HL-LHC
  - Choice of basic options – β^*, crossing scheme
  - Luminosity leveling techniques
  - Imperfections, mitigation of beam-beam
- Develop self-consistent simulations of the beam-beam phenomena with other dynamical effects
  - Interplay with machine impedance
  - Crab cavity, noise, offset, etc.
- Support new ideas

HL-LHC Performance Estimates

'Stretched' Baseline Parameters following 2nd HL-LHC-LIU:

Parameter	nominal	25ns	50ns
N	1.15E+11	**2.2E+11**	**3.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	**1.12**	**0.89**
x-ing angle [μrad]	300	590	590
beam separation [σ]	9.9	12.5	11.4
β^* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	**18.5**	**17.2**
IBS longitudinal [h]	61 -> 60	**20.4**	**16.1**
Piwinski parameter	0.68	**3.12**	**2.85**
geom. reduction	0.83	**0.305**	**0.331**
beam-beam / IP	3.10E-03	**3.3E-03**	**4.7E-03**
Peak Luminosity	1 10^{34}	**7.4 10^{34}**	**8.5 10^{34}**
Virtual Luminosity	1.2 10^{34}	**24 10^{34}**	**26 10^{34}**
Events / crossing (peak & leveled L)	19 -> 28	**207**	**476** **140** **140**

6.2 10^{14} and 4.9 10^{14} p/beam

➔ sufficient room for leveling (with Crab Cavities)

Virtual luminosity (25ns) of
$L = 7.4 / 0.305\ 10^{34}\ cm^{-2}\ s^{-1}$
$= 24\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 5)

Virtual luminosity (50ns) of
$L = 8.5 / 0.331\ 10^{34}\ cm^{-2}\ s^{-1}$
$= 26\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 10)

(Leveled to 5 $10^{34}\ cm^{-2}\ s^{-1}$ and 2.5 $10^{34}\ cm^{-2}\ s^{-1}$)

HL-LHC Base Beam-Beam Parameters

- N_p=2.2x10^{11}, ε=2.5 μm
- θ=590 μrad = const
- β^*=15cm = const

- ξ = 0.01 (3 IPs)
- A/σ = 12.5
- Level with crab only

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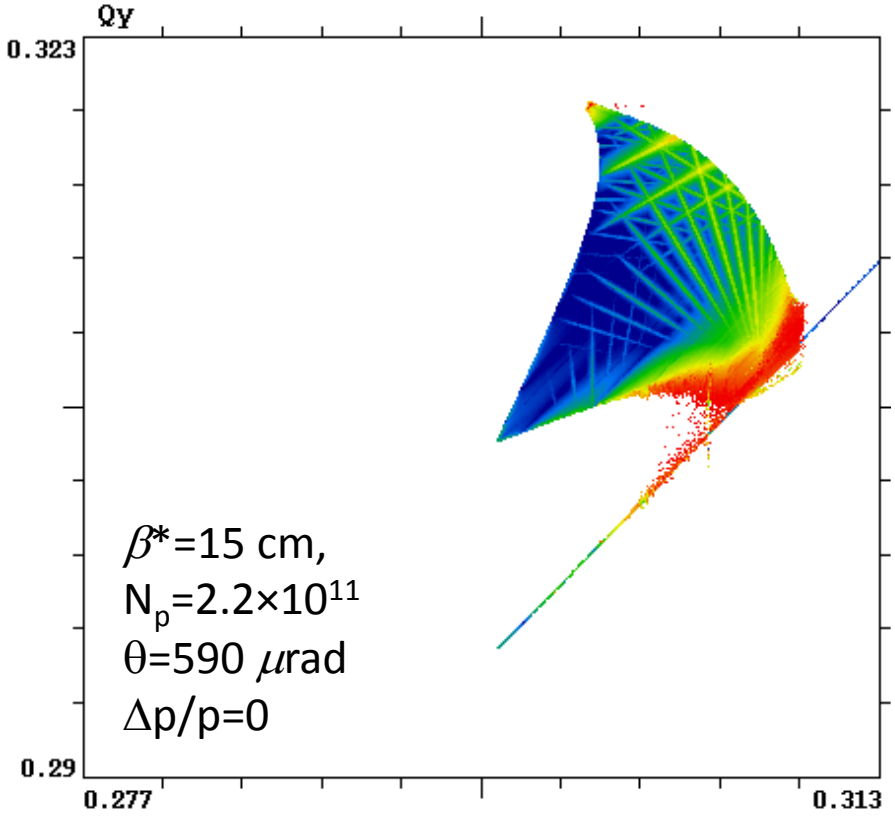
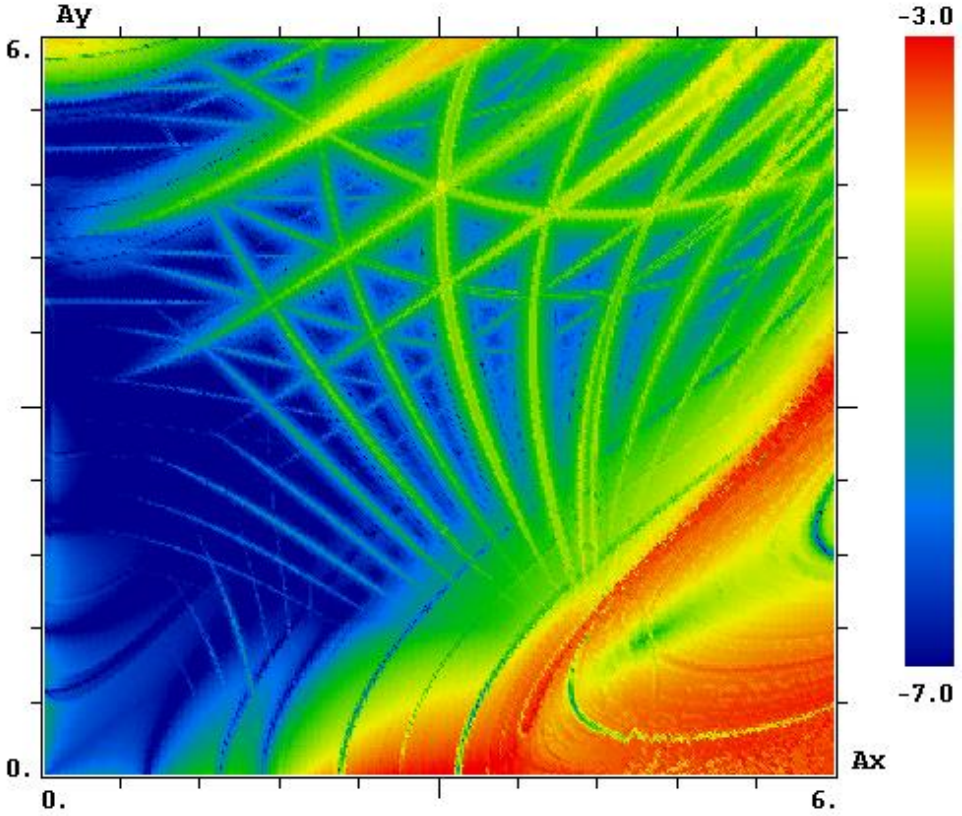
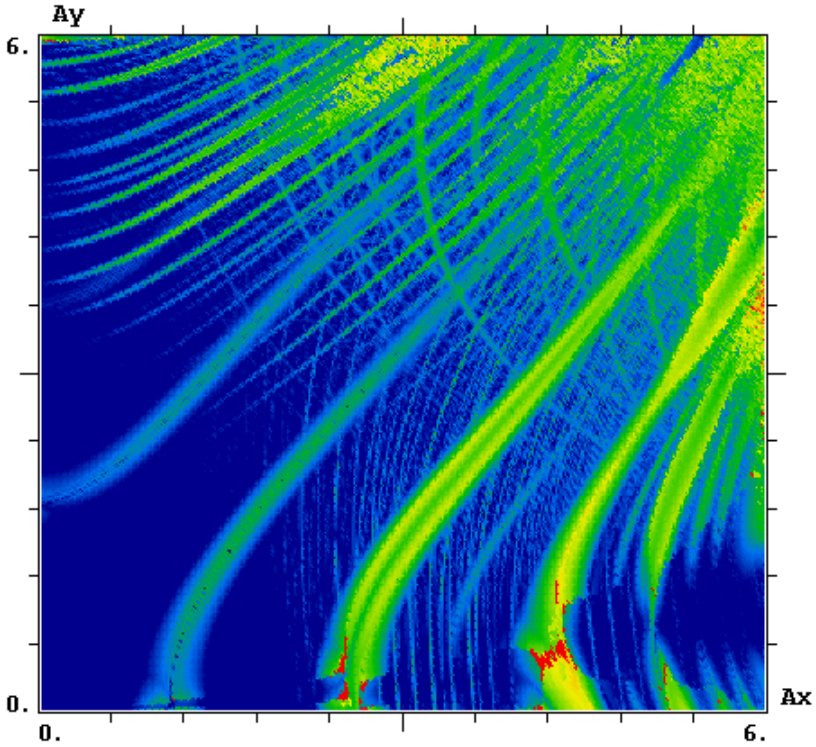
Frequency Map Analysis



