BBLR Compensation at HL-LHC – Simulation Results

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Acknowledgments: C.Milardi, A.Patapenka, H.Schmickler, G.Stancari, M.Zobov

Simulations and Measurements of LRBB in LHC
November 30, 2015, Lyon

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Outline

1. Integrated luminosity performance without/with wire compensators
   - Parameter space of wire compensation
2. LRBB compensation algorithm
3. Compensation performance in simulations
   - Robustness
4. Comments on implementation (G.Stancari)

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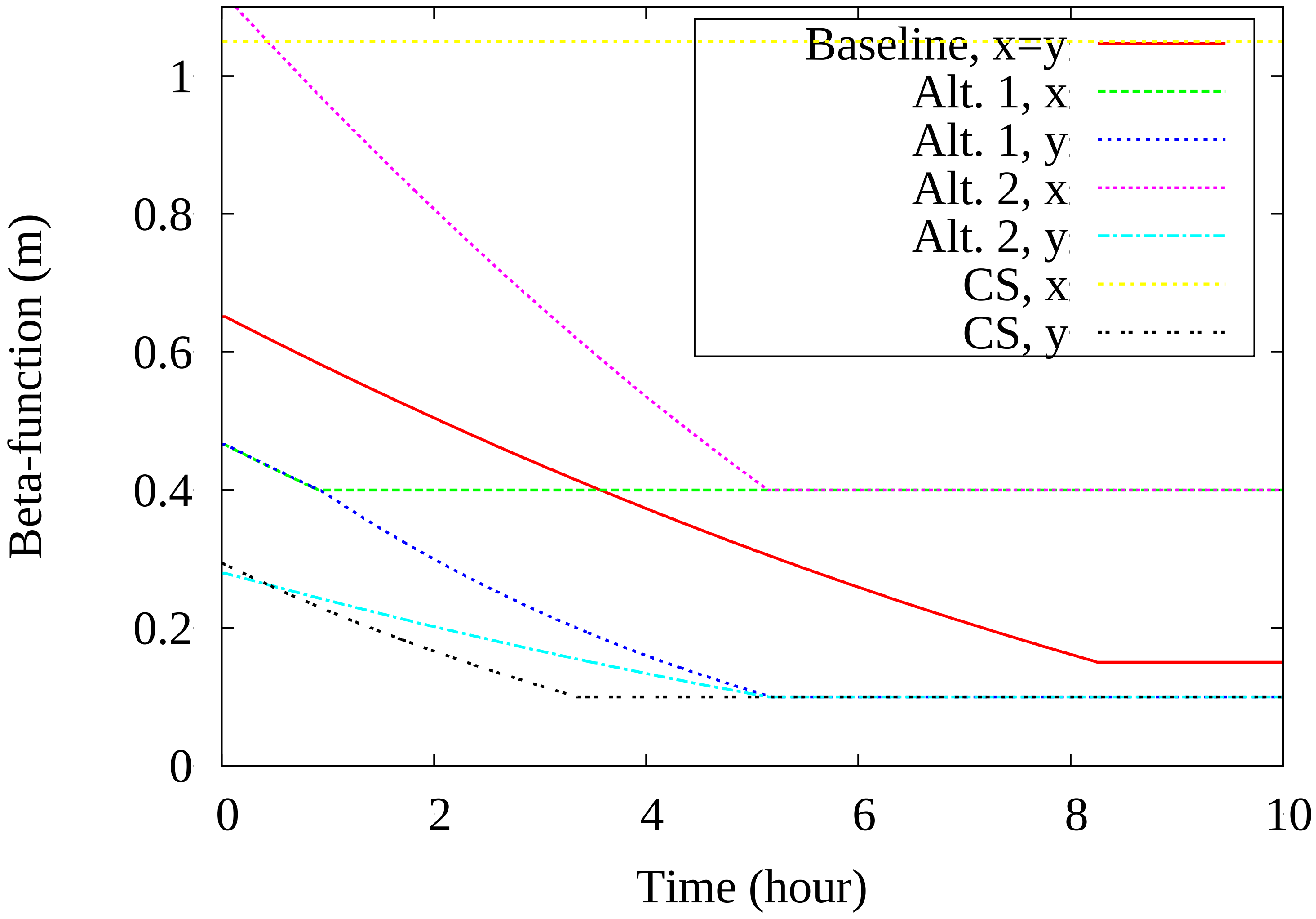
Luminosity Leveling at 5×10^{34}

baseline vs. alternative scenarios

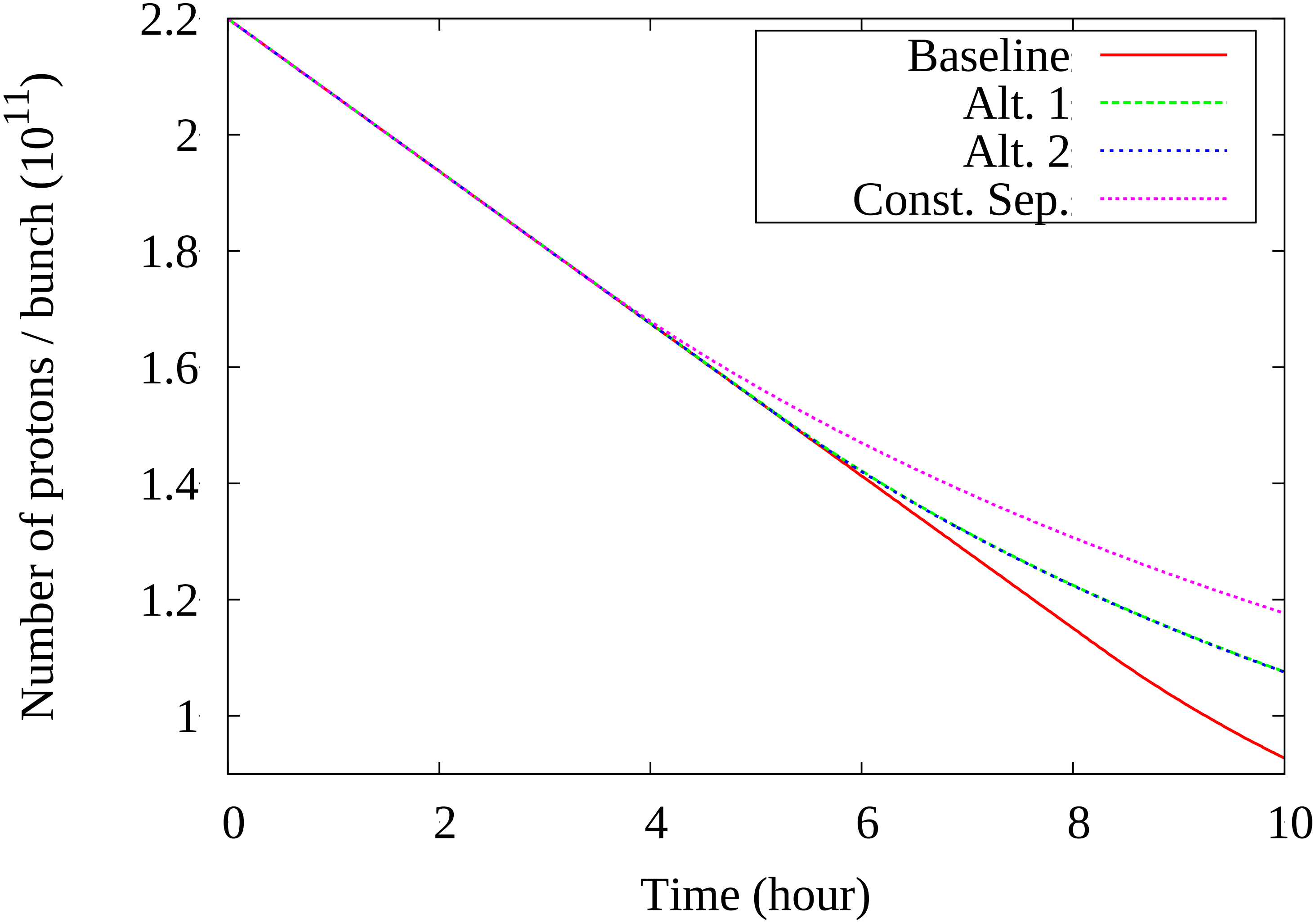
Parameters	Baseline	Alt. 1	Alt. 2
Energy [TeV]	7		
Bunch spacing [ns]	25		
Number of collisions at IP1,5	2736		
Particles/bunch [10^{11}]	2.2		
Norm. emittance [μm]	2.5		
Bunch length [cm]	7.50	10.0	
β^*_x/β^*_y [cm] from start to end of levelling	68/68 $\rightarrow$ 15/15	47/47 $\rightarrow$40/10	112/28 $\rightarrow$40/10
Crossing angle [μrad]	590 (12.5 σ)	280 (9.7 σ)	
Levelled luminosity [10^{34}cm^{-2}s^{-1}]	5.0		
Virtual luminosity [10^{34} cm^{-2}s^{-1}]	19.6	10.5	
Levelling time [h]	8.3	5.2	
Pile up [events /crossing]	138		
Peak PU density [mm^{-1}]	1.25	1.31	
Luminous region (r.m.s.) [cm]	4.4	4.3	
Integrated luminosity [fb^{-1}] in 8 h $\rightarrow$ 10 h	1.44 $\rightarrow$1.75	1.34 $\rightarrow$ 1.55	

Luminosity Leveling at 5×10^{34}

baseline vs. alternative scenarios



Luminosity Leveling at 5×10^{34}
baseline vs. alternative scenarios



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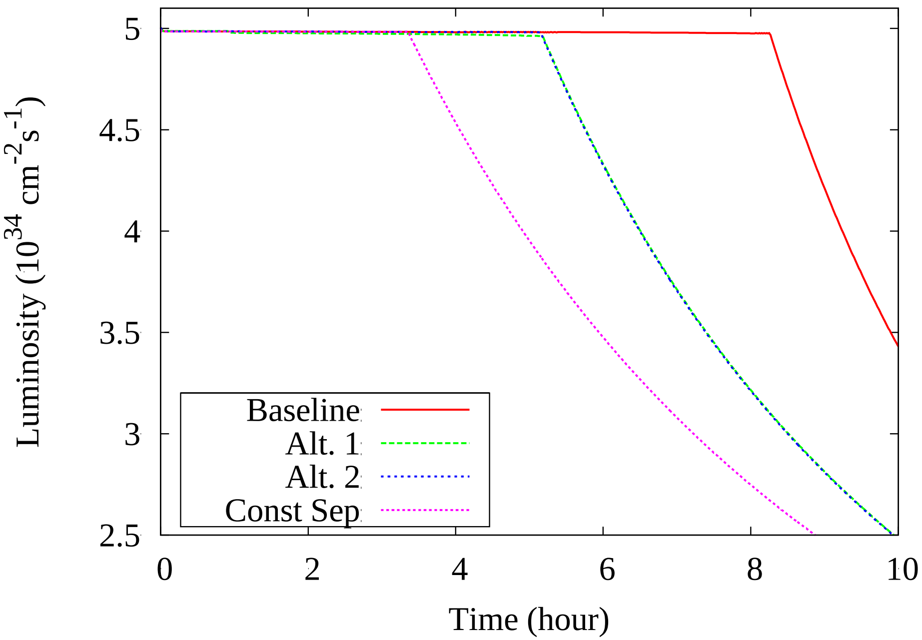
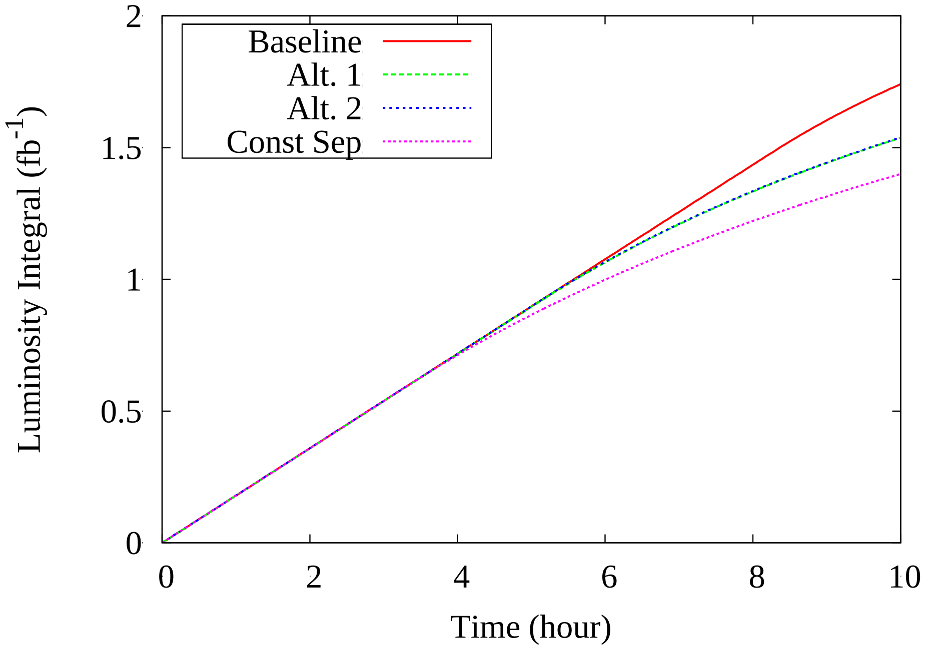
Luminosity Leveling at 5×10^{34}

baseline vs. alternative scenarios





- ✓ The luminosity performance is equivalent to baseline for store duration 6-8 hours and reduced ~10% (5%*) for 10 hours
- ✓ Pile-up and pile-up density are equivalent
- ✓ Longer bunches – less e-cloud and IBS (growth rate -40%!)

