High Luminosity LHC

LARP

Beam-beam effects: Status and Plans

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

2nd Joint HiLumi LHC-LARP Annual Meeting

November 14-16, 2012

Contributions by: A.Burov, S.Fartoukh, 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).

Task 2.5 Study Topics

- Investigate the options for HL-LHC
  - Choice of basic options – β^*, crossing scheme
  - Luminosity leveling techniques - talk by T.Pieloni
  - Imperfections, mitigation of beam-beam
- Develop self-consistent simulations of the beam-beam phenomena with other dynamical effects
  - Interplay with machine impedance - talk by S.White
  - 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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Collaboration

- LARP
  - S.White (Toohig fellow, BNL), J.Qiang, S.Paret (LBNL), A.Burov (LARP LTV), A.Valishev (FNAL)
- HL-LHC
  - T.Pieloni (CERN Beam-Beam Group), F.Zimmermann (CERN), D.Shatilov (BINP), M.Zobov (LNF/INFN), B.Muratori (Cockroft), K.Ohmi (KEK)

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.
- Strong-Strong
  - BeamBeam3D. Many users – LBNL, FNAL, BNL
  - COMBI. Good for multi-bunch simulations

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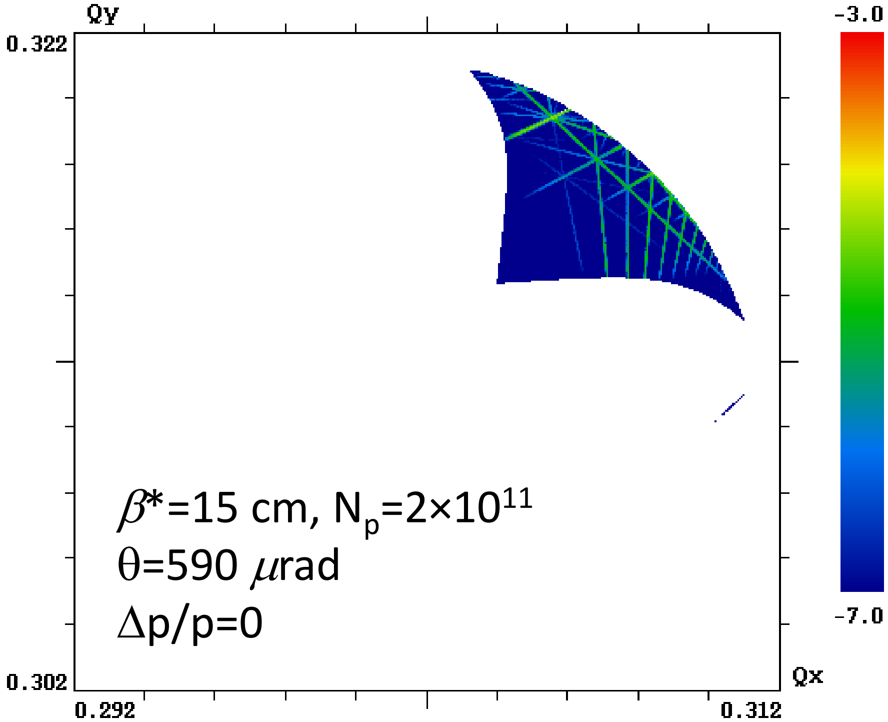
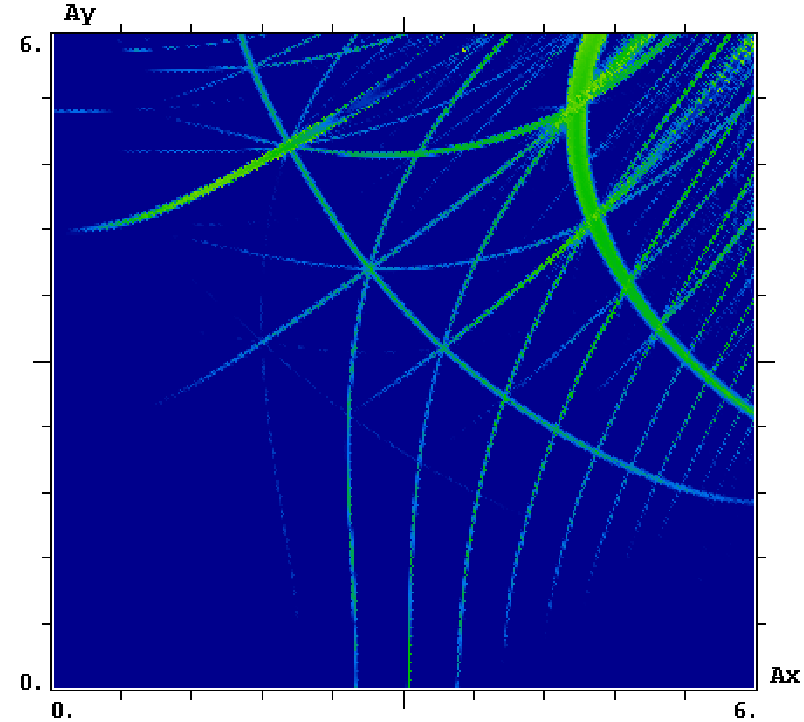
Frequency Map Analysis of HL-LHC options

- FMA uses 2^{10}-2^{13} tracking turns for multiple initial conditions to determine tune 'jitter' along the trajectory