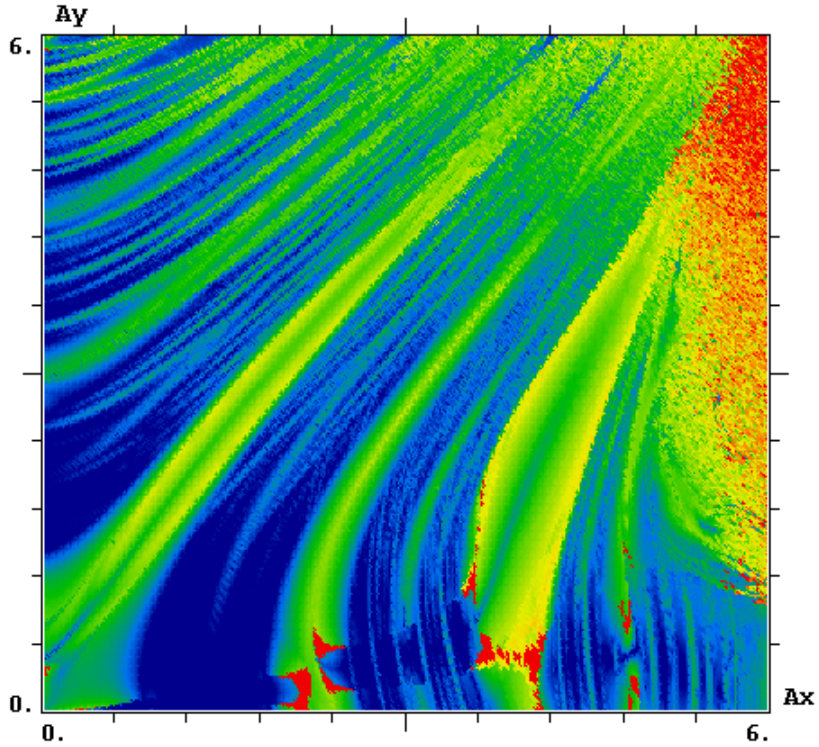


Lifetrac: full HL-LHC lattice (element-by-element, sextupoles) + beam-beam (head-on & long-range), 2^{11} turns

Frequency Map Analysis of HL-LHC options



β^*=15cm θ=590μrad Δp/p=1.1e-4



β^*=15cm θ=590μrad Δp/p=2.2e-4

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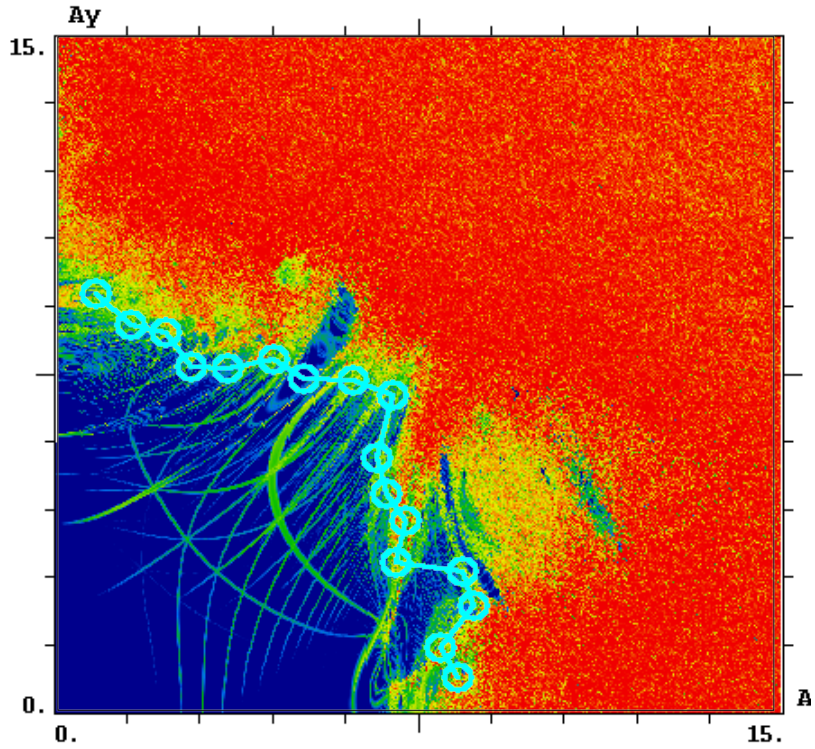
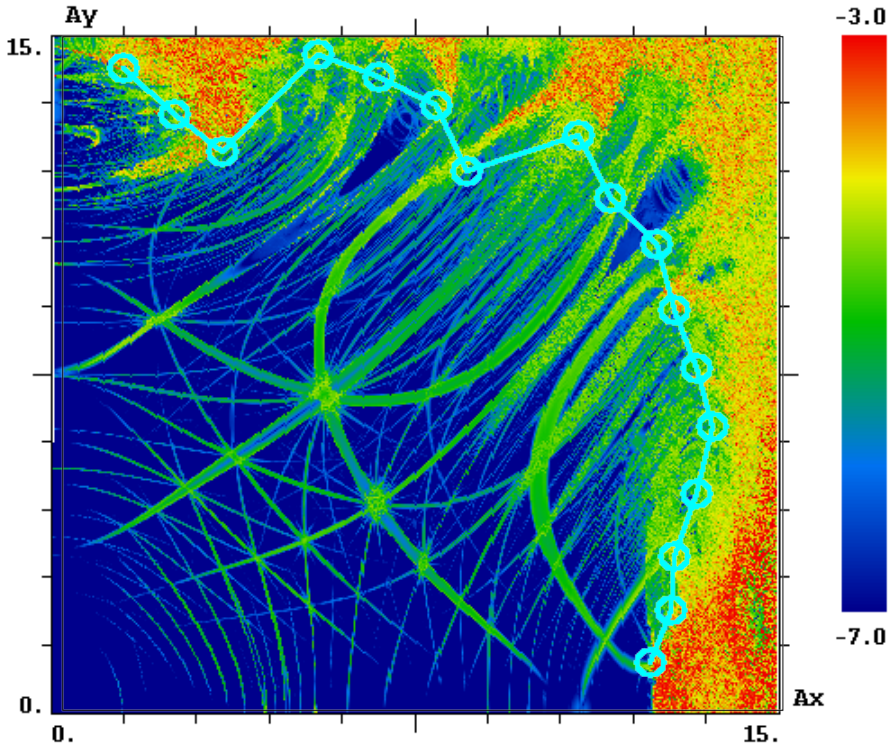
From FMA to Dynamical Aperture





β^*=15cm θ=590μrad Δp/p=0
σ_z=7.5cm

β^*=33cm θ=590μrad Δp/p=0
σ_z=4cm

Linear HL-LHC lattice (no sextupoles) + beam-beam (head-on & long-range)
DA based on 10^6 tracking turns, FMA – 2^{13} turns