* Without and with IBS & SR

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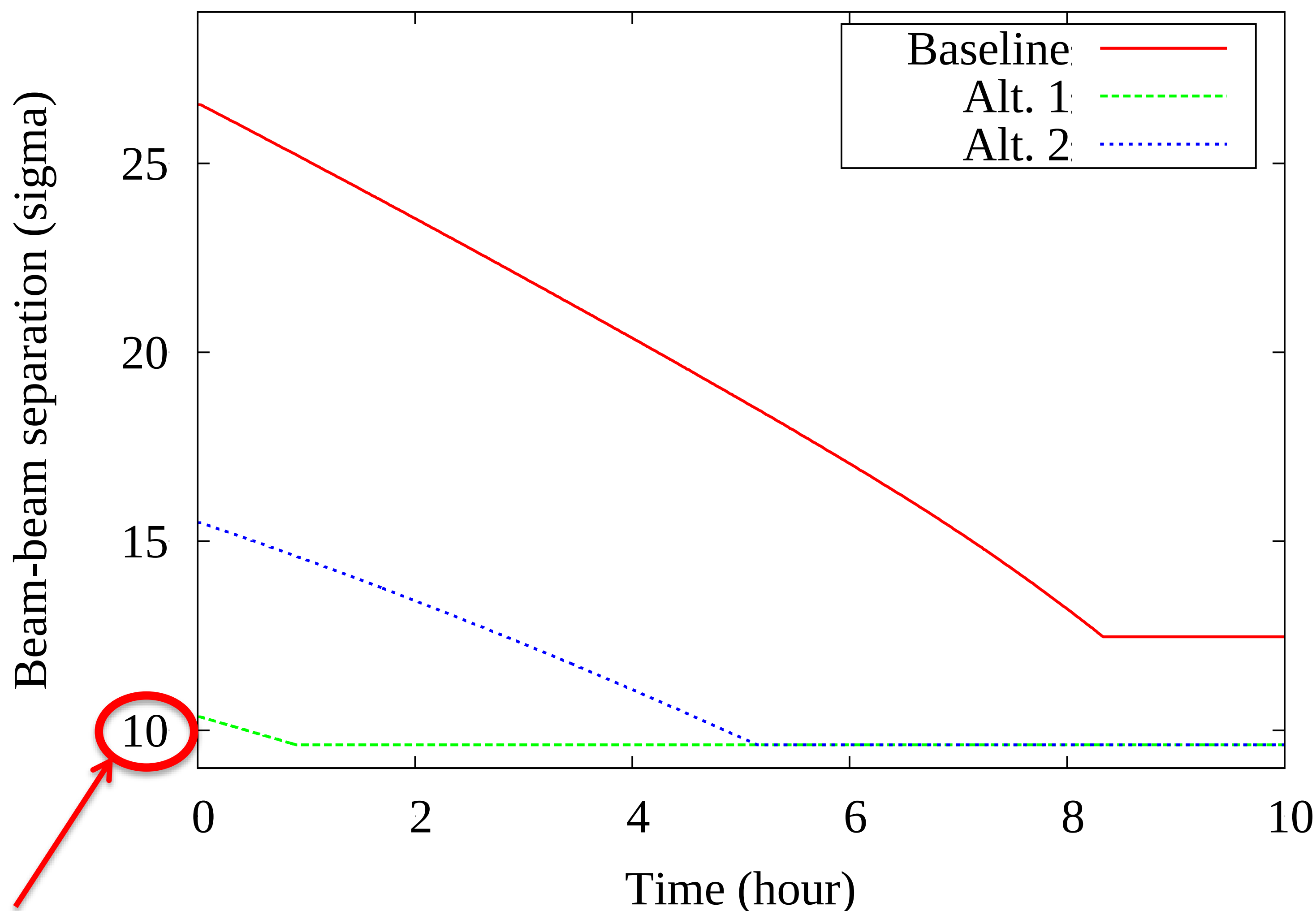
Luminosity Leveling at 5×10^{34}

baseline vs. alternative scenarios



Clearly a small separation!

LRBB Correction Algorithm

- LRBB and wire field

$$\int ds\, [B_y + i\, B_x]_{\text{eq}} = \sum_{k=1}^{\infty} [B_k + i\, A_k]\, z^{k-1} \quad \text{with} \quad B_k + i\, A_k \equiv \frac{\mu_0\, (IL)_{\text{eq}}}{2\pi} \times \frac{1}{z_0^k}$$

10.5A per LR collision at Np=2.2E11

- Beam-beam separation

$$d_{bb}(s) \sim d_{bb}(-s) \approx \left[\sqrt{\beta_x(s)\beta^*} + \sqrt{\beta_y(s)\beta^*}\right] \Theta_c/2$$

- Beta-function ratio

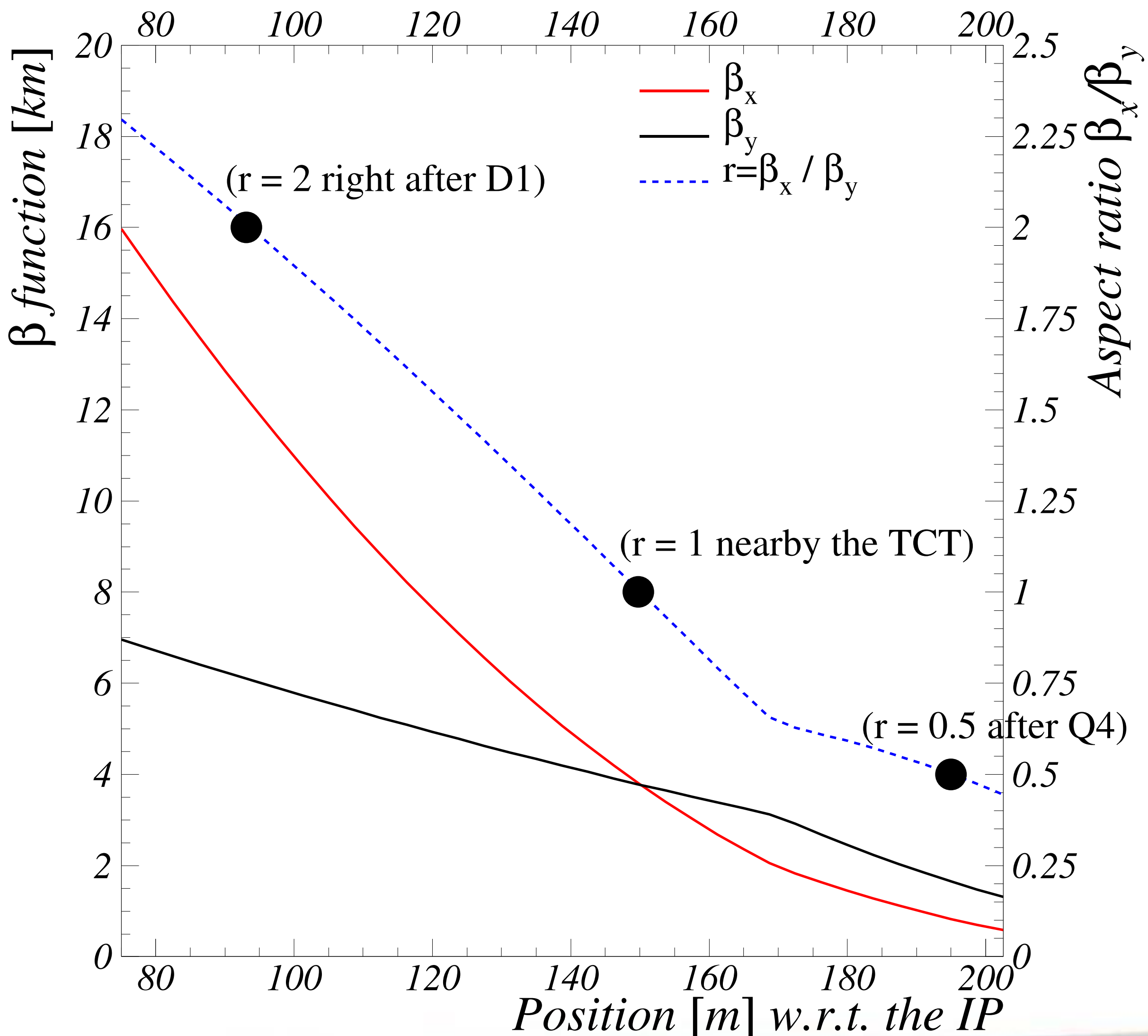
$$r_w \equiv \frac{\beta_x^{w.\text{R}}}{\beta_y^{w.\text{R}}} = \frac{\beta_y^{w.\text{L}}}{\beta_x^{w.\text{L}}}$$

- Resonance Driving Terms

$$c_{pq}^{LR} \equiv \sum_{k \in LR} \frac{\beta_x^{p/2}(s_k)\beta_y^{q/2}(s_k)}{d_{bb}^{p+q}(s_k)},\ p \geq 0,\ q \geq 0$$

S.Fartoukh, A.Valishev, Y.Papaphilippou, D.Shatilov, PRSTAB, in press

Beta Aspect Ratio



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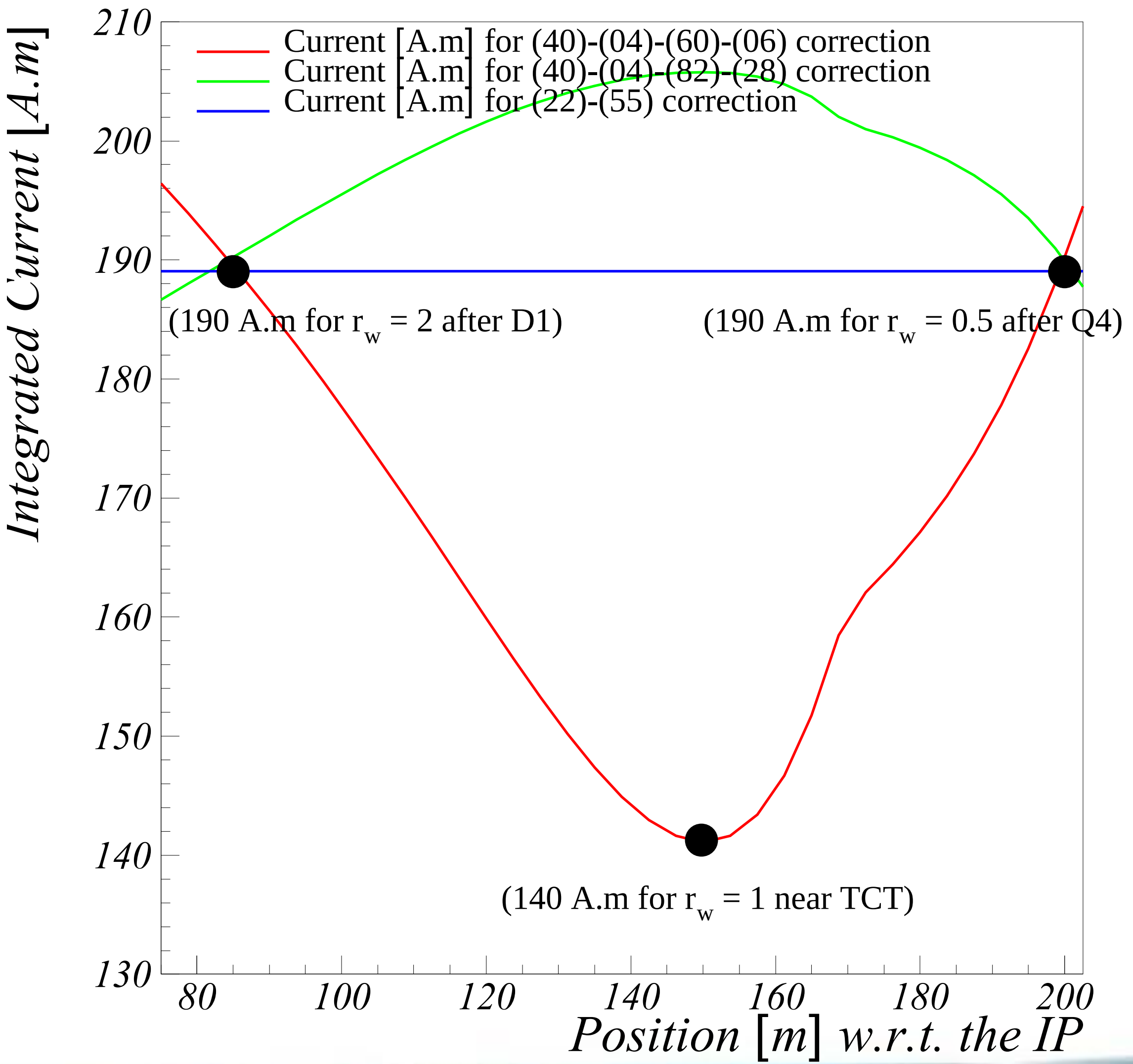
Optimized Wire Current - Baseline