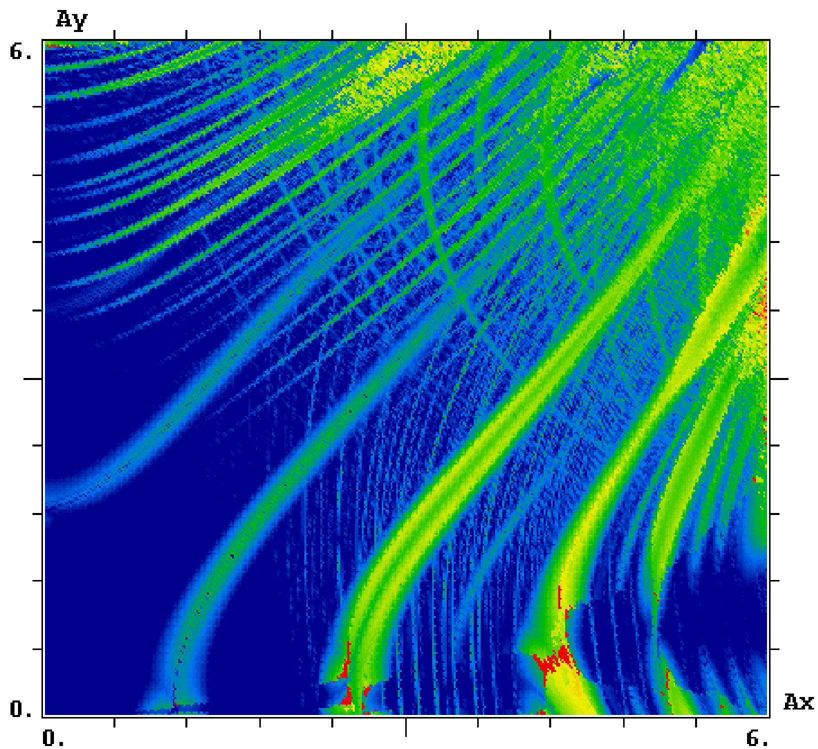




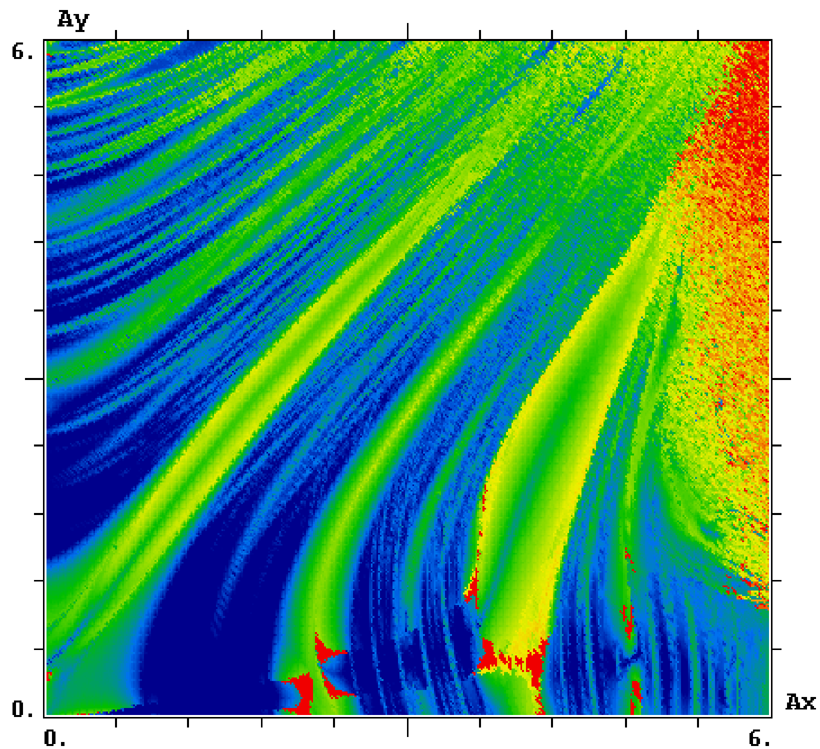
Linear HL-LHC lattice (no sextupoles) + beam-beam (head-on & long-range)