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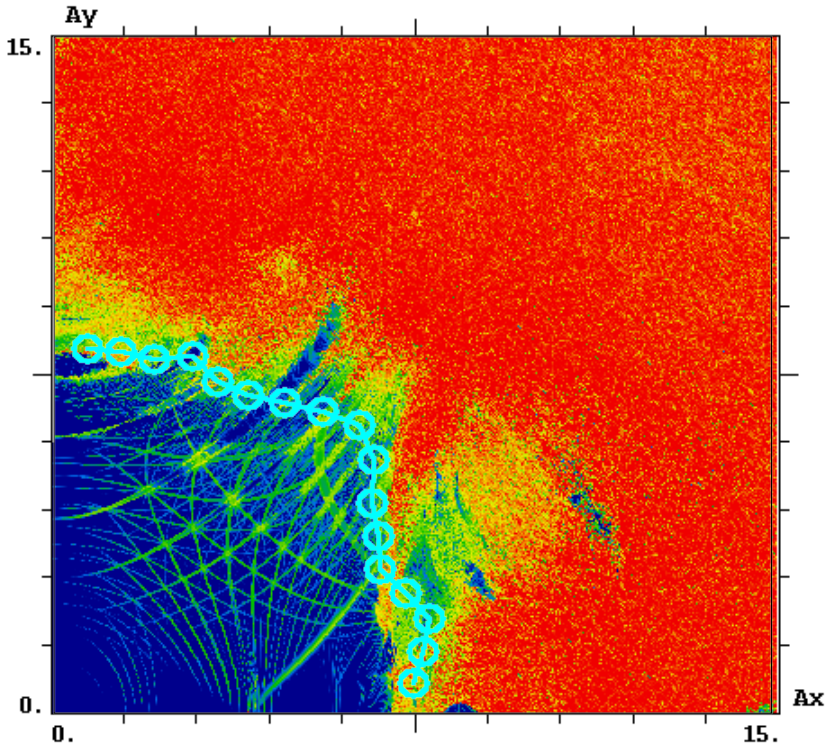
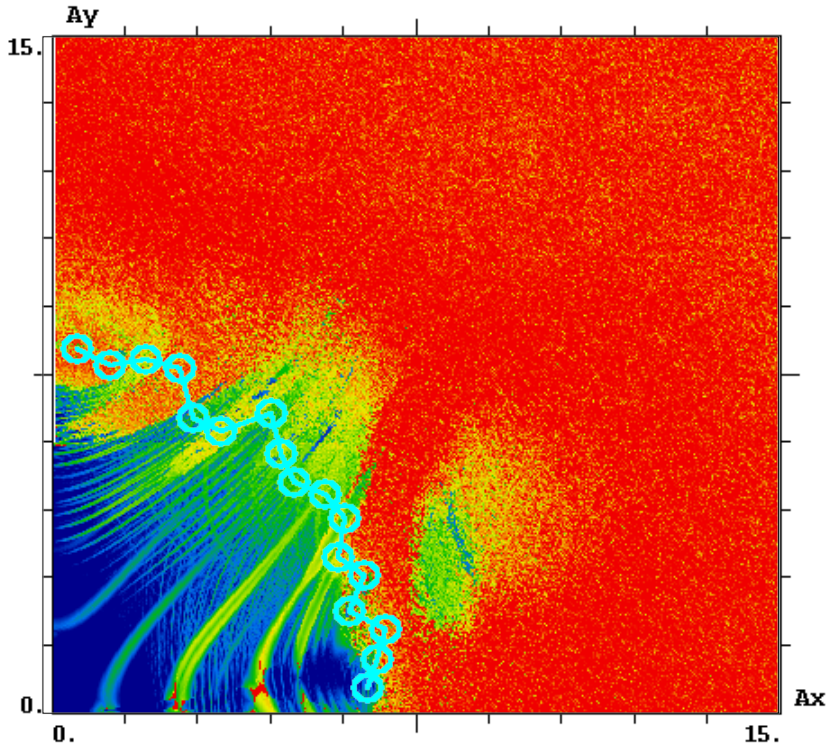
From FMA to Dynamical Aperture





β^*=40cm θ=360μrad Δp/p=0
σ_z=4cm

β^*=15cm θ=590μrad Δp/p=1.1e-4
σ_z=7.5cm

Linear HL-LHC lattice (no sextupoles) + beam-beam (head-on & long-range)
DA based on 10^6 tracking turns, FMA – 2^{13} turns

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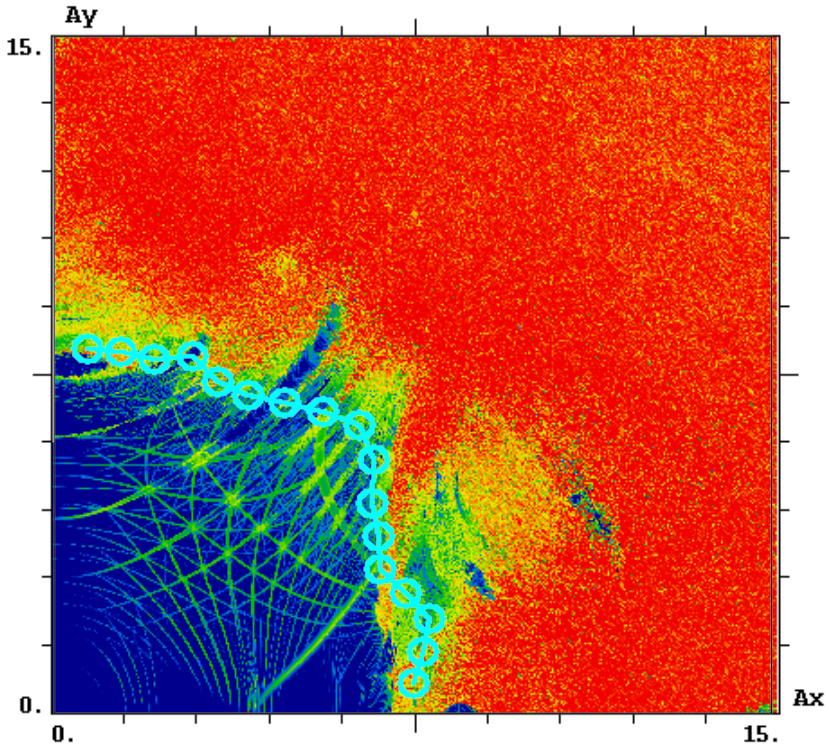
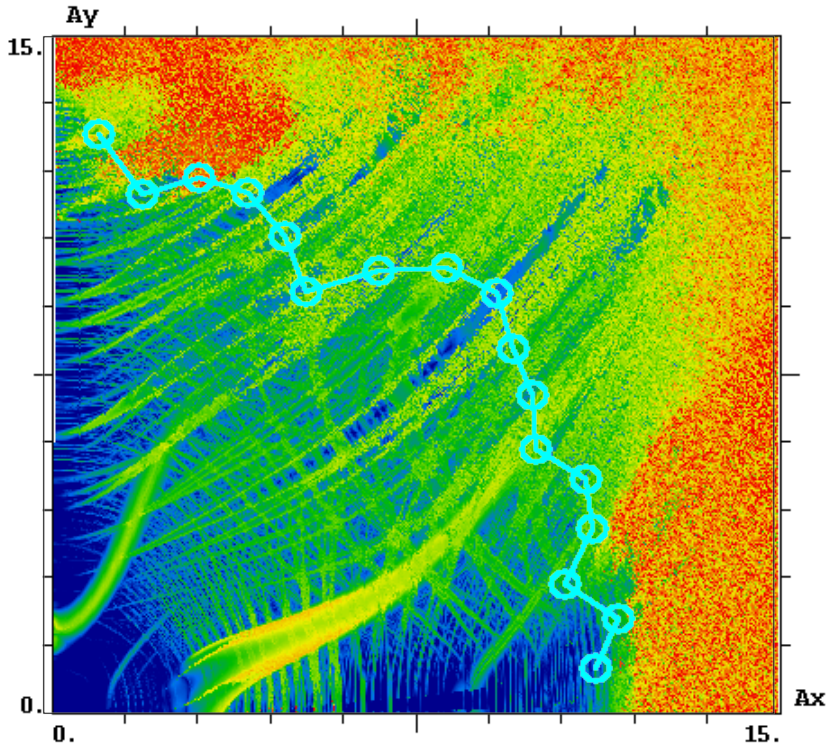
From FMA to Dynamical Aperture



β^*=40cm θ=360μrad Δp/p=0
σ_z=4cm



β^*=33cm θ=590μrad Δp/p=1.1e-4
σ_z=4cm

Linear HL-LHC lattice (no sextupoles) + beam-beam (head-on & long-range)
DA based on 10^6 tracking turns, FMA – 2^{13} turns