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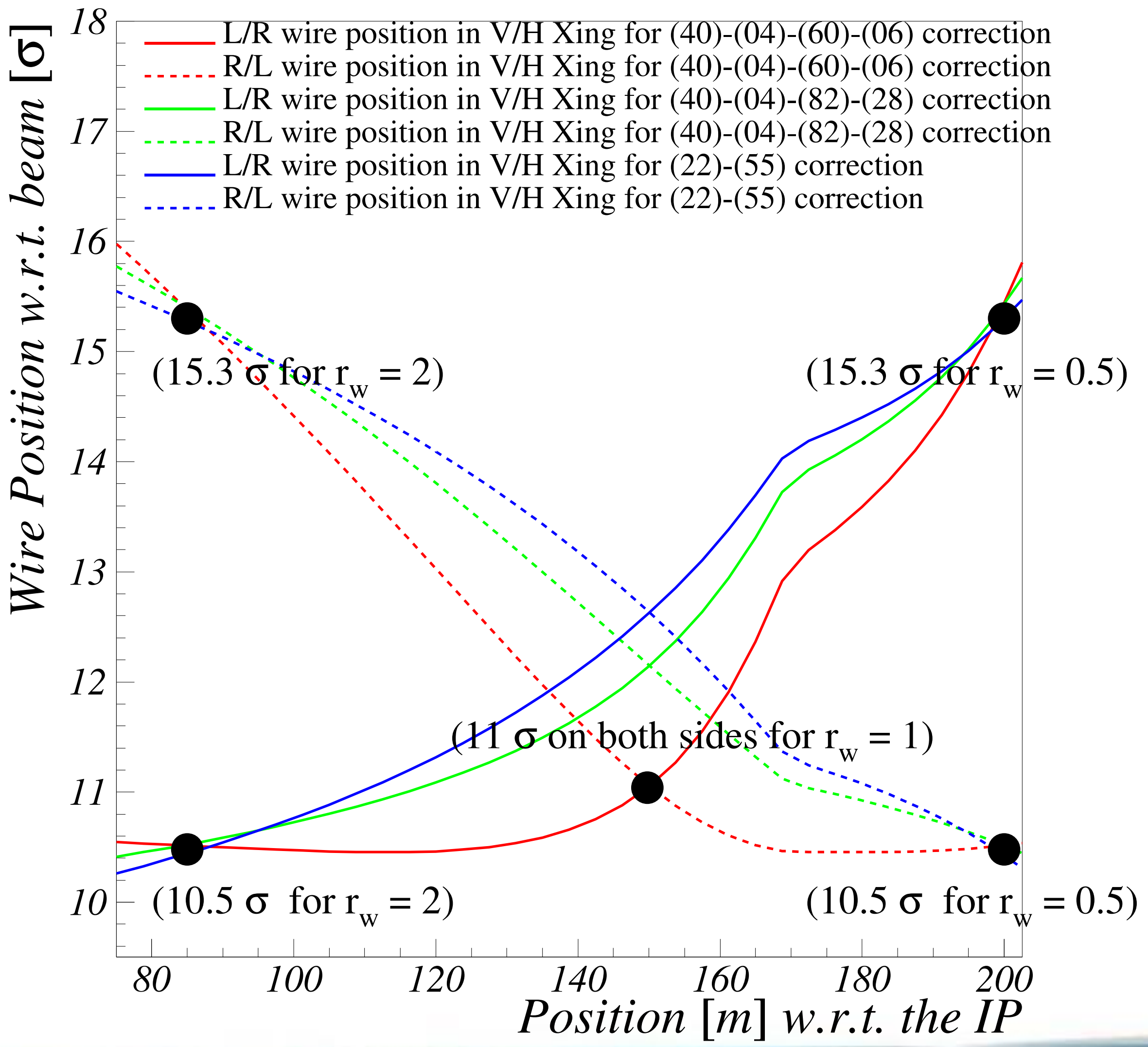
Optimized Wire Distance - Baseline



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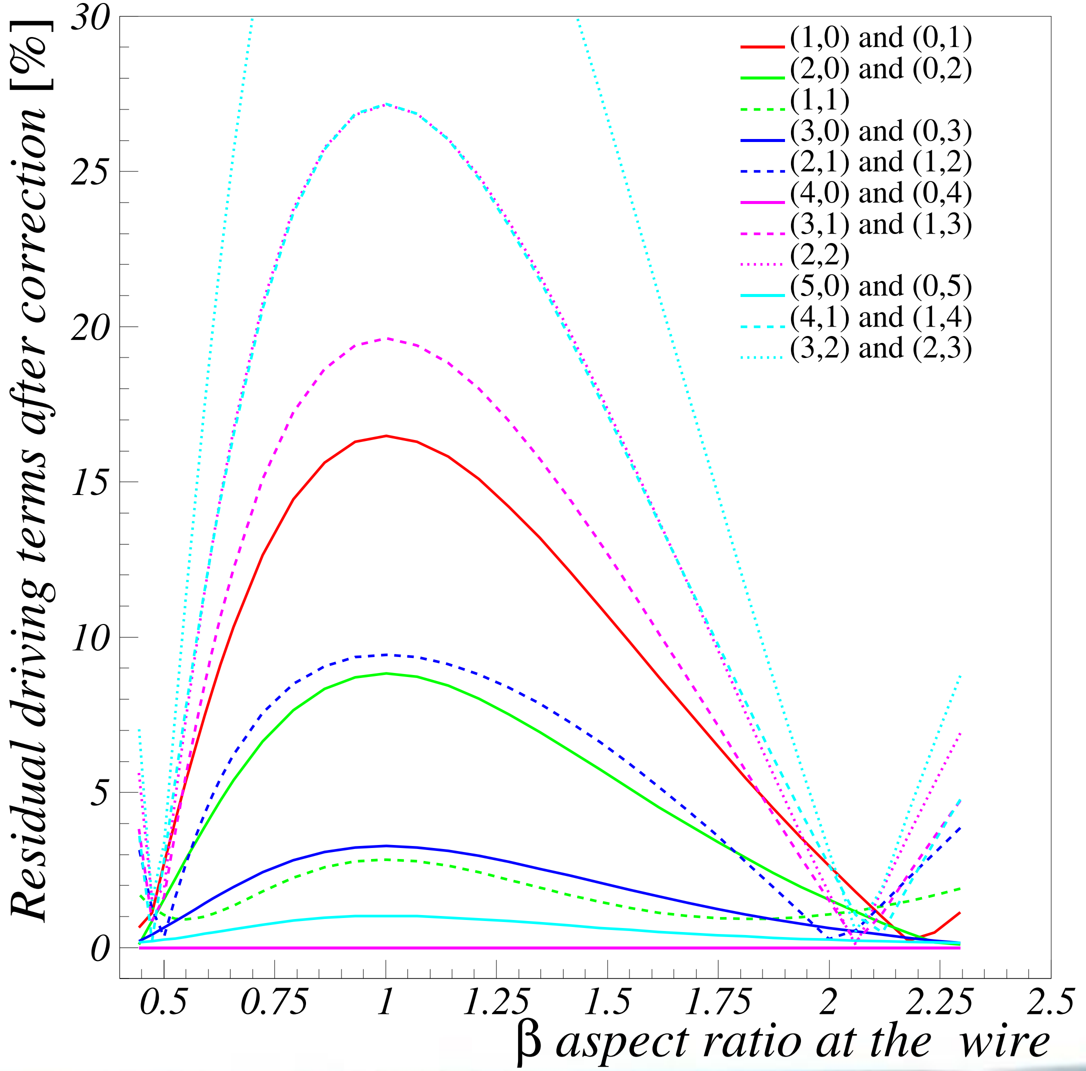
Residual RDT vs. r – Round

(40)-(04)-(60)-(06) correction



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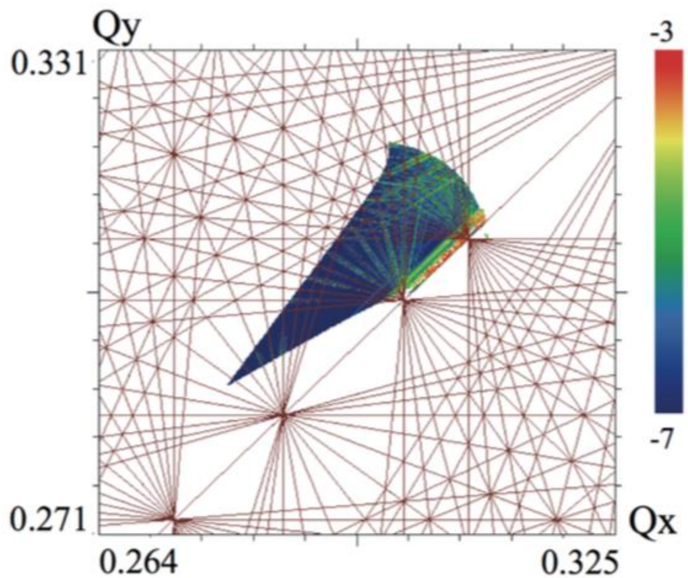
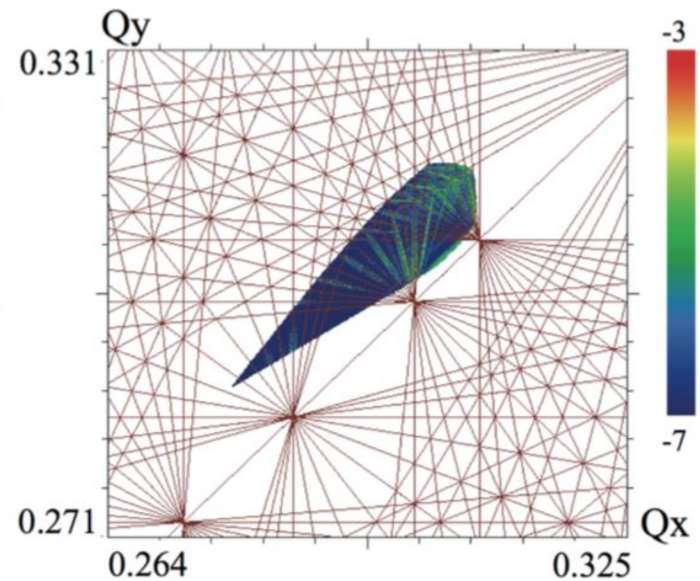
FMA – Round Optics 15/15, Np=2.2×10^{11}