D.Shatilov, A.Valishev

Frequency Map Analysis of HL-LHC options



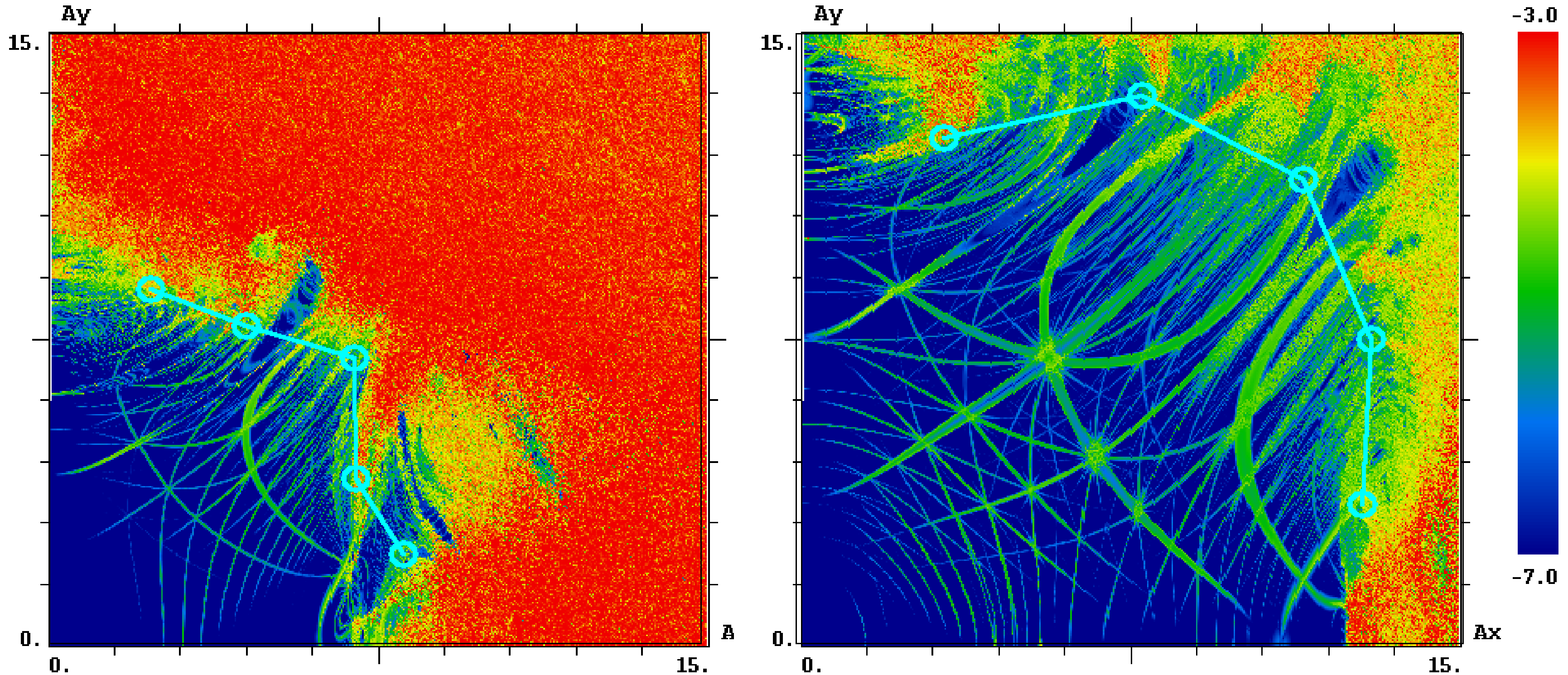
β^*=15cm θ=590μrad Δp/p=1.1e-4



β^*=15cm θ=590μrad Δp/p=2.2e-4

D.Shatilov, A.Valishev

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

D.Shatilov, A.Valishev

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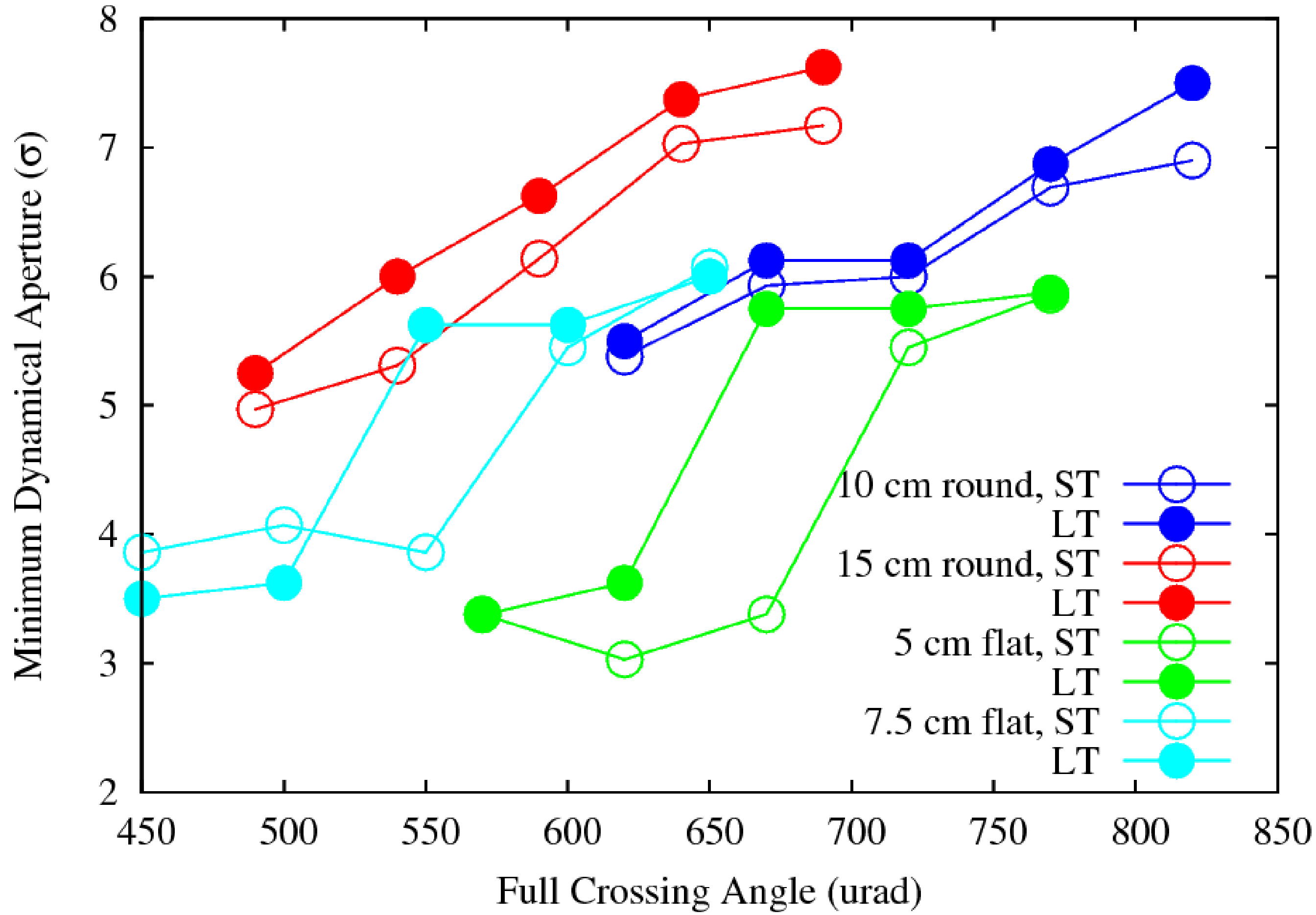
Expansion of Lifetrac Tracking Model

- Originally, Lifetrac used simplified modeling of machine lattice: linear maps between IPs
- Machine nonlinearities can play an important role in beam-beam. Also, proper implementation of chromatic effects is essential
- Recently, Lifetrac was expanded to include the complete model of LHC, a la madx/sixtrack