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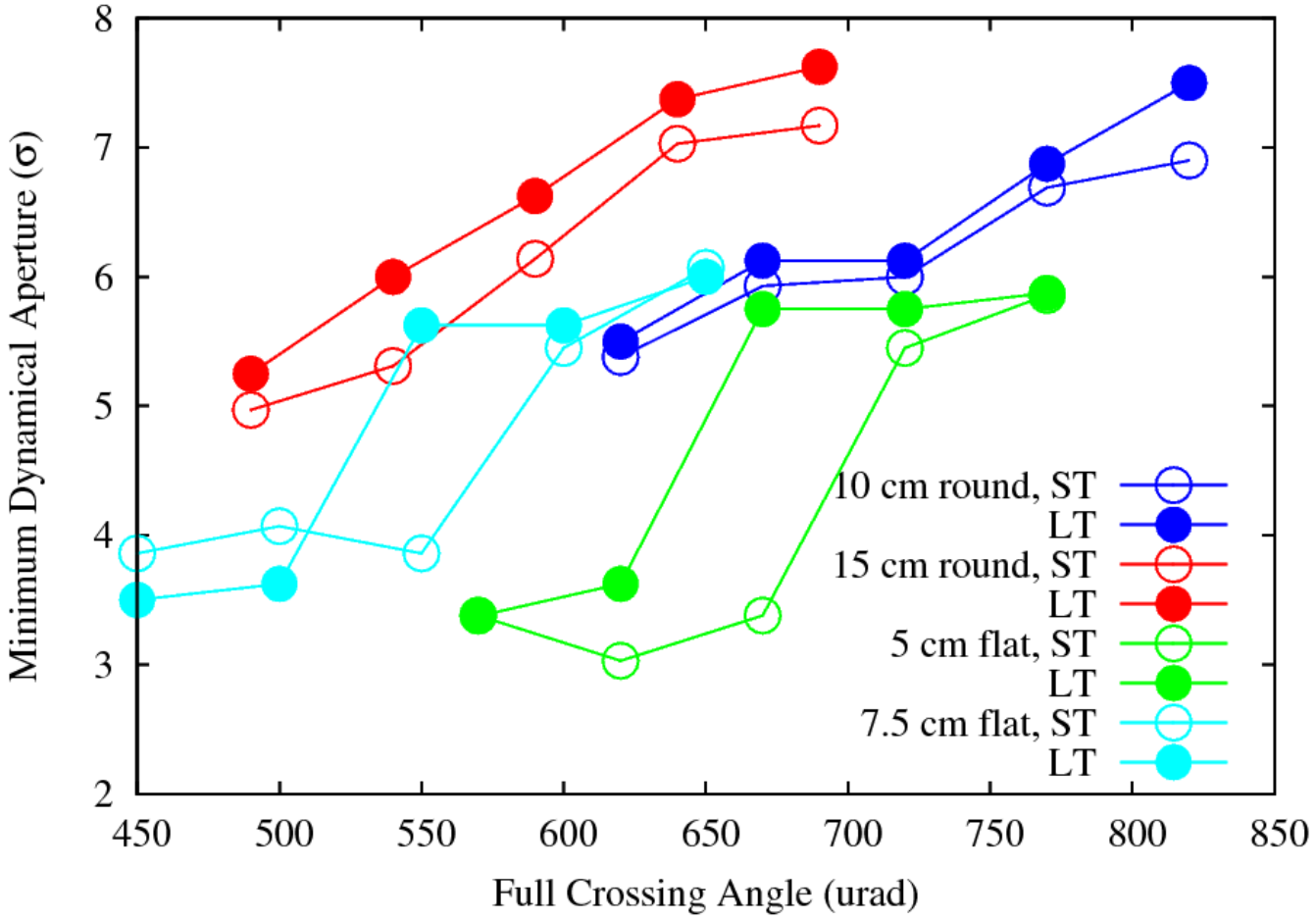
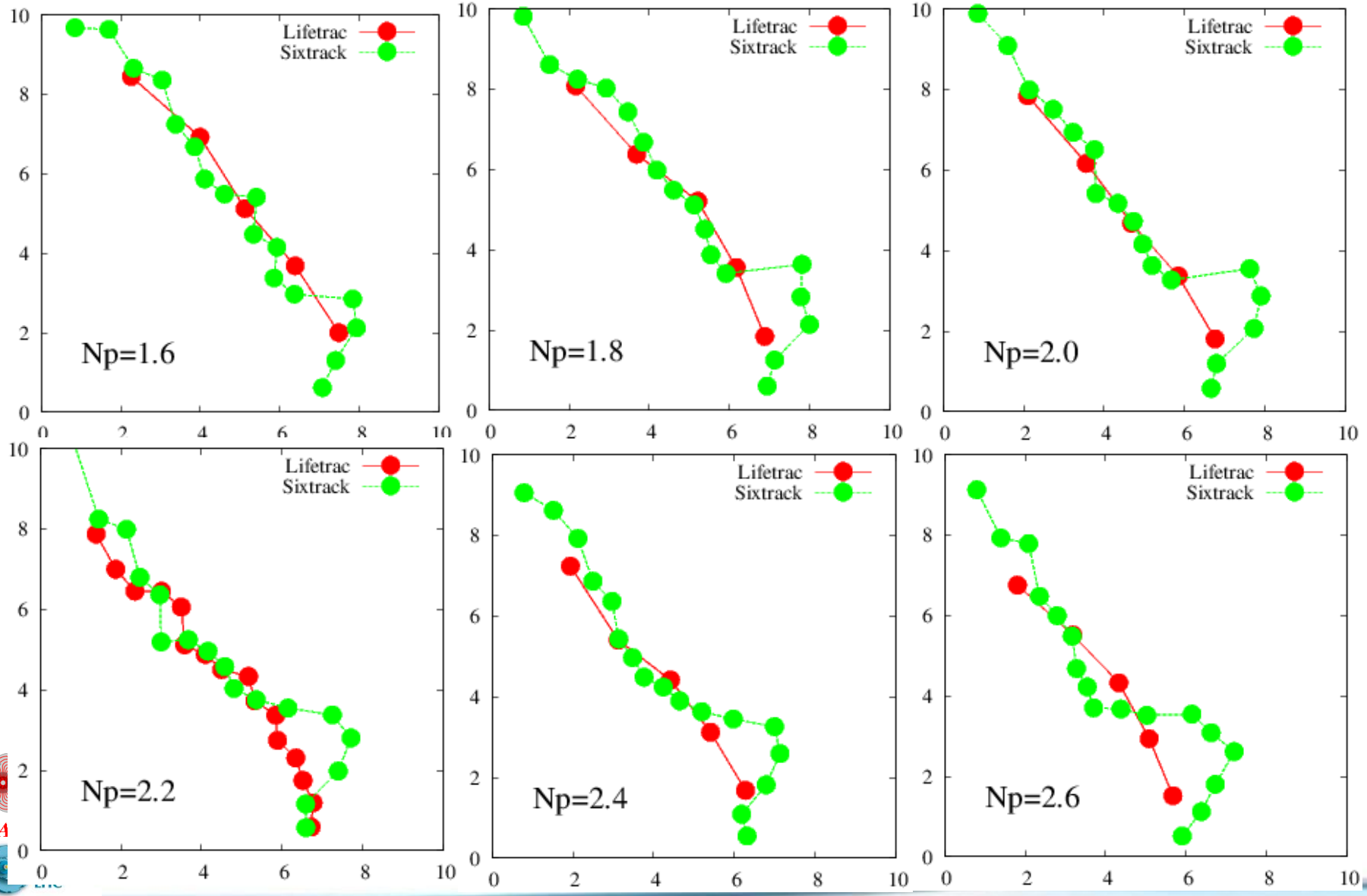
DA Studies Sixtrack vs. Lifetrac