590 μrad

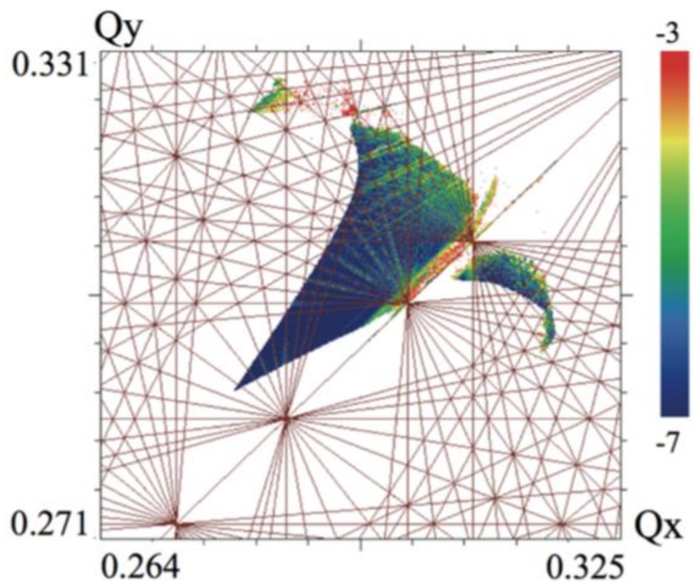


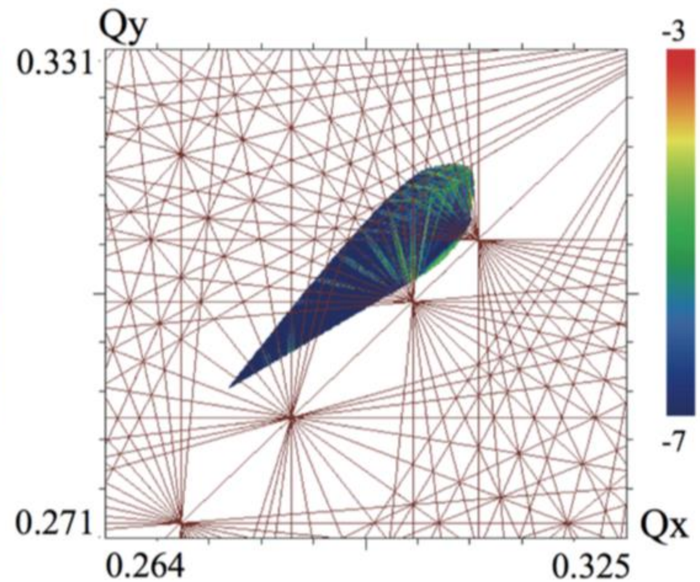
No correction



With correction

450 μrad





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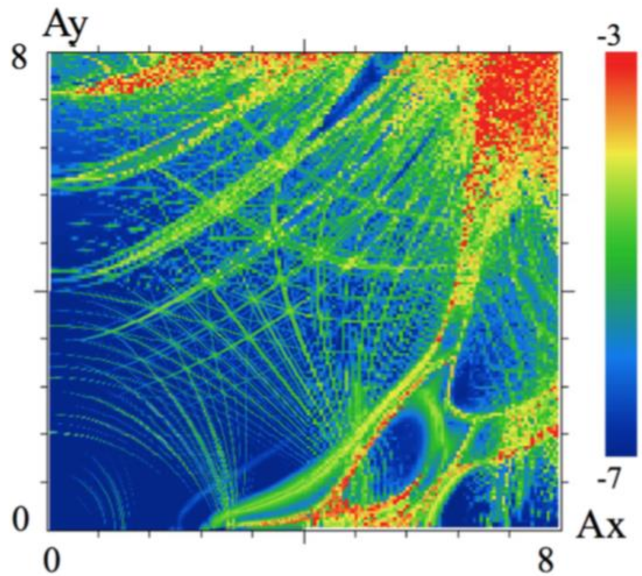
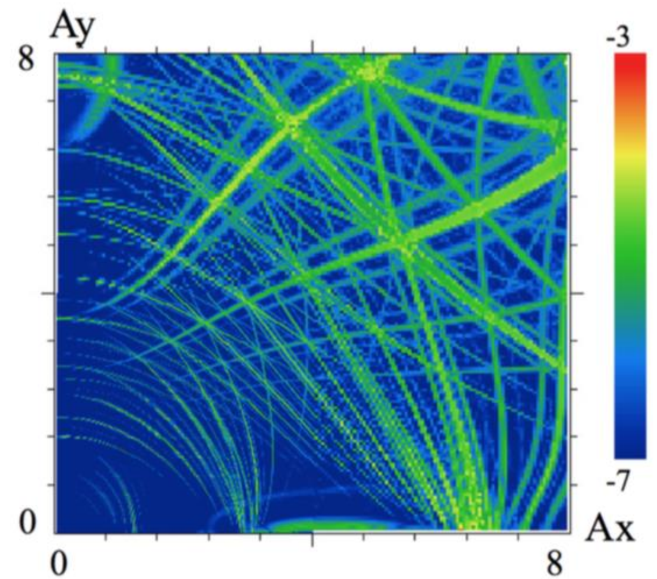
FMA – Round Optics 15/15, Np=2.2×10^{11}