D.Shatilov, A.Valishev

DA Simulations



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

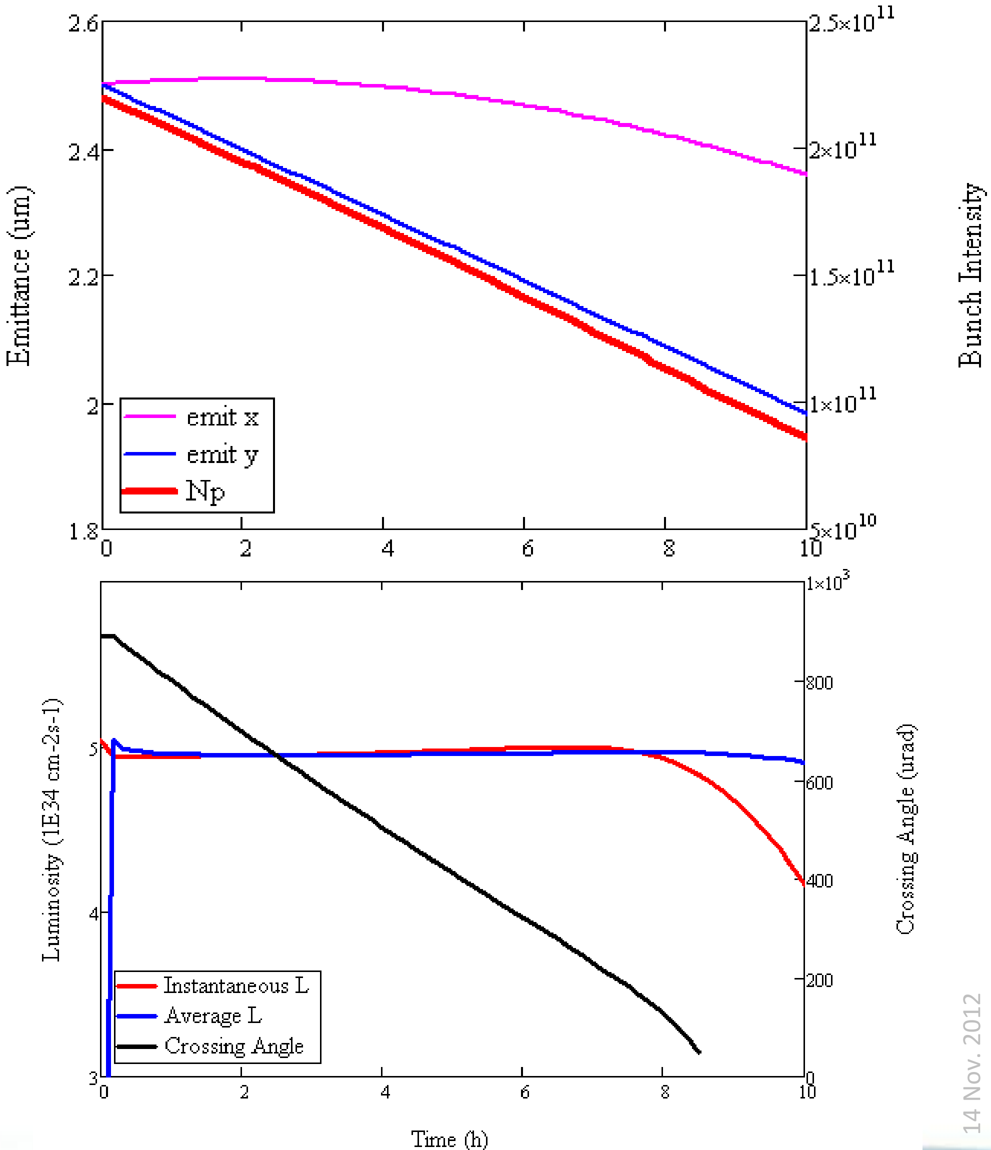
S.White, A.Valishev

Further Steps in Weak-Strong Modeling

- Implement multipole errors (interface with Task 2.3)
- More simulations of FMA and DA
  - A new EPFL fellow joined CERN beam-beam group
- Move to simulations of beam lifetime
  - Benchmark wrt June, 2012 beam-beam MD
  - Compare to model of luminosity evolution