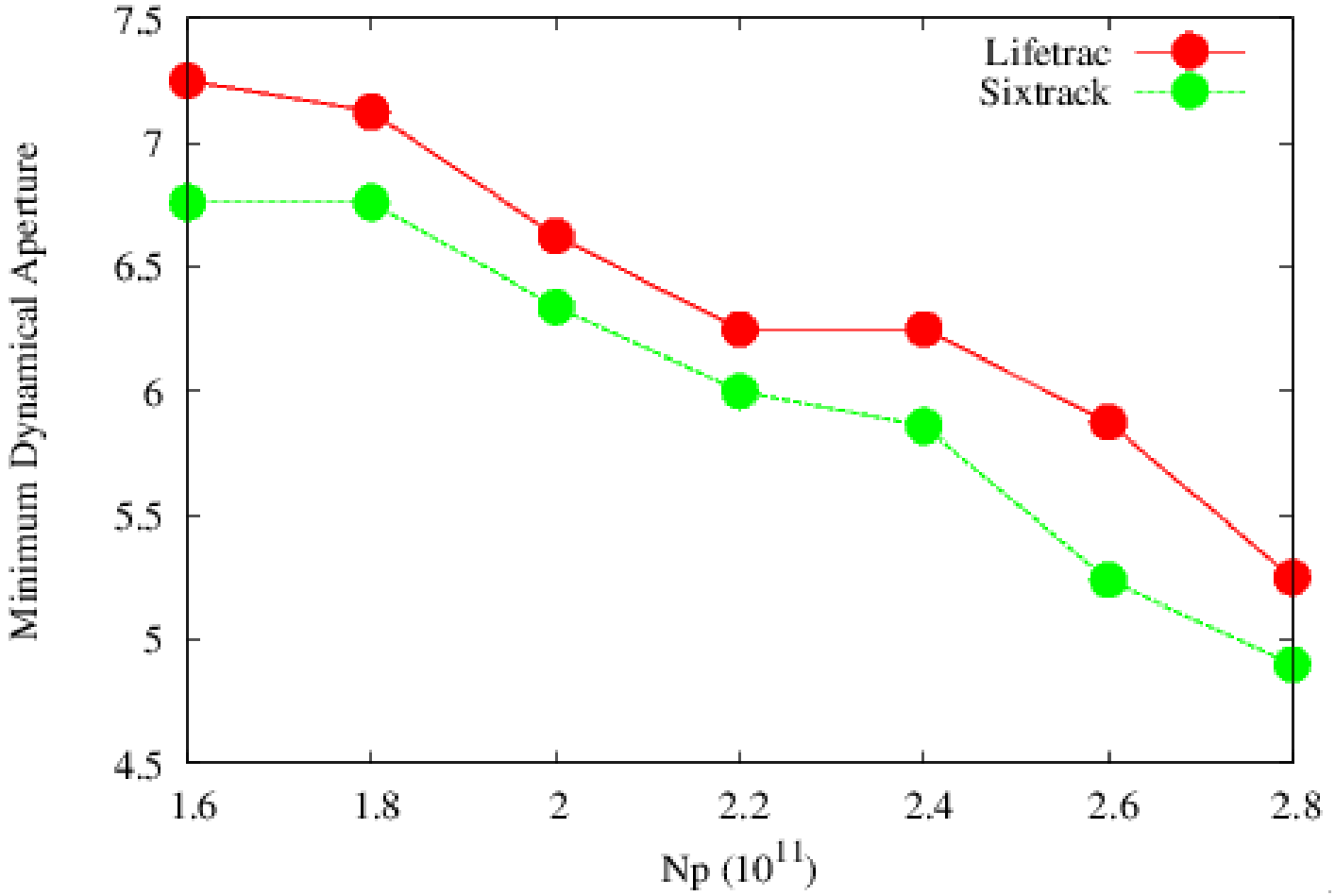
HL-LHC lattice without magnetic errors (only chroma sextupoles)
DA based on 10^6 tracking turns. $N_p=2\times10^{11}$, $\varepsilon=2.5\mu$m

S.White, A.Valishev

DA Studies Sixtrack vs. Lifetrac



DA Studies – Intensity Scan



HL-LHC lattice without magnetic errors (only chroma sextupoles)
DA based on 10^6 tracking turns. β^*=0.15m, θ=590 μrad, ε=2.5μm

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Conclusion for Baseline

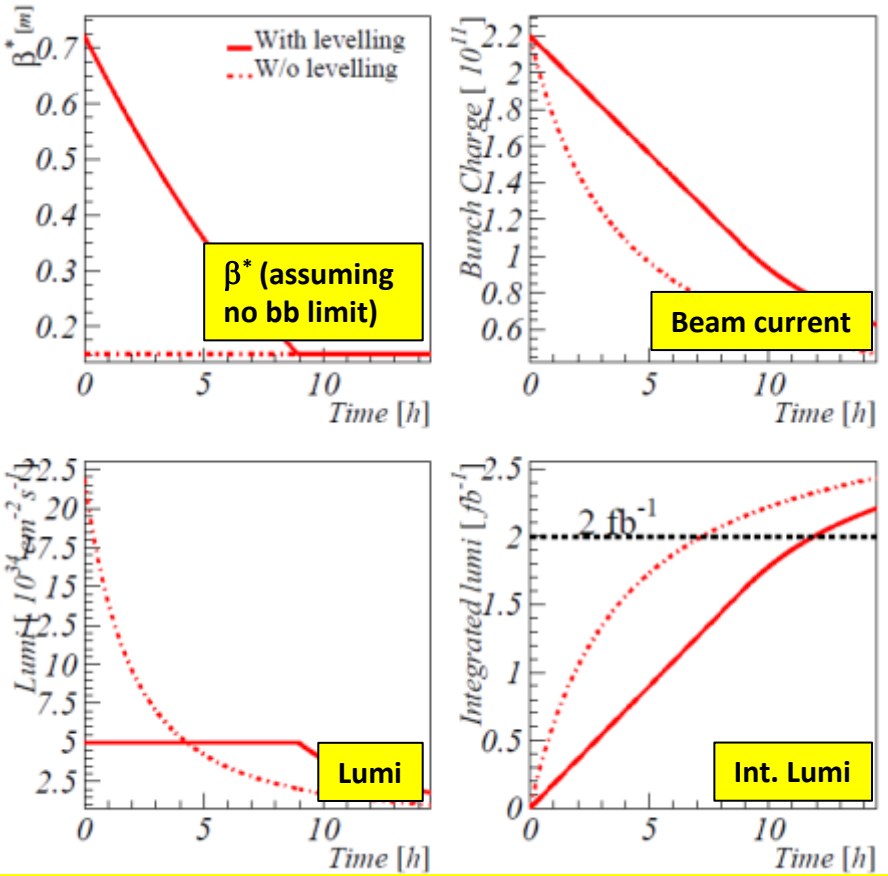
- Weak-strong studies predict the scenario OK
- Work in progress:
  - Effect of multipole errors
  - Multiparticle tracking

Evolving HL-LHC Baseline

DRAFT by S.Fartoukh for CM20

	LHC nominal	HL-LHC 25 ns
# Bunches	2808	2808
p/bunch [10^{11}]	1.15 (0.58A)	**2.2 (1.11 A)**
$\gamma\varepsilon_{x,y}$ [μm]	3.75	**2.5**
ε_L [eV.s]	2.5	2.5
σ_z [cm]	7.5	7.5
$\sigma_{\delta p/p}$ [10^{-3}]	0.1	0.1
β* [cm]	55	**15 (→ 10)**
X-angle [μrad]	300 (10.0 σ)	**590 (→ 720)** (12.5 σ)
Lumi loss factor	0.83	0.31
Peak lumi [10^{34}] (with full Piwinsky angle)	1.0	7.4
Virtual lumi [10^{34}] (w/o Piwinsky angle)	1.2	21.9
$T_{leveling}$ [h] @ 5E34	n/a	**9.0**
#Pile up @5E34	25	**140**

Main HL-LHC beam & optics parameters



Time evolution of main parameters

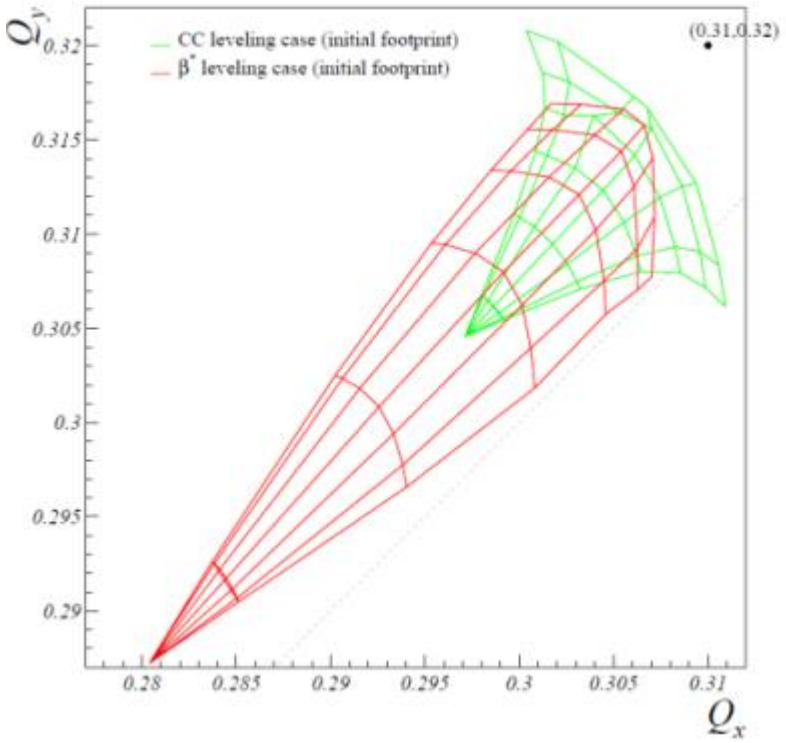
(assuming no emittance growth)

→ Only the β* profile will actually depend on the details of the leveling technique (bb limit, if any?)