590 µrad

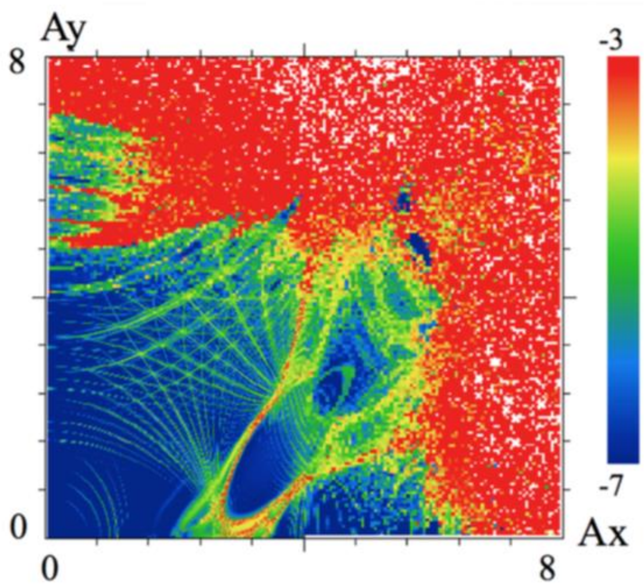


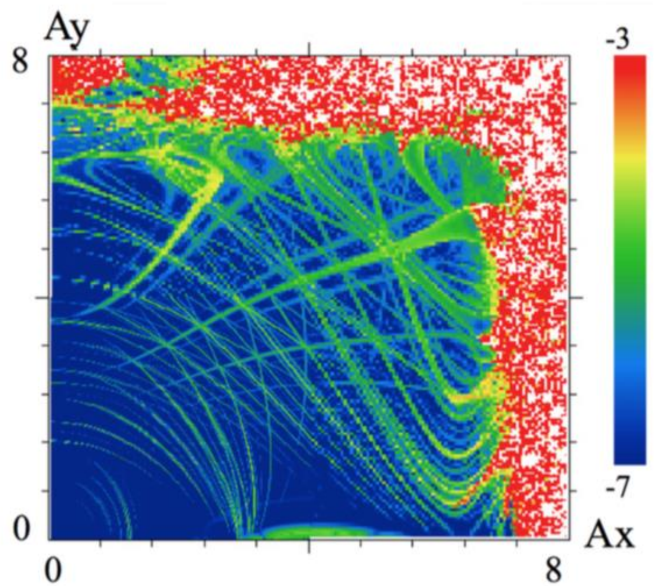


No correction

With correction

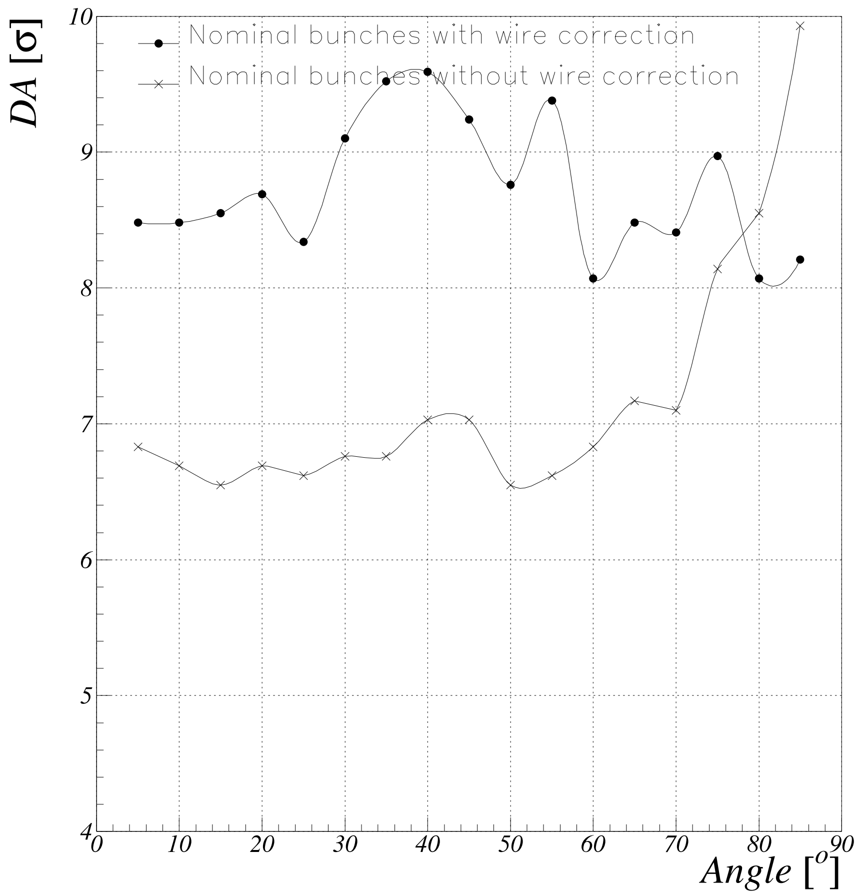
450 µrad



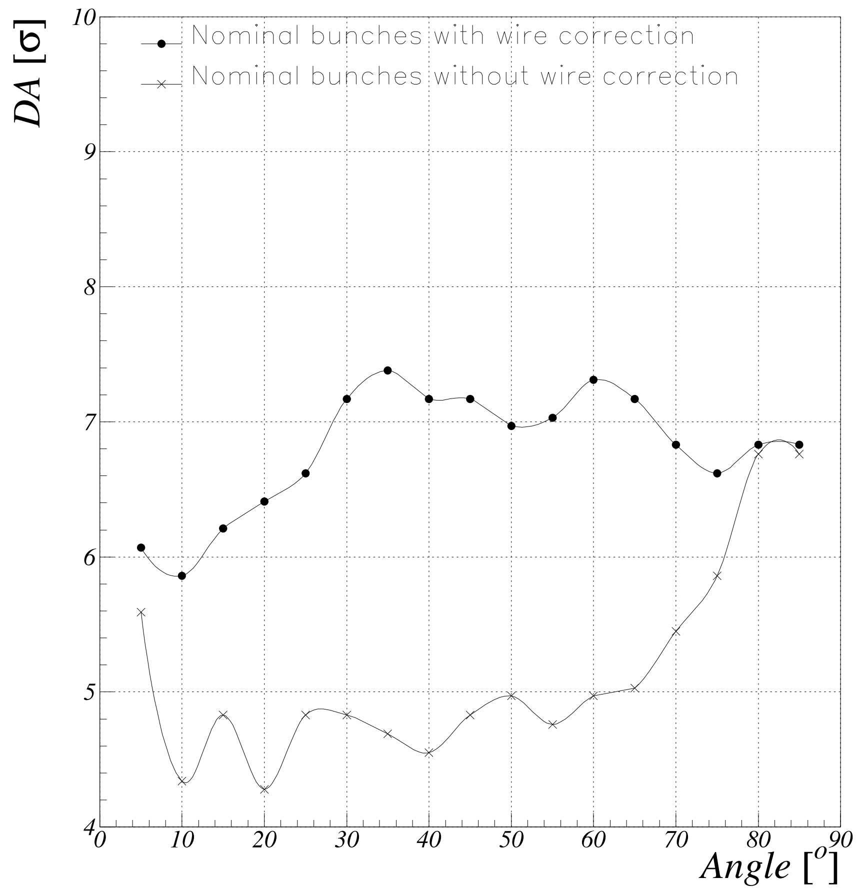


Dynamical Aperture – Round Optics
15/15, Np=2.2×10^11

(40)-(04)-(82)-(28) correction



590 µrad



450 µrad

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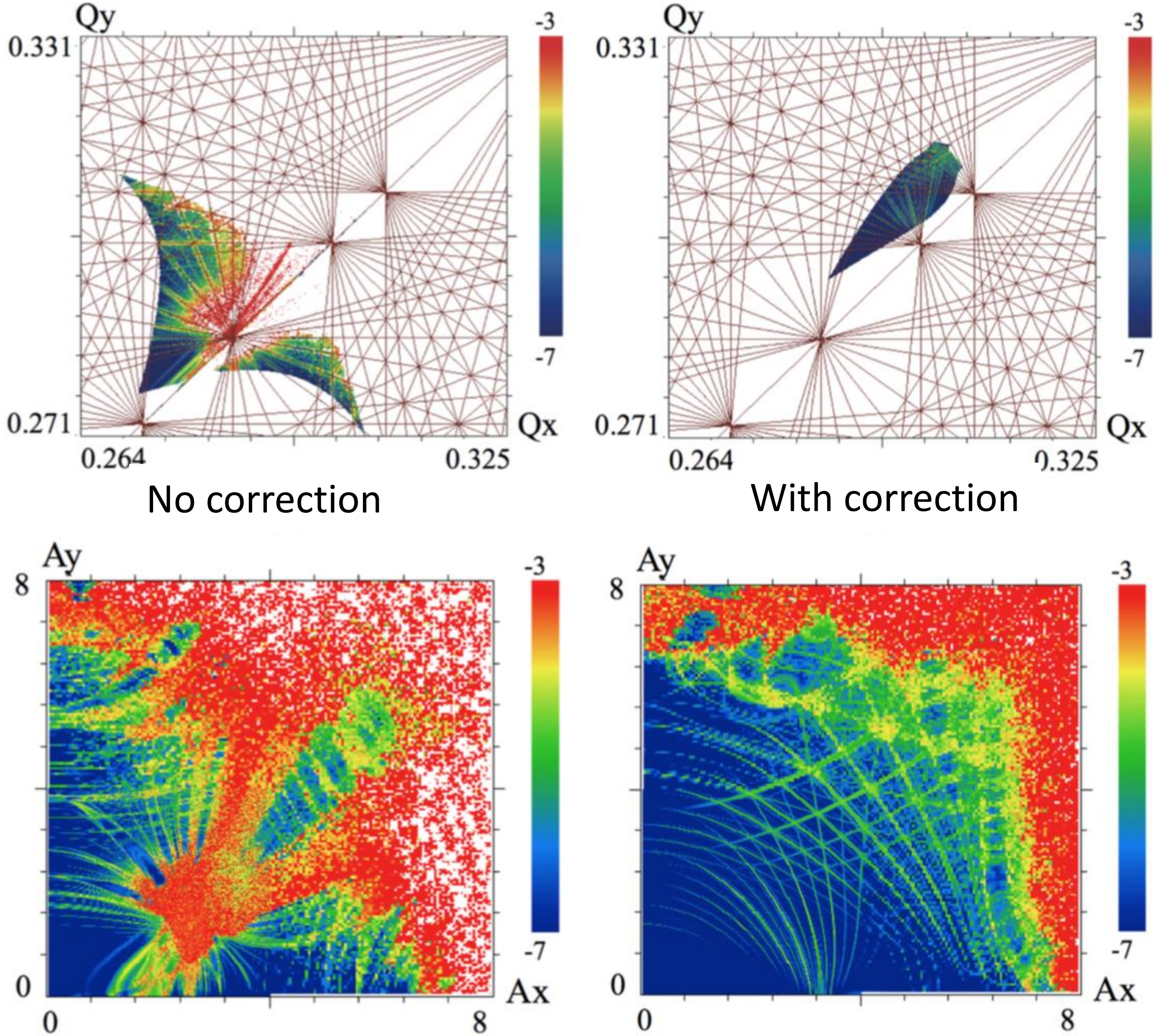
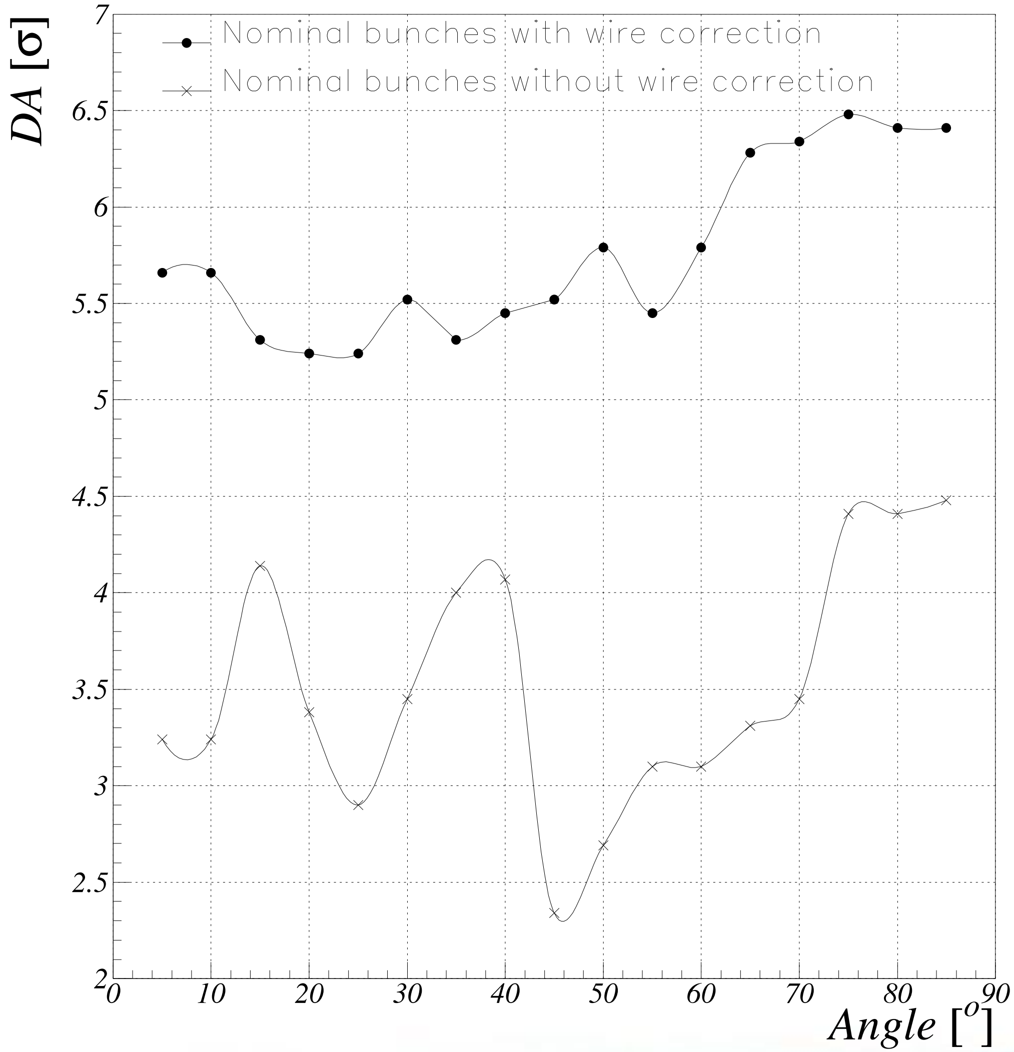
FMA – Flat Optics 10/40, 300μrad, $N_p=2.2\times10^{11}$



Dynamical Aperture - Flat Optics 10/40, 300μrad, Np=2.2×10^{11}

(40)-(04)-(82)-(28) correction

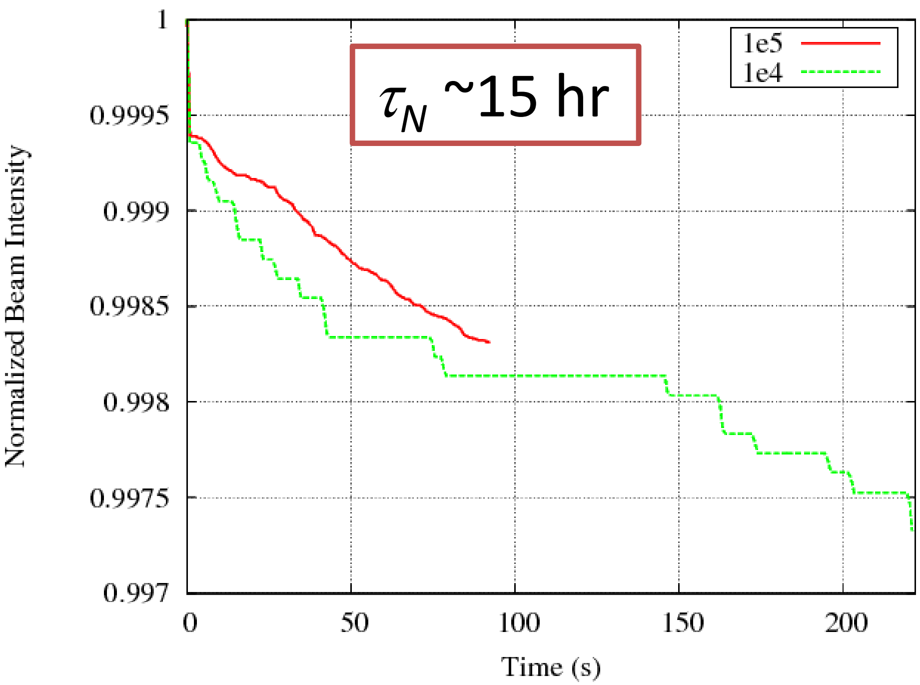


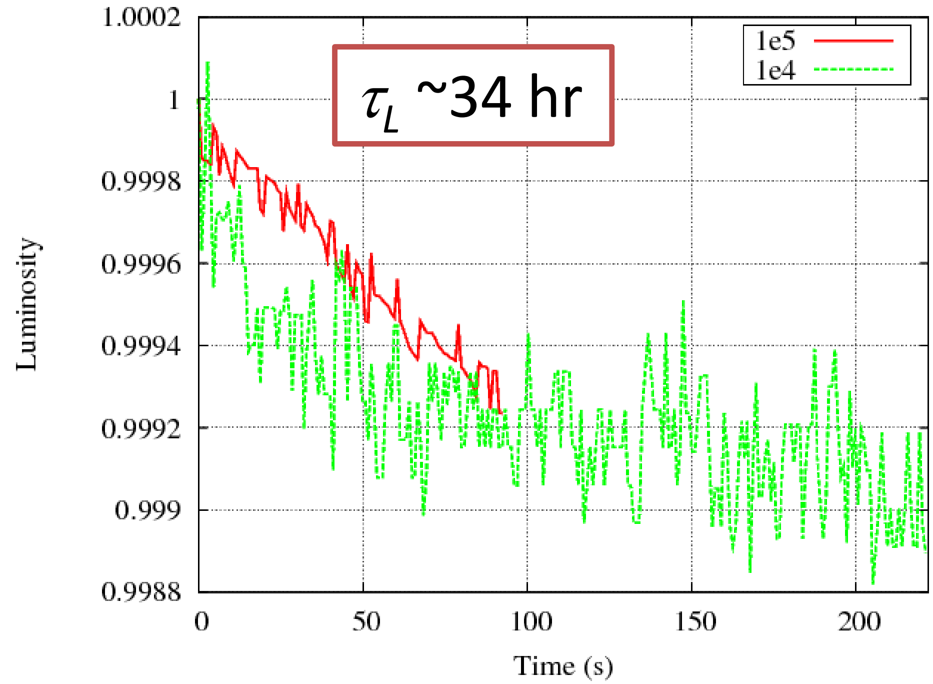
Compensation performance in simulations:

Application to alternative scenario

Macroscopic Beam Parameters
End of Leveling at 5×10^{34}, no compensation

β^* = 40/10cm, x=280 urad
IP8=on, CC=off





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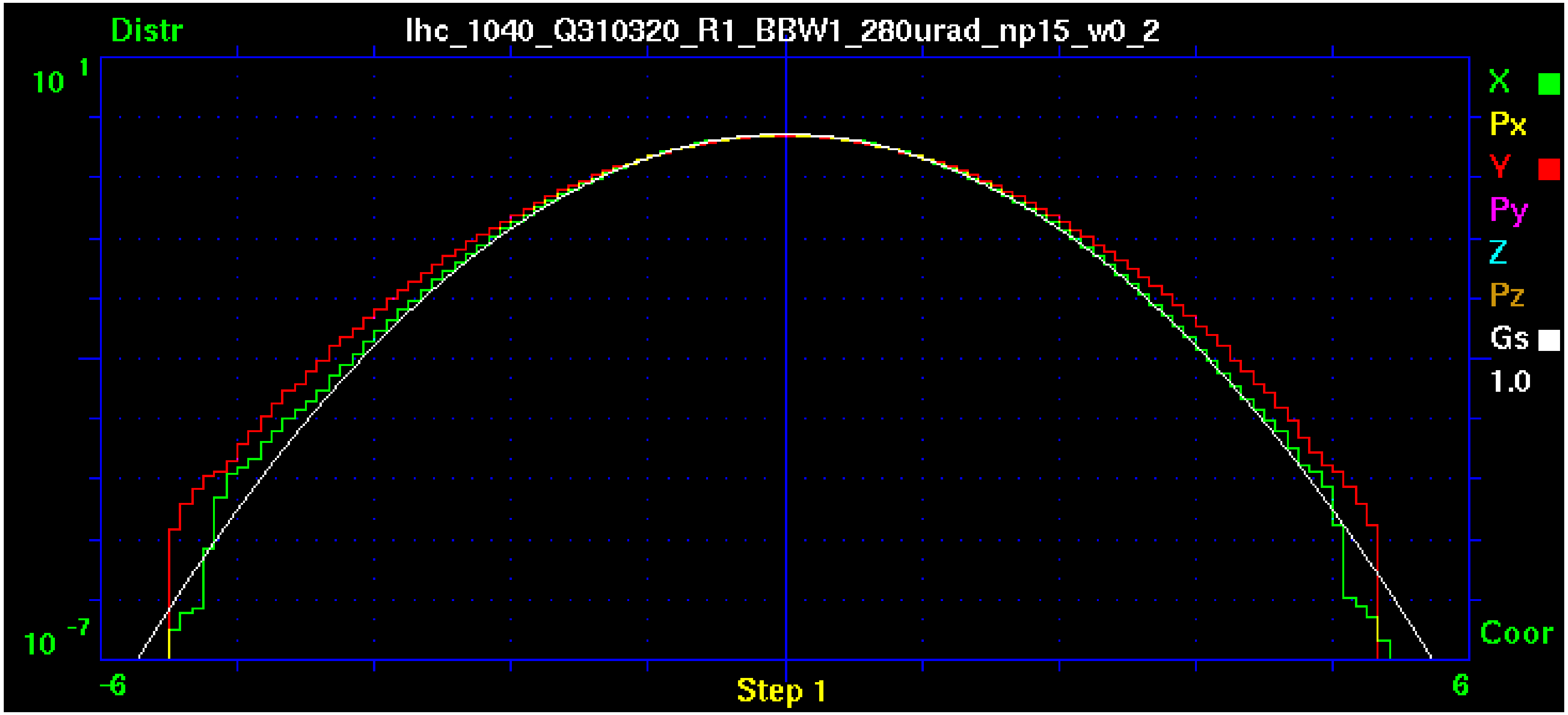
Evolution of Tails, 1E5 particles

β^* = 40/10cm, x=280 urad
IP8=on, CC=off



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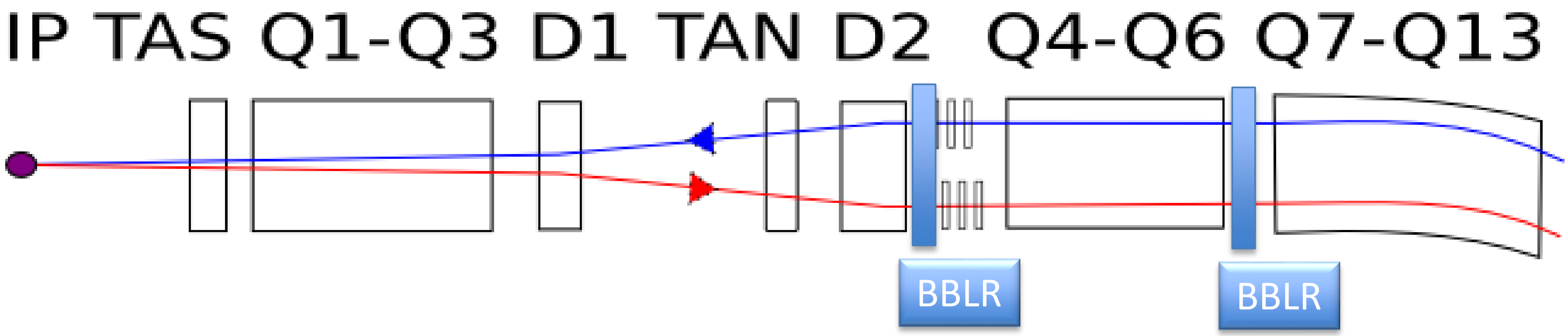
Wire configuration



1. Distance from IR 150 m (r=1, not most optimal)
2. Distance from IR 197 m (r=0.5)

- Minimum distance to beam 9.3 σ
- Current 125 Am (Partial compensation)

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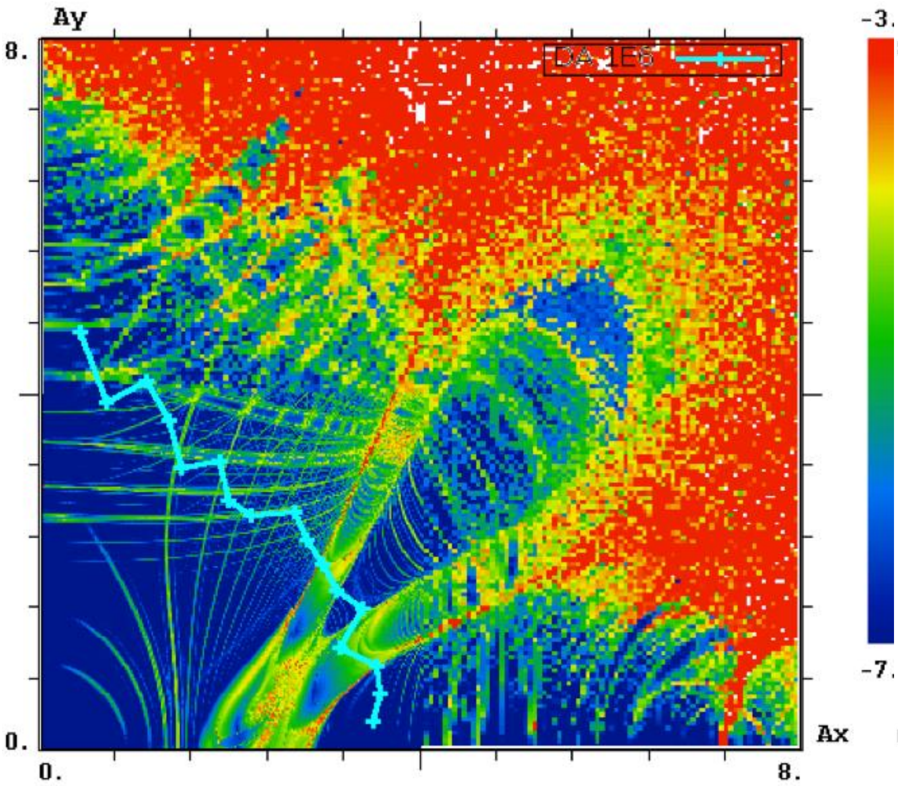
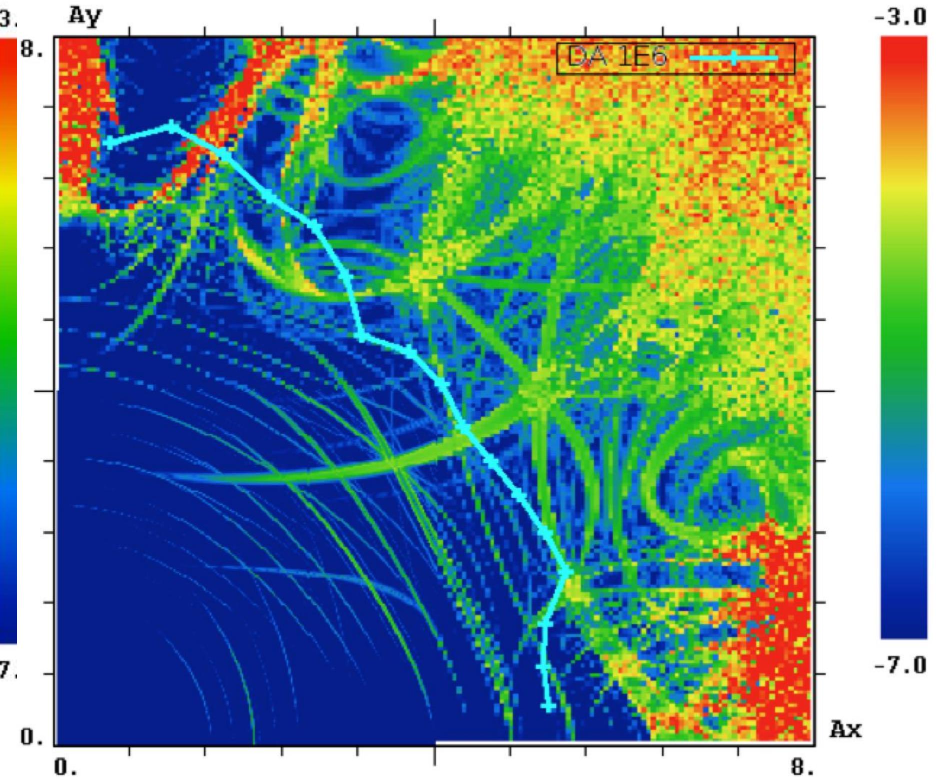
FMA/DA Flat Optics β^*=40/10cm, 280urad, Np=1.5×10^{11} – end of leveling

BBLR=off, DA=3.2



BBLR=on, DA=5.4



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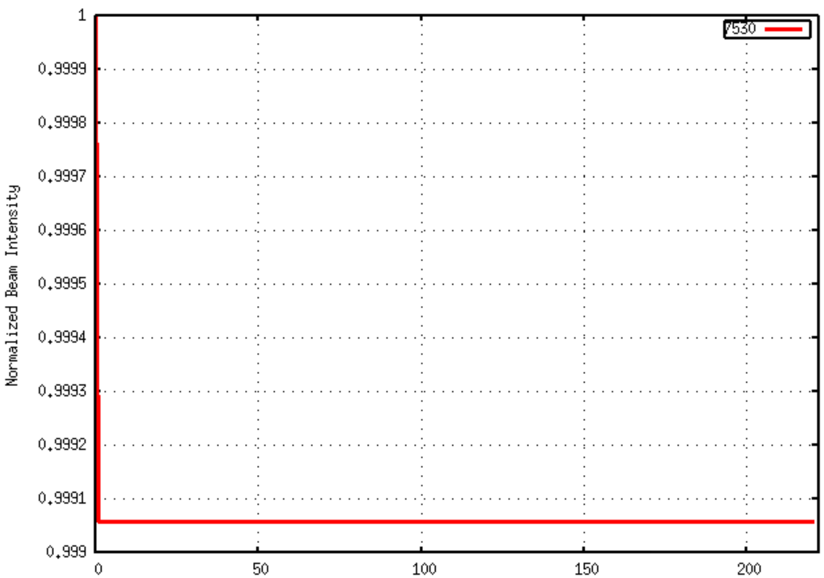
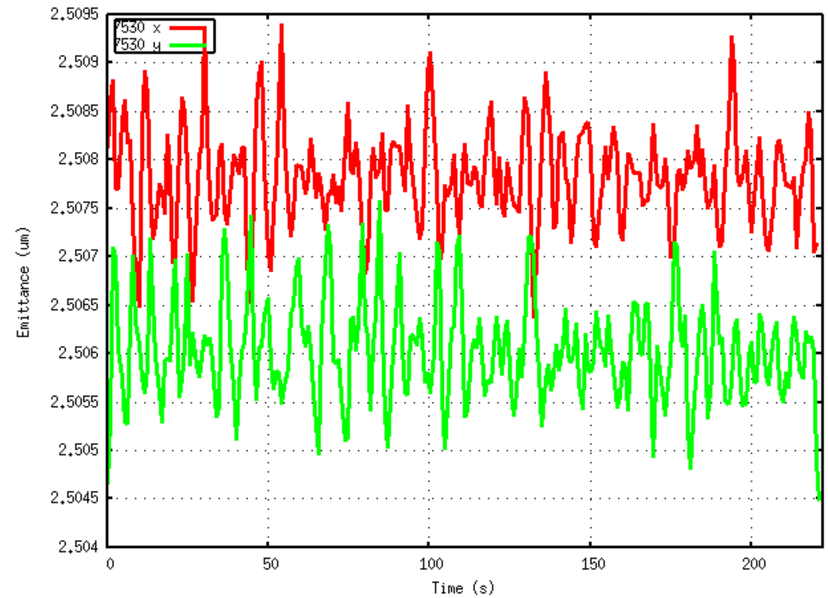
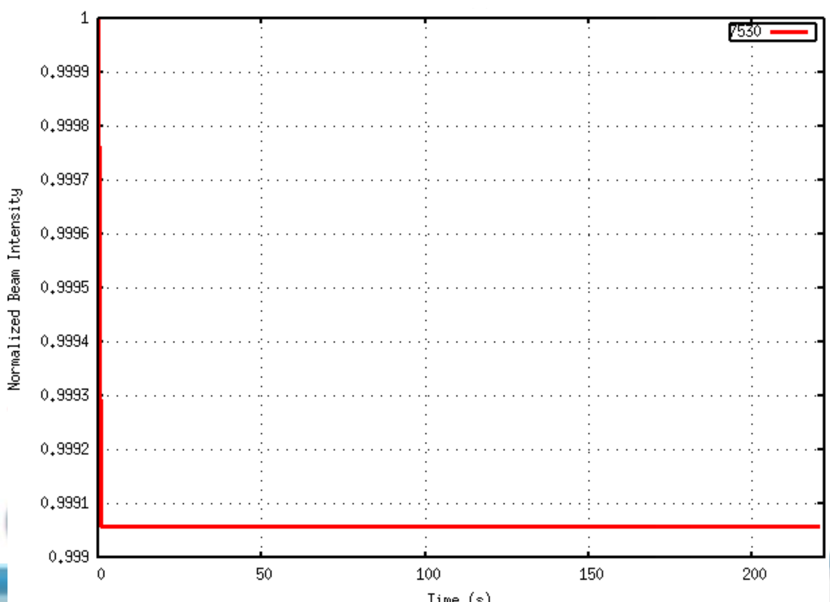
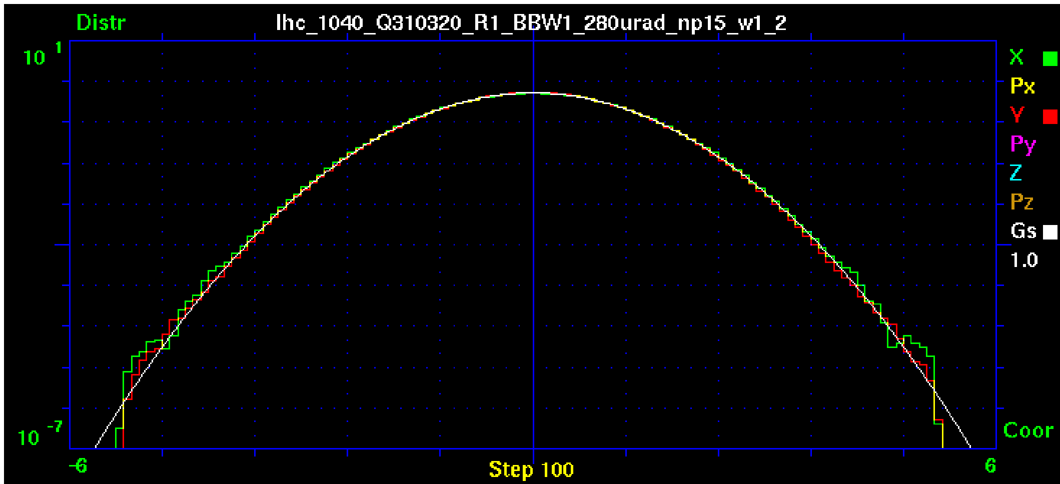
Macroscopic Beam Parameters
End of Leveling at 5×10^{34}, with compensation