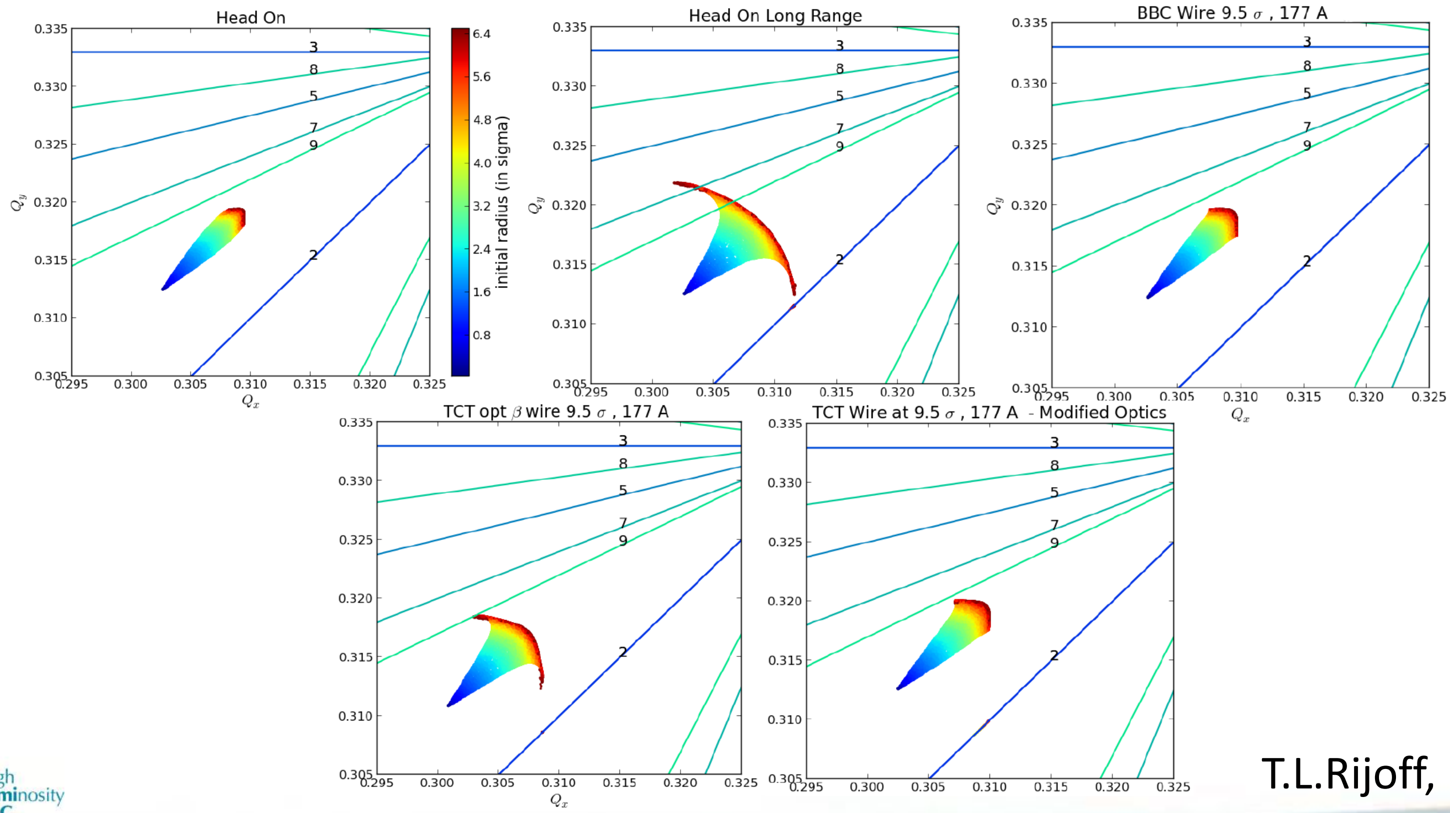
Model of Luminosity Evolution

- Components
  - Particle burn in collisions
  - Intrabeam scattering
  - SR damping
  - Noise
  - Residual gas
  - Lumi leveling
- Goal
  - Evaluate magnitude of beam-beam effects



Wire Compensation of Long-Range Effects

- Wire beam-beam compensators are a possible way to mitigate long-range beam-beam effects
- Recent simulations predict that a properly placed wire allows to reduce crossing angle by 1-2σ while maintaining the same DA



T.L.Rijoff, F.Zimmermann

14 Nov. 2012

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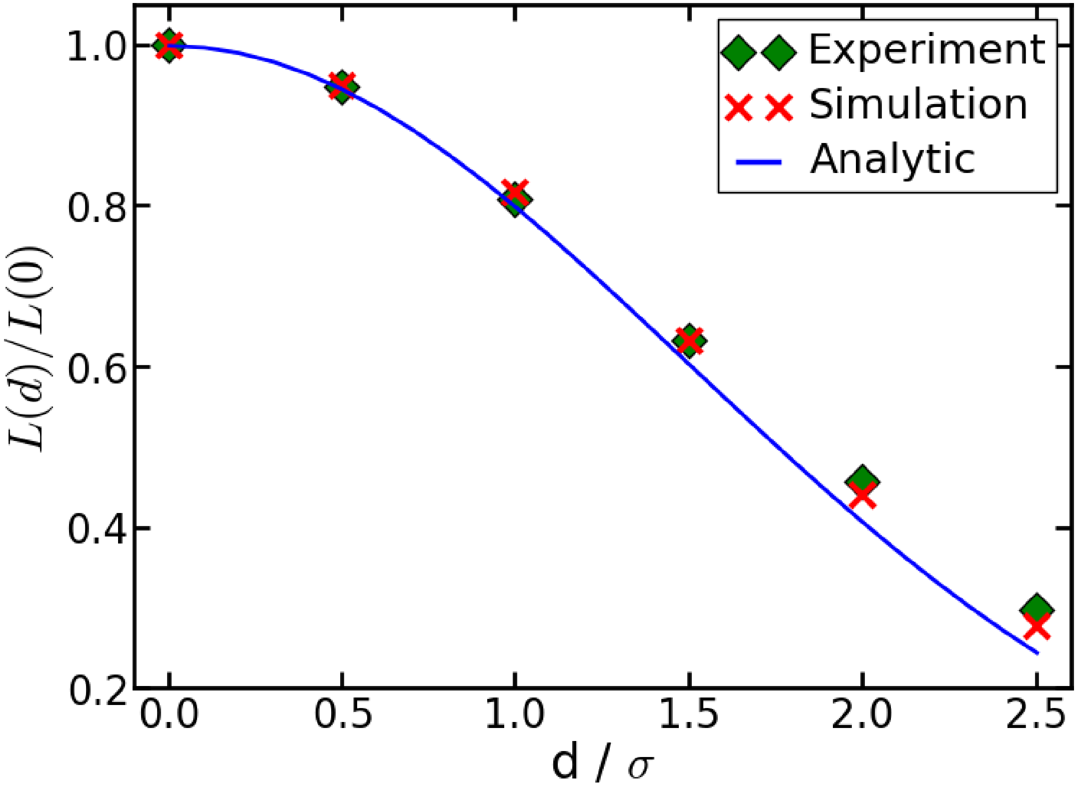
Recent Beam-Beam Studies at LBNL

- Simulation of luminosity leveling via separation
  - Collisions with separated beams
  - Impact on luminosity and beam parameters
  - Comparison with experiment (MD in 2011)
- Simulation of emittance growth in present LHC due to beam-beam effects
  - Comparison of simulation with data from operations in 2012
  - Test of feedback model and noise sensitivity of BeamBeam3D
  - Preparation for simulations with crab cavities