Evolving HL-LHC Baseline

DRAFT by S.Fartoukh for CM20

→ β^* leveling seems to be the main option but leading a **b-b tune shift of up to ΔQ_{bb}=0.033 for 3 experiments (IR1, IR5 & IR8)**



Parameters	Leveling with c.-c.	Leveling with β^*
# bunches	2808	
bunch charge [10^{11}]	2.2	
emittance [μm]	2.5	
r.m.s. bunch length [cm]	7.5	
full X-angle [μrad]	590	
initial β* [cm]	15	72
c.-c. initial voltage [MV]	- 6.6 ("anti-crabbing")	12.5 ("full crabbing")
initial Piwinsky angle	4.76	0
initial lumi loss factor	0.21	1.0
levelled lumi [10^{34}cm^{-2}s^{-1}]	5.0	
initial luminous region [cm]	**1.1**	**5.3**
initial bb tune shift for 3 IRs (IR1, IR5 & IR8)	**0.016** (0.011+2×0.0025)	**0.033** (3×0.011)

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HL-LHC new Beam-Beam Parameters

- N_p=2.2x10^{11}, ε=2.5 μm
- θ=590 μrad = const
- β^*=72➔15cm
  - A/σ = 26➔12.5

- ξ = 0.033 (3 IPs) initially, 0.014 at the end of fill
- Level with β^*

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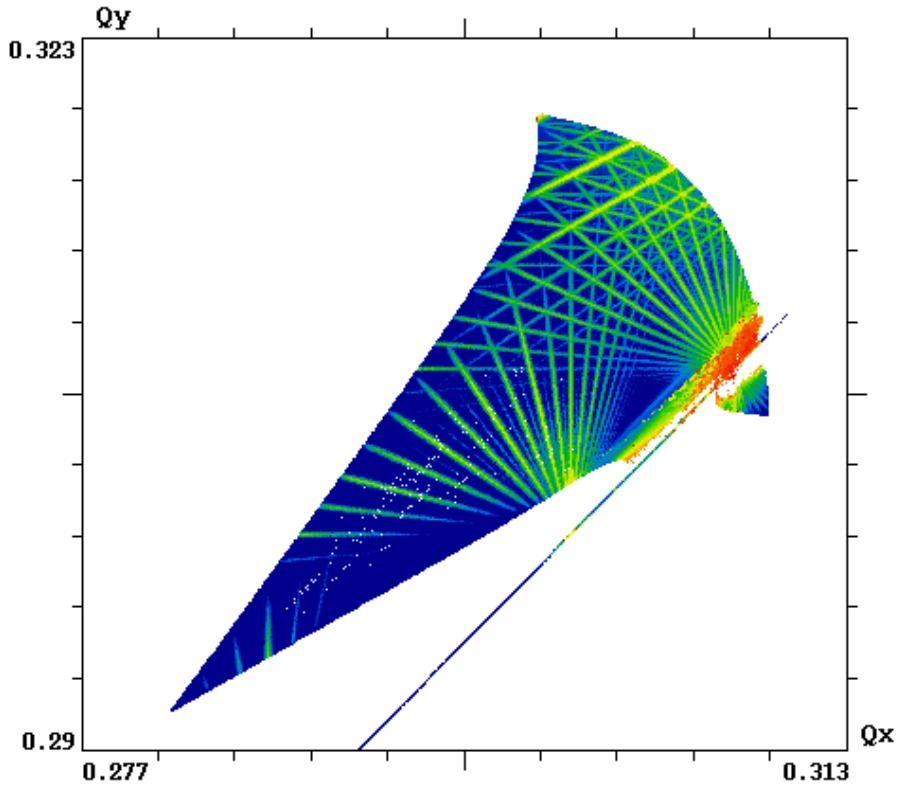
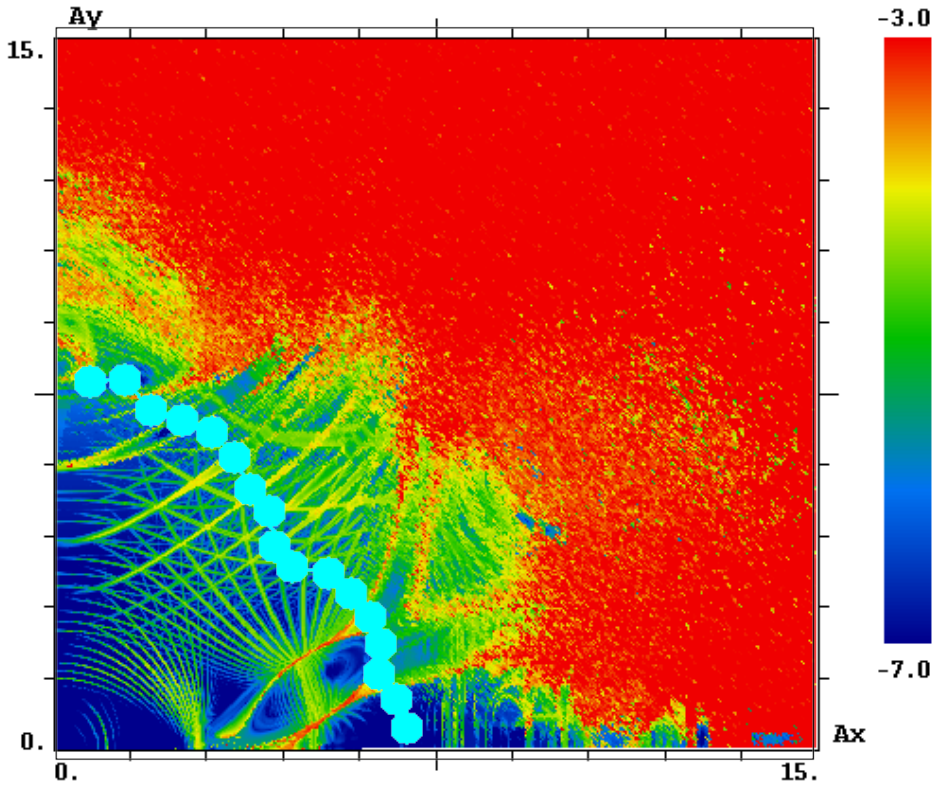
DA for Beginning of Fill

BB tune shift of ξ = 0.033 is ok even with A/σ = 12.5 !

with full crab on, no imperfections though





HL-LHC lattice without magnetic errors (only chroma sextupoles)
DA based on 10^6 tracking turns. β^*=0.15m, θ=590 μrad, ε=2.5μm