β^* = 40/10cm, <u>x=280 urad</u>
IP8=on, CC=off, BBLR=on



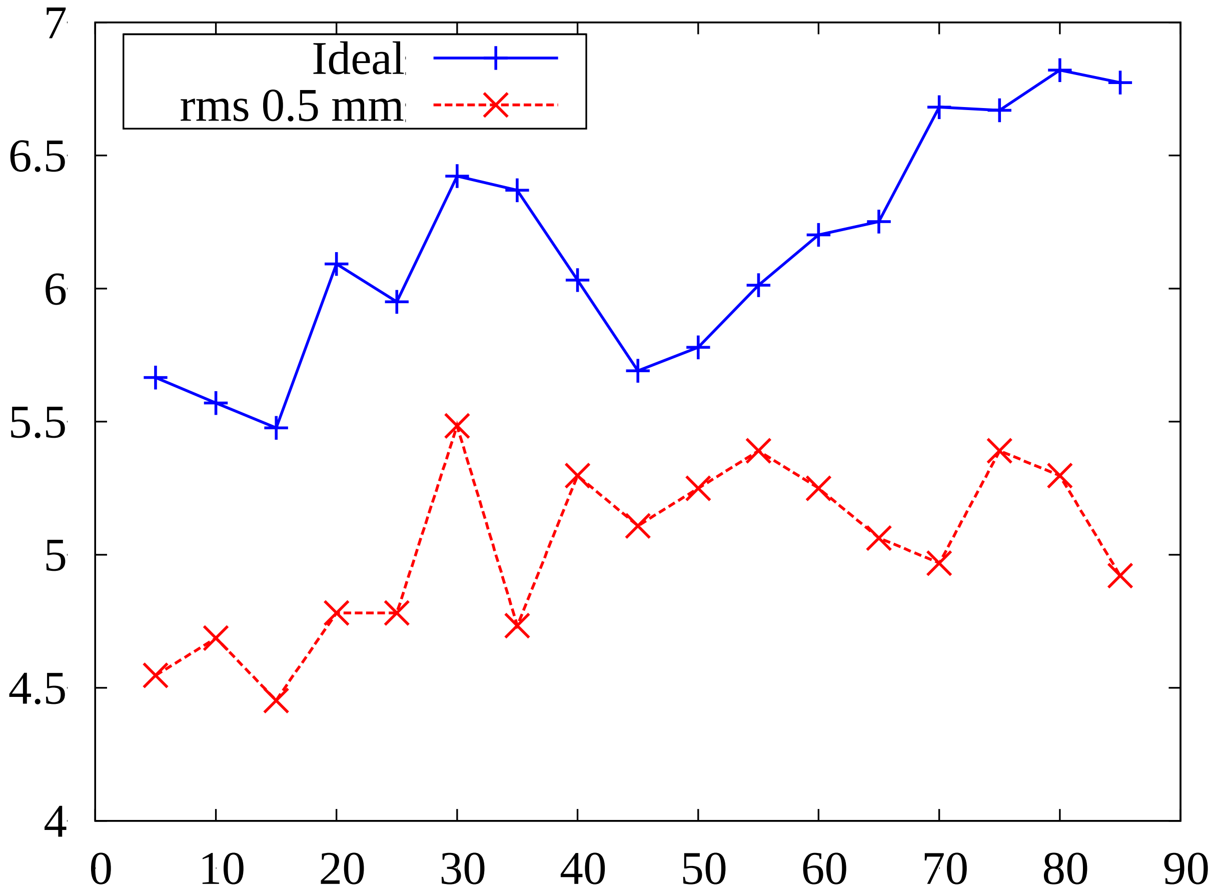






Robustness of compensation

- Wire at r=0.5, distance to beam ~ 3.9 mm
- Alignment errors of 0.5 mm rms in all 4 wires, both x and y



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Summary and Discussion

- Alternative HL-LHC scenario with reduced crossing angle and flat optics to restore performance without CC is feasible with long-range beam-beam compensation
- Wires restore DA from 3 to *almost* 6 sigma at smallest separation of 9.4 at end of fill (worst case, non-optimal wire location). Macroscopic parameter evolution is unaffected by beam-beam
- Wires need to be at 9.3 sigma, a solution with larger distance has not been found
- Wires need to be turned on towards the end of fill, the required current is 125 A×m – good for immaterial wire with E-Lens, would require 20 A×m EL. Benefits:
  - No impedance contribution
  - Can take care of pacman bunches

Summary and Discussion

- In all proposed options wire is at 9-10σ beam, or 7-8σ collimation
- For wire embedded in TCT: wire-jaw=3mm, +10-11σ beam = total distance 14-15σ beam
- A satisfactory compensation with wire at 14σ could not be found
- E-lens wire is a natural solution
  - 125 A·m corresponds to ~20 A·m for 5keV e^- beam. I_{e-}=7A for L=3m

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Backup

Motivation for BBLR in HL-LHC

1. Flat optics + wires

(S. Fartoukh, 5th HL-LHC coordination meeting, 2013)

HL-LHC Plan B without crab cavities

- Implication of flat optics – no mutual compensation of long-range collisions at IP1,5 requires large crossing angle to create 16-17 σ separation.
- Current wires can be used to allow reducing crossing angle and recover geometrical luminosity loss.

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Motivation for BBLR in HL-LHC

2. V-V crossing scheme (S. Fartoukh, F.Cerutti – WP10)

allows strong mitigation of the heat load from the debris produced at the IP and arriving in D2/Q4

- Same as 1 – no mutual compensation of long-range collisions at IP1,5 requires large crossing angle to create 16-17 σ separation.
- Current wires can be used to allow reducing crossing angle and preserve the crab cavity voltage.
- For full flexibility, do we then need to foresee 8 wires per IR (one in each transverse plane, per beam, and per IP side)?

Motivation for BBLR in HL-LHC

3. Flexible tool for overcoming intensity limitations (S. Fartoukh)

wires allow to restore full freedom in the choice of octupole polarity

- minimize the octupole strength and preserve the DA which otherwise may be limited in the ATS (M.Fitterer, 19 Nov. 2014).

Motivation for BBLR in HL-LHC

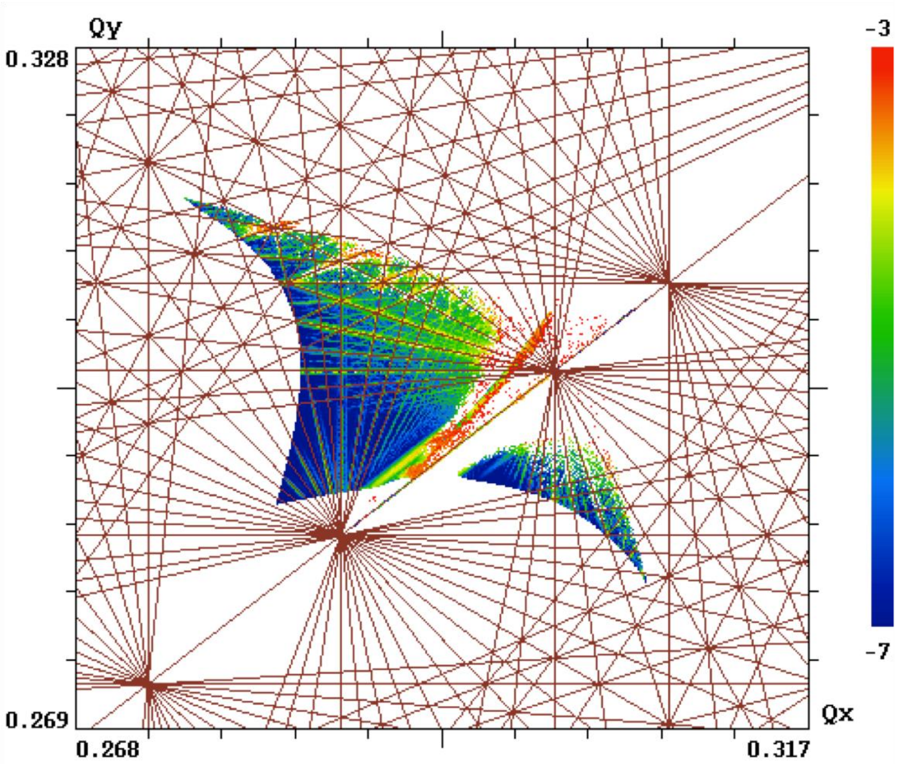
4. Crab-Kissing scheme (S. Fartoukh, Phys. Rev. ST Accel. Beams 17, 111001, 2014)

Together with crab cavities and flat optics, wires are a key ingredient allowing to reduce the pile-up.