S.Paret, J.Qiang

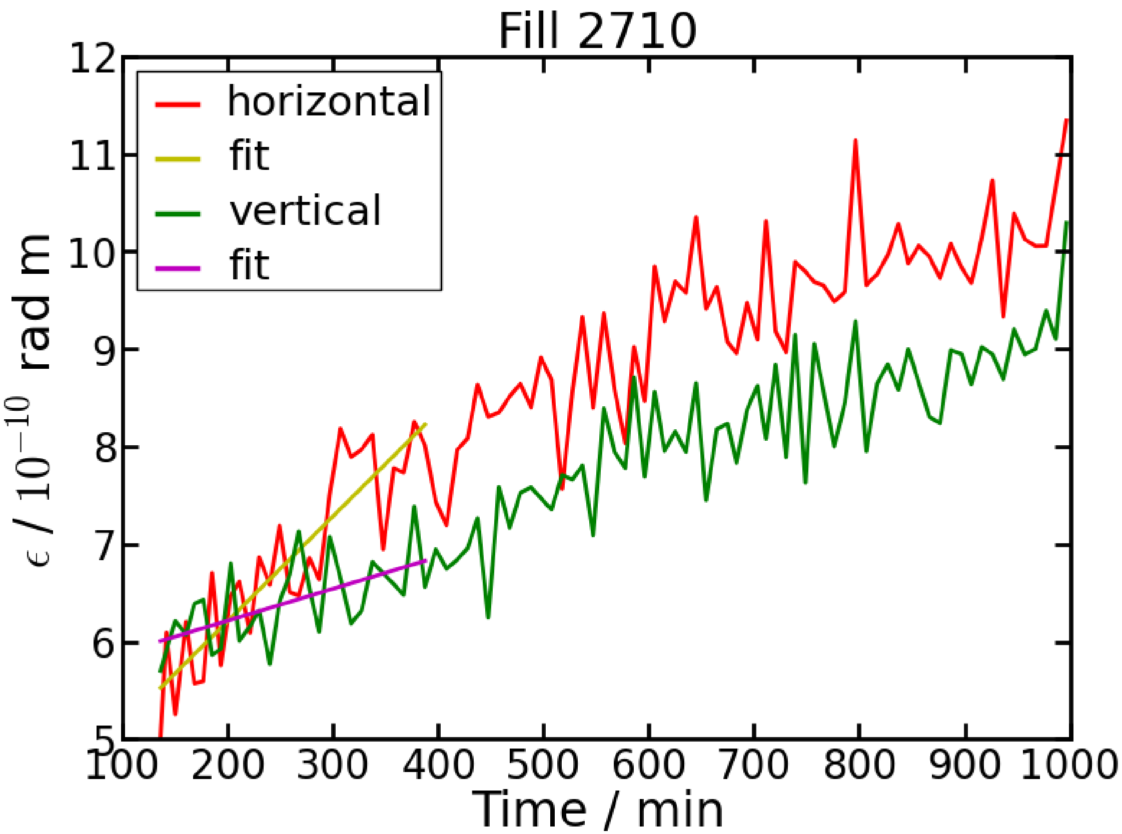
Luminosity vs. Transverse Separation



Simulation (S. Paret et al., WEO1C06, HB2012) agrees well with LHC MD (G. Papotti et al., TUPZ025, IPAC2011)

S.Paret, J.Qiang

Baseline Emittance Growth



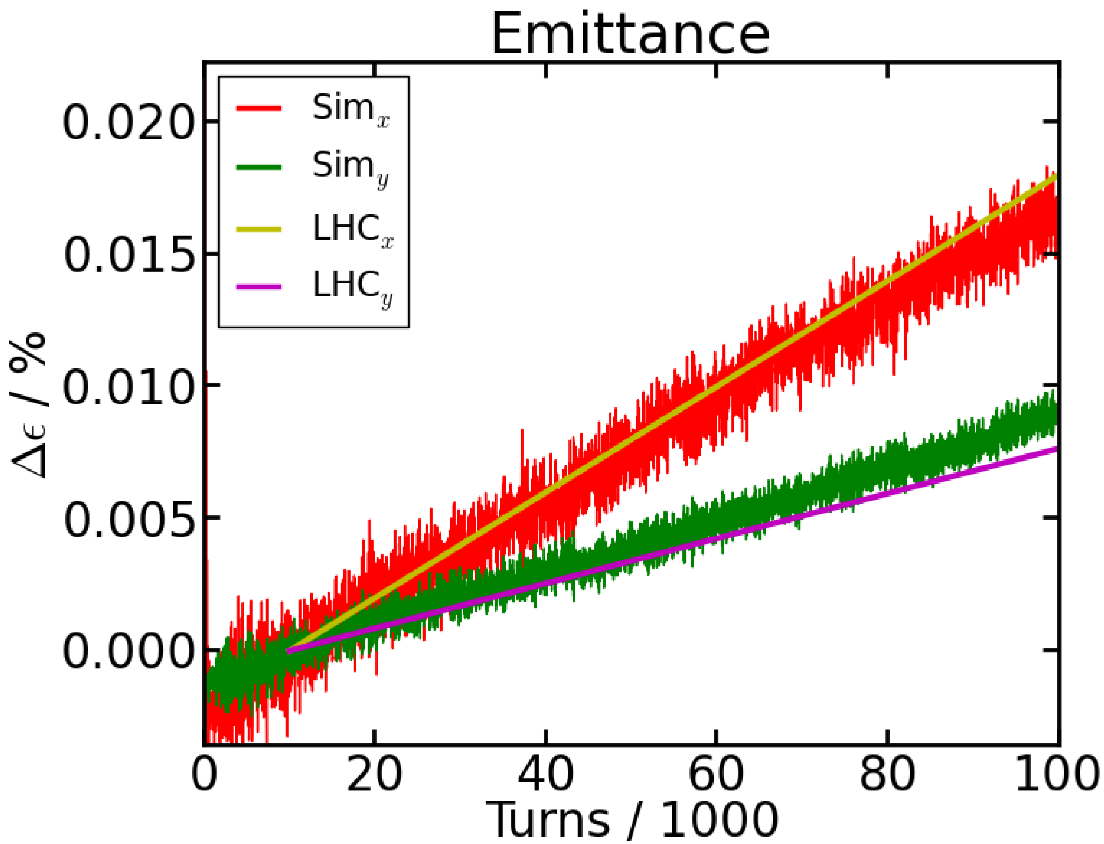
Initial linear growth rate:
12.8 %/h hor.
3.4 %/h ver.

<u>Exclusion of IBS</u>
Horizontally IBS accounts for ≈ 5 %/h **
➔ Max. 8 %/h due to beam-beam effects

LHC operation data (G. Trad, CERN) was used as reference for simulations
** M. Schaumann, J. Jowett, CERN-ATS-Note-2012-044 PERF

S.Paret, J.Qiang

Simulation of Emittance Growth



feedback gain = 0.35

<u>rms offset fluctuation</u>
at β = 137 m
2.6 µm in *x*
0.9 µm in *y*

Simulated emittance growth agrees with LHC data for reasonable noise level
Validation of emittance simulations provides base for future work
with HiLumi beam parameters and crab cavities