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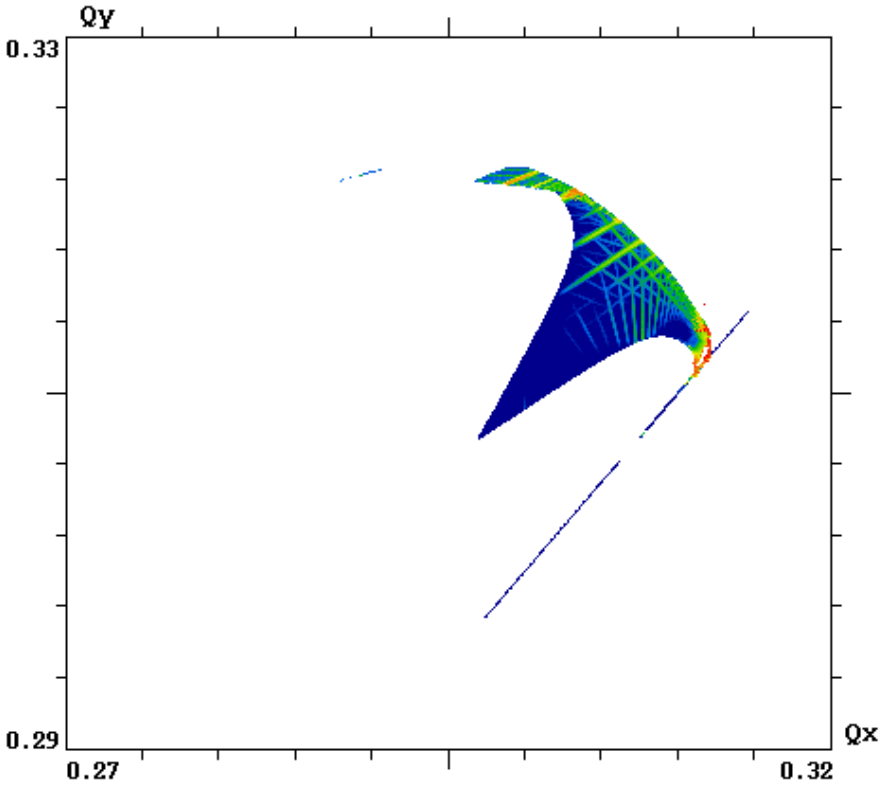
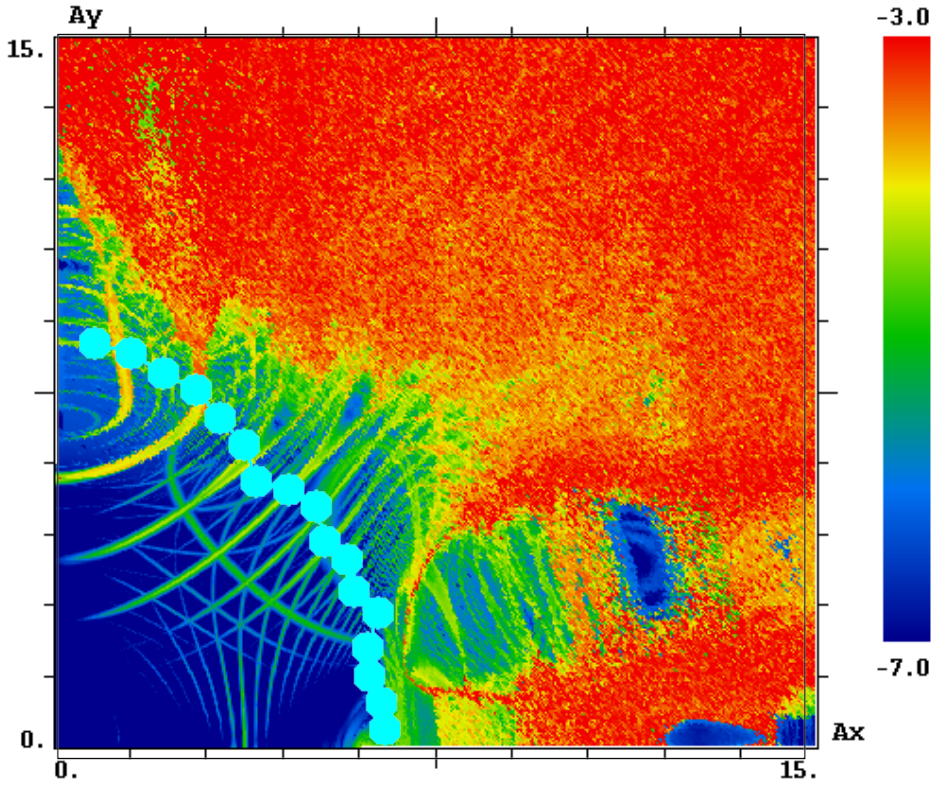
Can X-Angle (Crab Voltage) be reduced?

θ=480 μrad (Crab Voltage 10 MV) corresponds to A/σ= 10 at end of fill with Np=0.95x10^{11} ξ=0.014 – OK, IF emittance growth is contained!





HL-LHC lattice without magnetic errors (only chroma sextupoles)
DA based on 10^6 tracking turns. β*=0.15m, θ=480 μrad, ε=2.5μm

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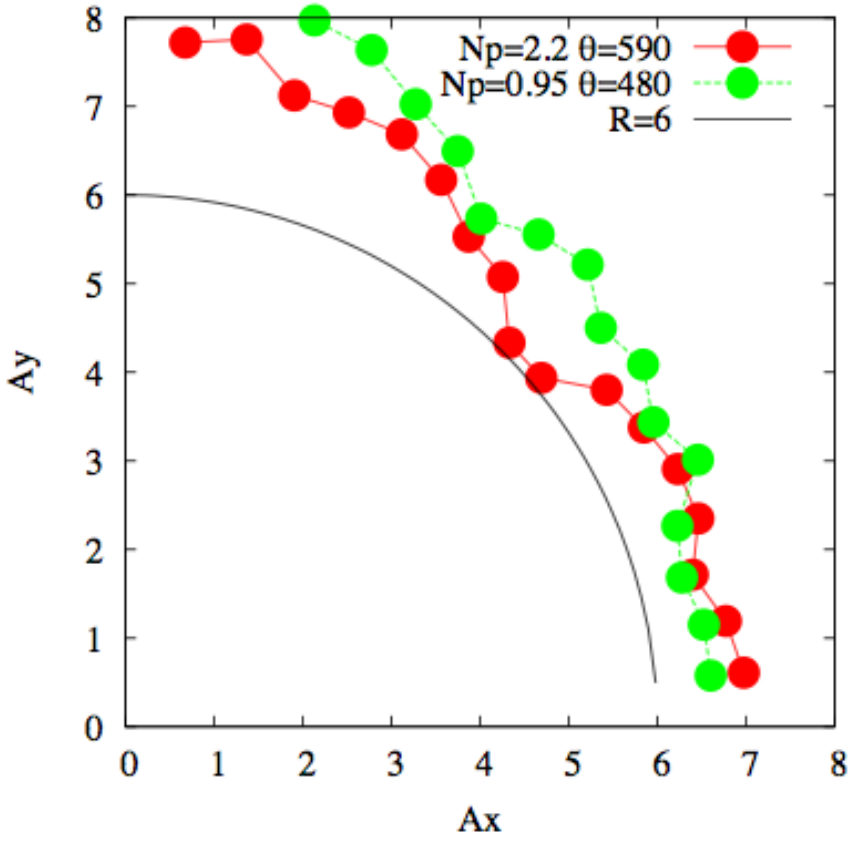
Summary of DA for full crab ON

- Large margin at beginning of fill – easy to reduce x-angle
- 15% margin at end of fill with θ=480 μrad should allow some emittance growth
- What happens at intermediate steps?



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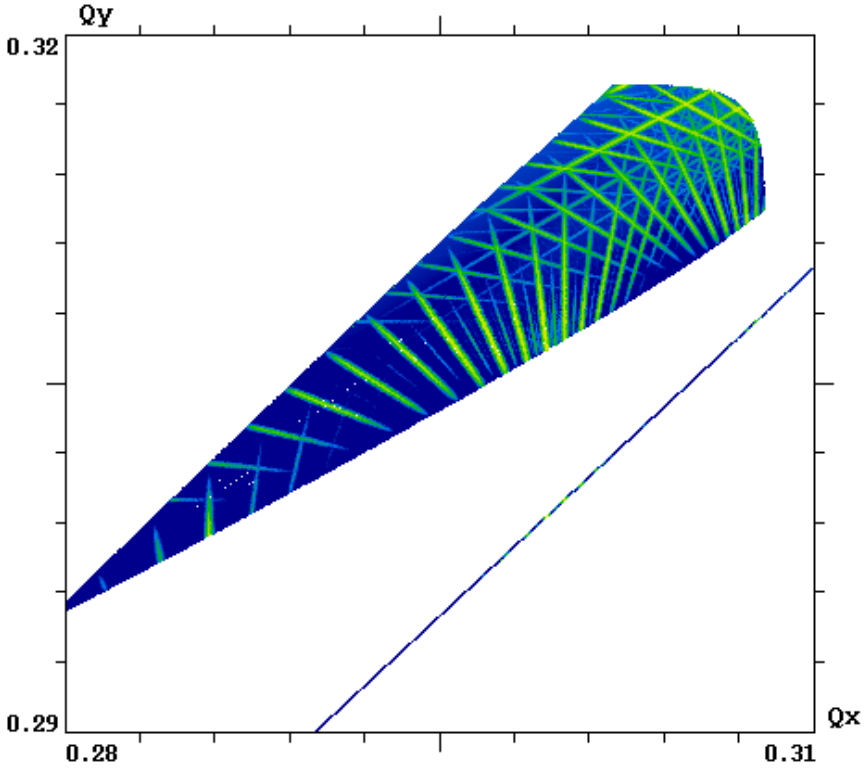
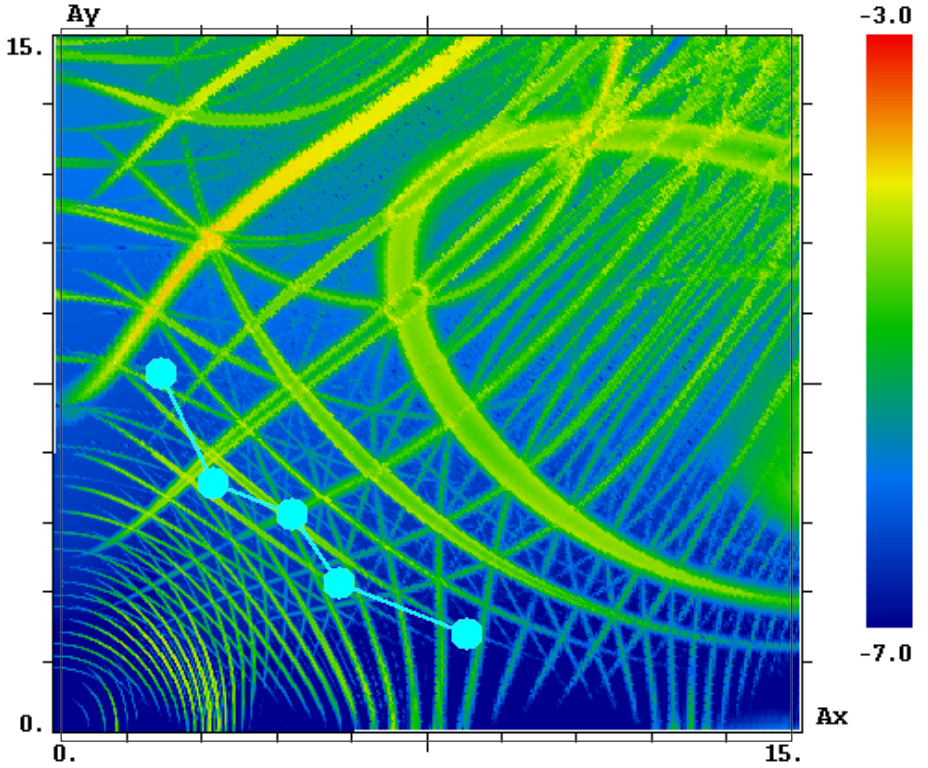
Will the New Option Work with 50ns?

β*=1.5m θ=590 μrad corresponds to A/σ = 35

with Np=3.5x10^{11} ε=3 μm ξ=0.043? (0.03) – preliminary OK!





HL-LHC lattice without magnetic errors (only chroma sextupoles)
DA based on 10^6 tracking turns.
In actual simulation: β=0.15m, θ=590x3 μrad*

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Study Topics

- Investigate the options for HL-LHC
  - Choice of basic options – β^*, crossing scheme
  - Luminosity leveling techniques
  - Imperfections, mitigation of beam-beam
- Develop self-consistent simulations of the beam-beam phenomena with other dynamical effects
  - Interplay with machine impedance
  - Crab cavity, noise, offset, etc.
- Help understand the experimental data from LHC as it becomes available
  - Also use RHIC for beam-beam experiments
- Support new ideas

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Circular Modes and Flat Beams for LHC

- A special type of coupled beam optics can convert planar betatron modes into circular modes
- For circular modes, the Space Charge tune shift is determined by the maximal emittance, being independent of the minimal one
- After acceleration, the beam can be transferred into the planar state, becoming flat – gain in luminosity
- With flat beams, leveling can be done with β^* in the crossing plane – no need for crab cavity

Luminosity Scenario with Flat Beams

	LHC nominal	HL-LHC 25 ns	HL-LHC Flat
# Bunches	2808	2808	2808
p/bunch [10^{11}]	1.15 (0.58A)	**2.2 (1.11 A)**	**2.2 (1.11 A)**
ε_L [eV.s]	2.5	2.5	2.5
σ_z [cm]	7.5	7.5	7.5
$\sigma_{\delta p/p}$ [10^{-3}]	0.1	0.1	0.1
$\gamma\varepsilon_{x,y}$ [μm]	3.75	**2.5**	**4.0, 0.4**
β^* [cm] (baseline)	55	**15**	**55, 15**
X-angle [μrad]	285	**590 (12.5 σ)**	**318 (10 σ)**
Lumi loss factor	0.84	0.30	0.85
Peak lumi [10^{34}]	1.0	7.4	19.7
Virtual lumi [10^{34}]	1.2	24.0	23.6
Leveling		Crab cavity	βx=11m down

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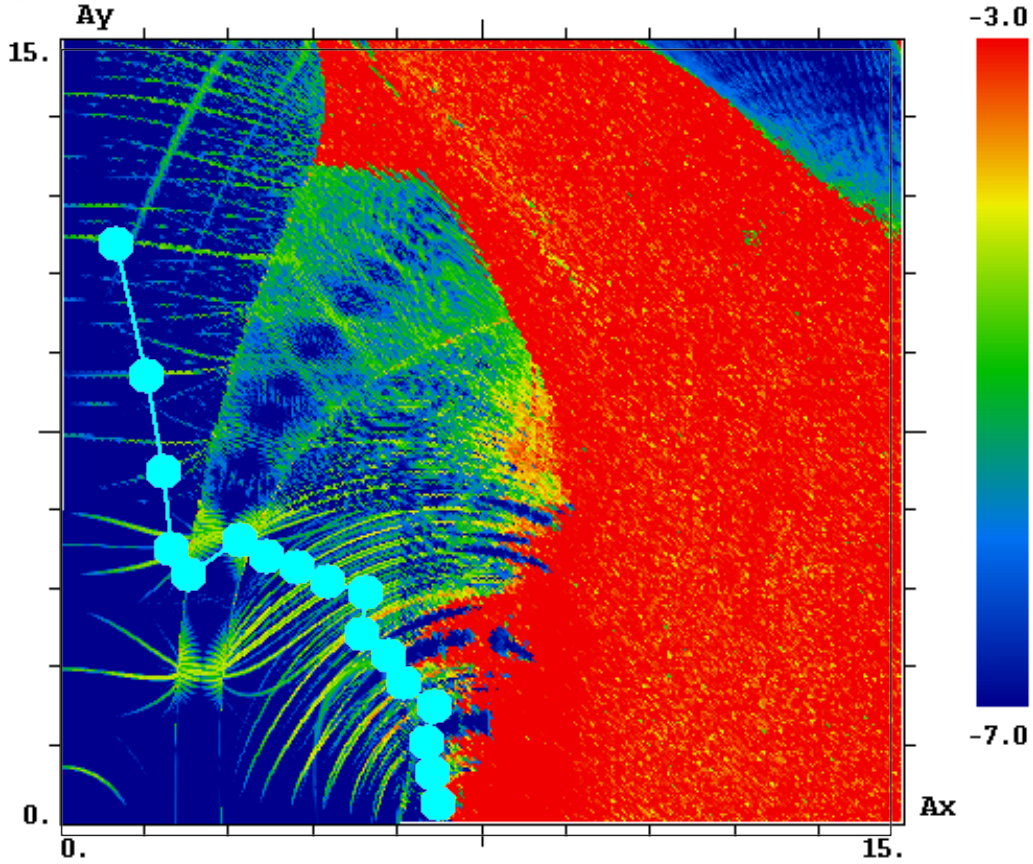
DA with Flat Beams

ξ_y = 0.03, ξ_x = 0.02, L=1.8x10^{35} – OK, although in a very simplified model!



Model HL-LHC lattice without nonlinearities.
DA based on 10^6 tracking turns.

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Summary

- Baseline HL-LHC scenario has been studied
  - No bb-imposed limitations so far
  - Good agreement between two codes
  - To do: effect of imperfections, multiparticle
- New scenario challenging in terms of bb
  - Preliminary results very encouraging – ξ=0.033 can be sustained
  - Crossing angle = CC voltage can be reduced ~20% assuming zero emittance growth
- Flat beams first look promising – no CC needed?

Asknowledgments

- Many thanks to D.Banfi, X.Buffat, A.Burov, S.Fartoukh, W.Herr, B.Muratori, S.Paret, T.Pieloni, J.Qiang, F.Schmidt, D.Shatilov, R.Tomas, S.White, F.Zimmermann…

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