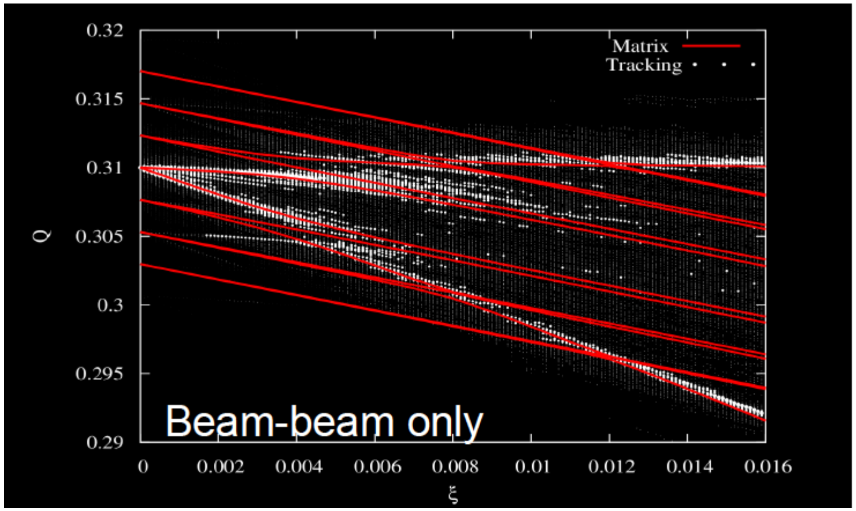
S.Paret, J.Qiang

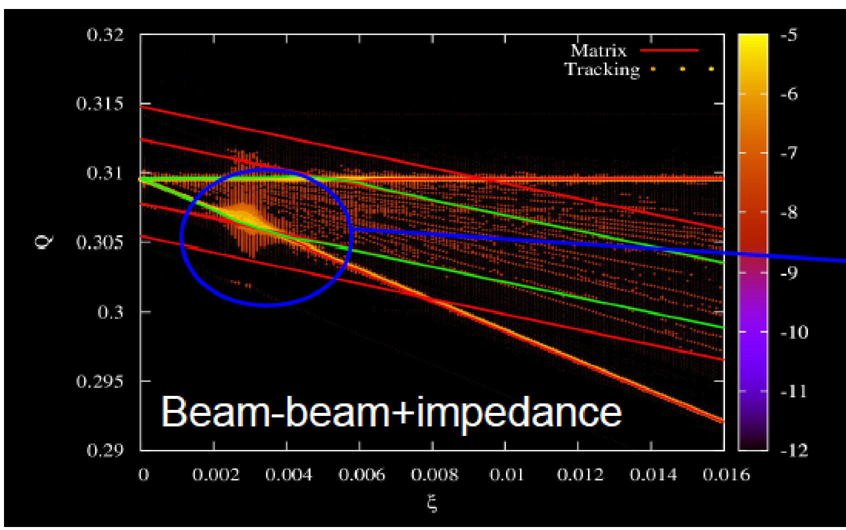
Combined Effect of Beam-Beam and Impedance

- Motivation
  - Instabilities are observed on a regular basis at the LHC
  - Source is not yet understood but could be related to an interplay between beam-beam and impedance
  - HL-LHC parameters could lead to enhancement of these effects - prediction tools are necessary in order to assess impact on performance
- Models
  - Two models were developed. A analytical model based on the work by Perevedentsev and a fully 3D self-consistent tracking code starting with BB3D from J. Qiang
  - Both models provide complementary information and are very useful to understand this complex phenomena

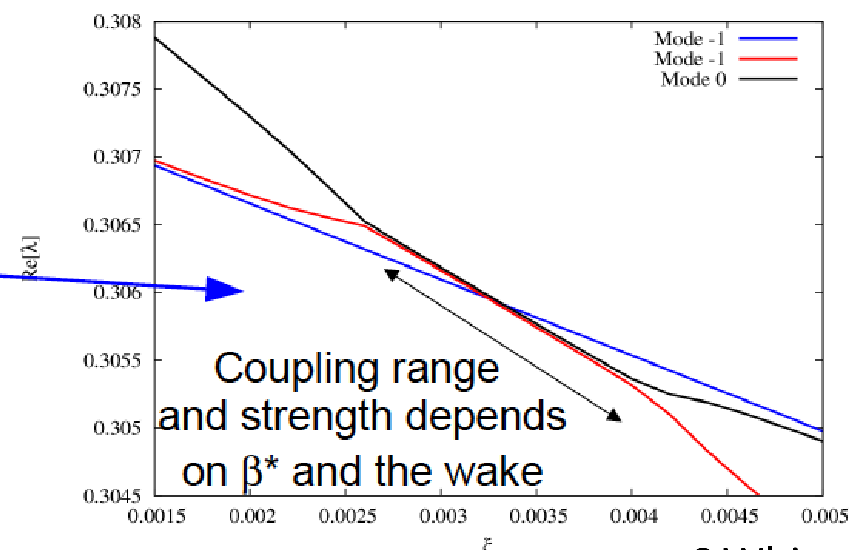
S.White

Highlights of Beam-Beam + Impedance





- Beam-beam only: always stable
- Beam-beam+impedance: coupling between the beam-beam modes and higher order headtail modes introduced
- Could lead to strong instabilities with growth rates comparable to TMCI



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Beam-Beam and Impedance: Outlook

- Status
  - Model is now fully benchmarked and consistent with expectations from theory
  - First very promising results: showed that in the presence of impedance the beam-beam coherent modes can become very unstable under specific conditions
- Outlook:
  - Benchmark these new results against data – plenty of data from LHC – studies ongoing – MD foreseen at the end of November
  - As soon as impedance model is available make predictions for HL-LHC including consequences of different leveling scenarios

S.White

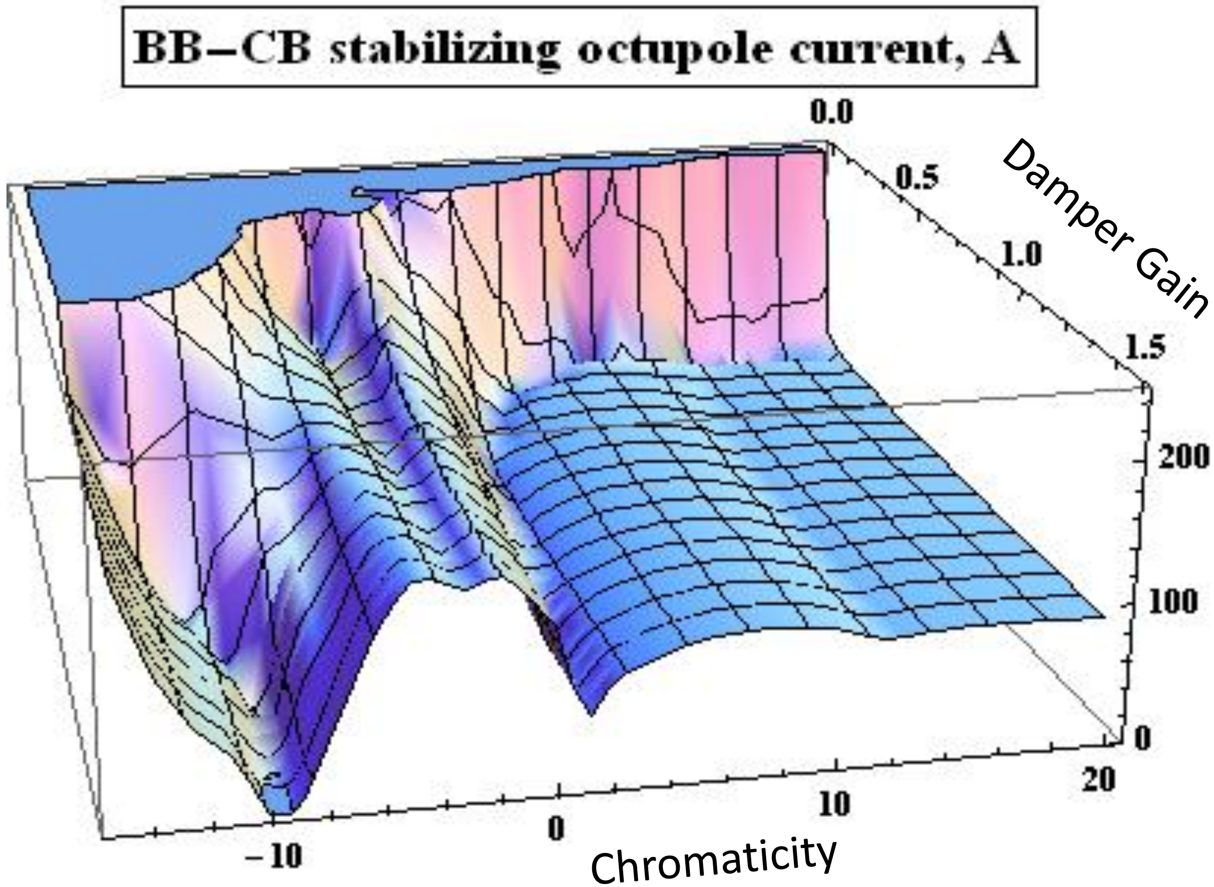
Nested Head-Tail Computations

- NHT is a Vlasov solver under development by A. Burov (FNAL/LARP-LTV) for analysis of transverse beam instabilities **.
- NHT assumes a multi-bunch beam with arbitrary distribution functions and train/batch structure with
  - Impedance
  - Damper gain
  - Transverse and longitudinal nonlinearities
  - Beam-beam collision scheme
- The program computes head-tail, radial and coupled-bunch structure of coherent modes for a given gain and chromaticity
- The threshold strength of the Landau elements (MO currents for LHC) is computed by means of pre-calculated stability diagrams

** Acknowledgements to V.Danilov, E.Metral, N.Mounet, S.White, X.Buffat, T.Pieloni

A.Burov

Example of NHT Computations



1xImpedance, coupled-bunch, coherent beam-beam $dQ_{bb}=\pm1Q_s$, MO+

A.Burov

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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

* A. Burov, "Circular modes for flat beams in LHC", HB2012

A.Burov

Luminosity Scenario with Flat Beams LHC

	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

A.Burov, A.Valishev

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Summary

- HiLumi-LARP beam-beam collaboration provides solid foundation for productive studies
- The basic methods and tools are well established
  - Preliminary assessment of HL-LHC (SLHCV3.1b) options
  - Now entering 'production' phase
- Novel results on coherent stability emerged as the result of collaboration activities
  - May be important for HL-LHC operation
  - Work continues to gain full understanding of beam stability

Asknowledgments

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

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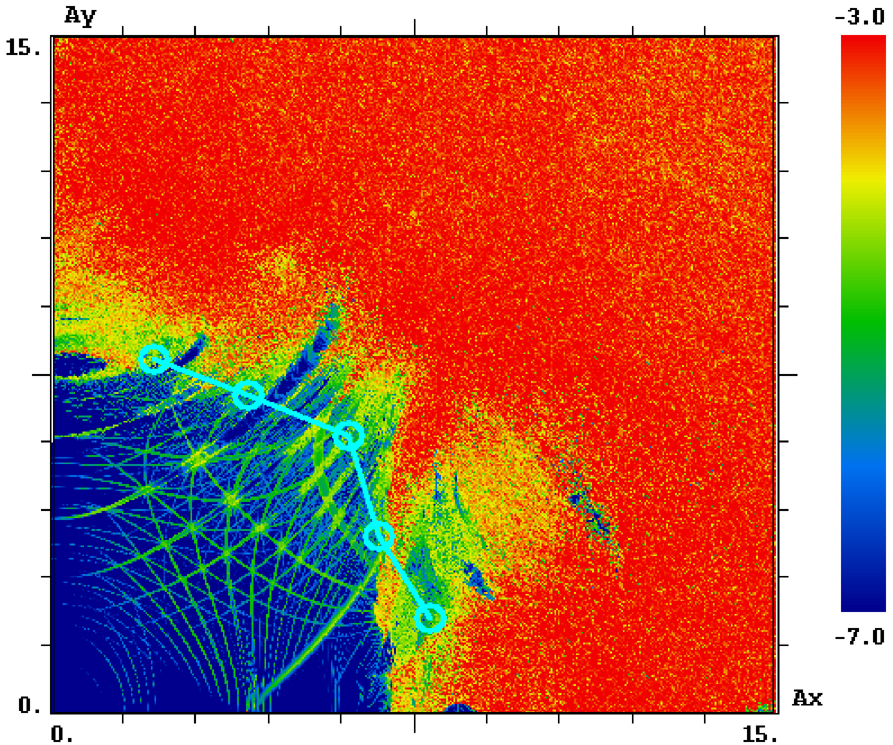
From FMA to Dynamical Aperture



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Σ_z=4cm

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