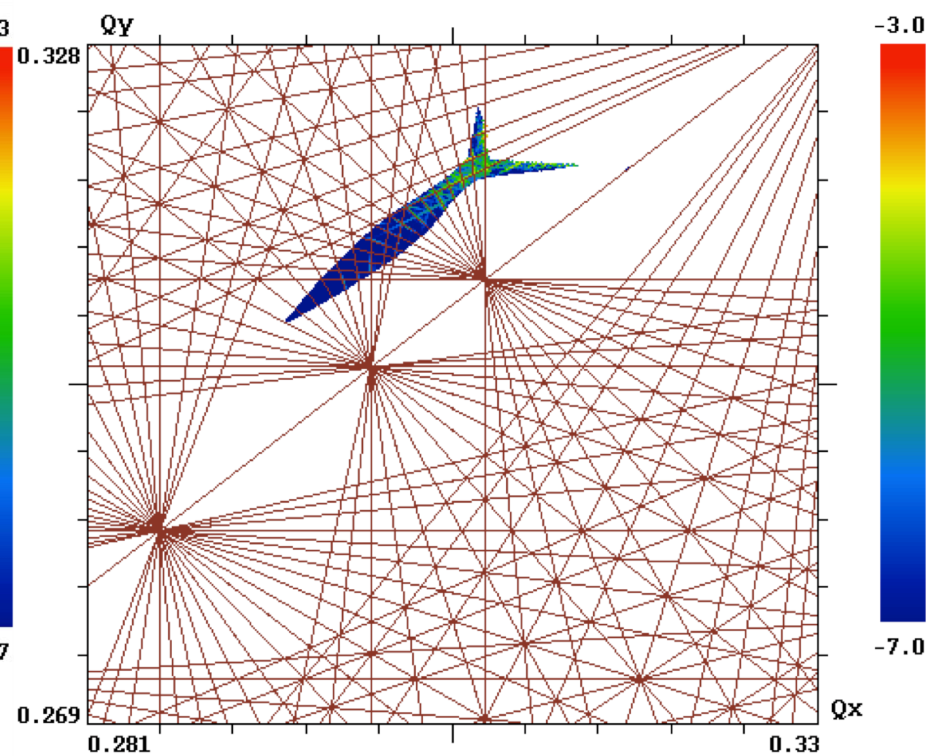
- CK requires crab cavities in two planes.

FMA Flat Optics β^*=40/10cm, 280urad, Np=1.5×10^{11}

BBLR=off



BBLR=on



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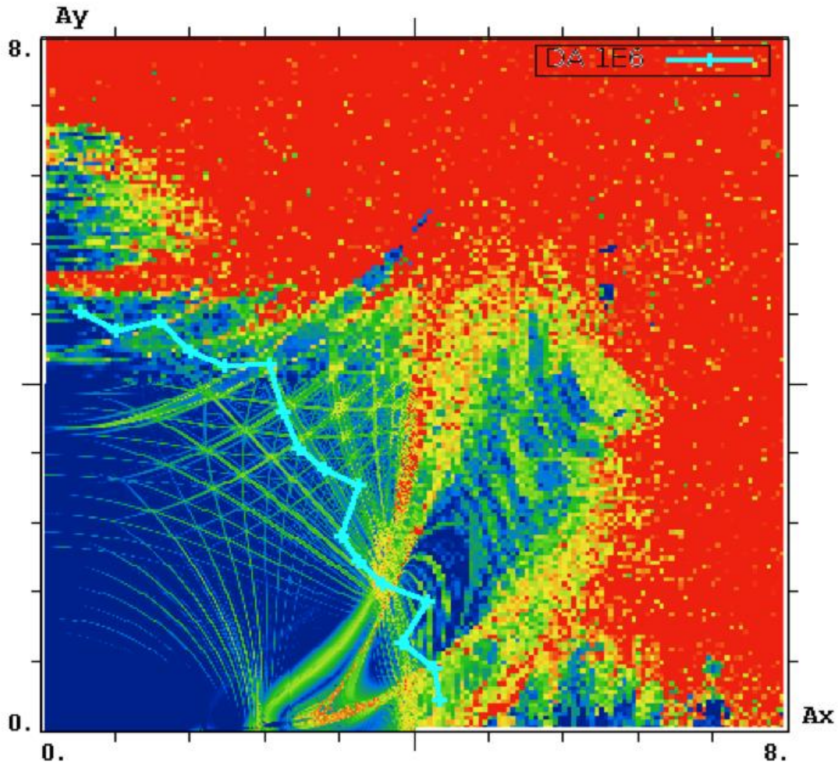
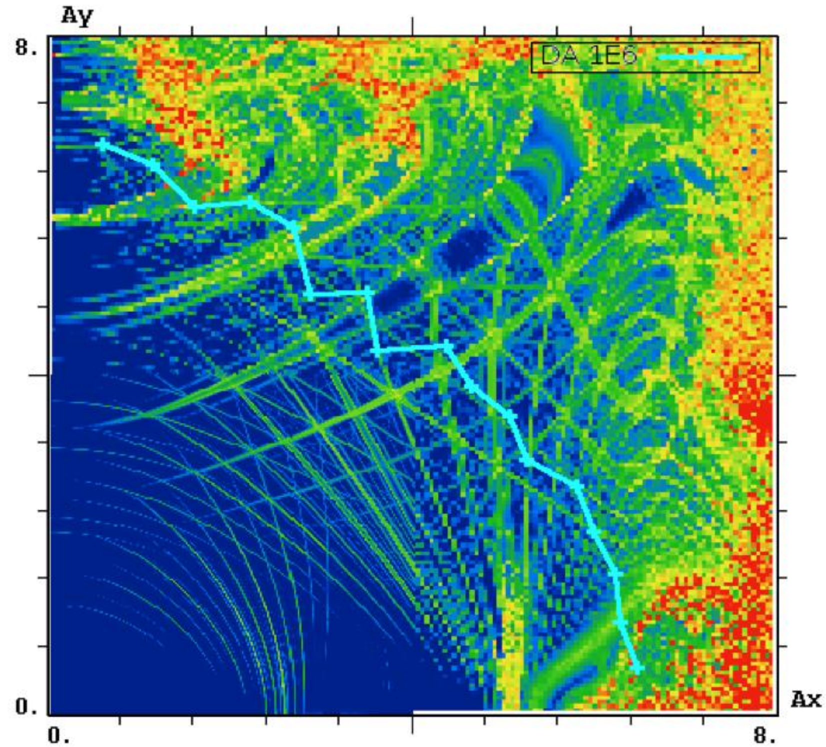
FMA/DA Flat* Optics β*=40/40cm, 280urad, Np=2.2×10^{11} – beginning of leveling

BBLR=off, DA=3.9



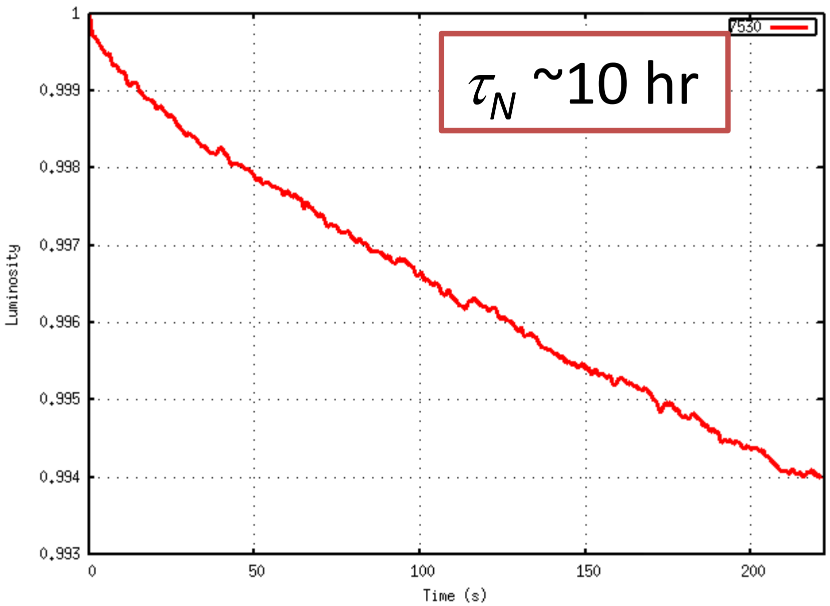
BBLR=on, DA=5.8

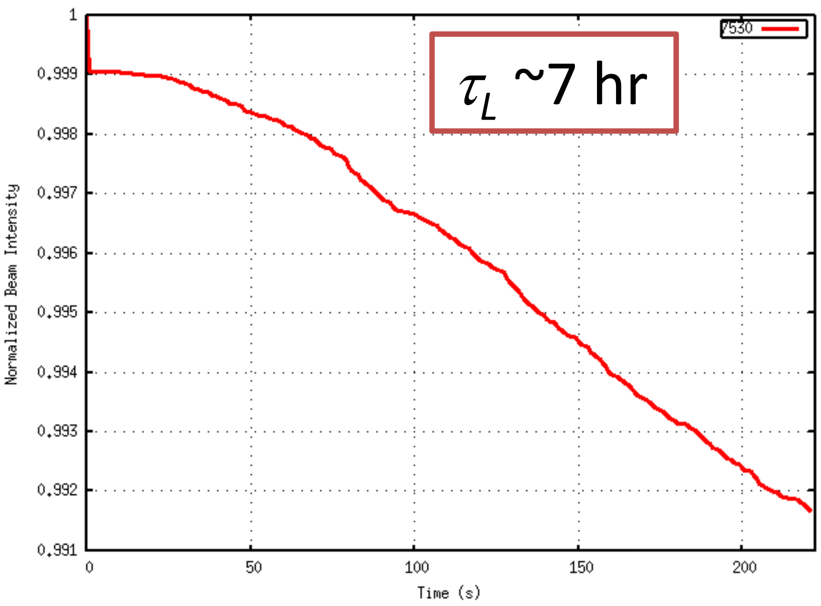


Wire at optimal* distance 10.3σ, PARTIAL COMPENSATION current 125 A×m

Macroscopic Beam Parameters
End of Leveling at 5×10^{34}, no compensation

β^* = 30/7.5cm, x=320 urad
IP8=on, CC=off





Significant degradation of luminosity lifetime (t~10 hr) and DA (3σ) at end of leveling, significant tail growth (1-2 orders of magnitude)

Evolution of Tails

β^* = 30/7.5cm, x=320 urad
IP8=on, CC=off

Code Benchmarking

Computer code validation against DAΦNE data

- In 2005, simulations with Lifetrac were used to justify the wire installation and *qualitatively* predict performance
- We used the latest version with the full account of machine detail and the latest simulation tools to reproduce the experimental data *quantitatively*

DAFNE Lifetime Optimization with BBLR

- C. Milardi, D. Alesini, M.A. Preger, P. Raimondi, M. Zobov, D. Shatilov, http://arxiv.org/abs/0803.1544 (2008)
  - … During the operation for the KLOE experiment two such wires have been installed at both ends of the interaction region. They **produced a relevant improvement in the lifetime of the weak beam (positrons) at the maximum current of the strong one (electrons) without luminosity loss, in agreement with the numerical predictions**.

The only demonstration of long-range compensation with wires in collider operations.

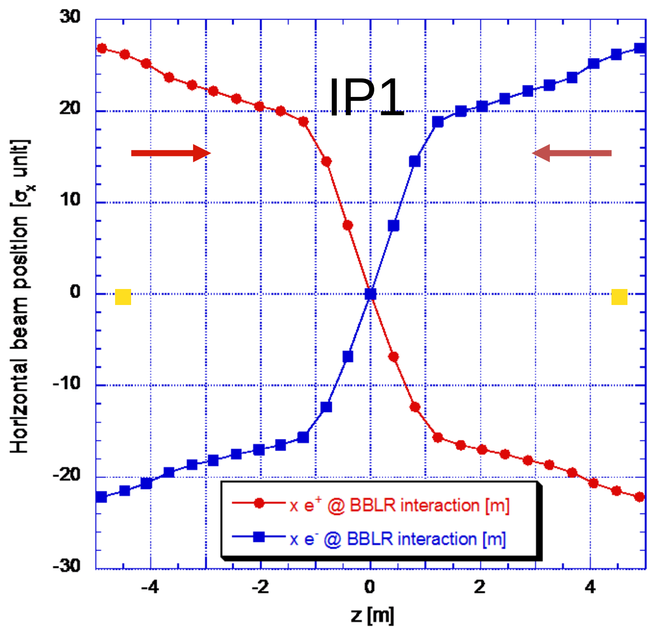
Slide courtesy C.Milardi

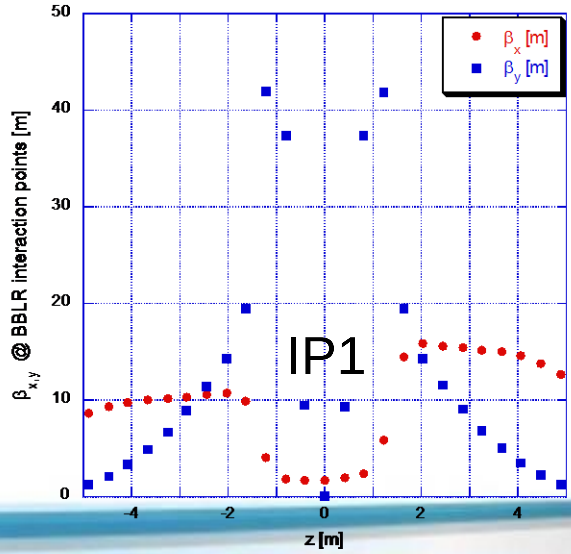
Parasitic Crossings in the DAΦNE IR1

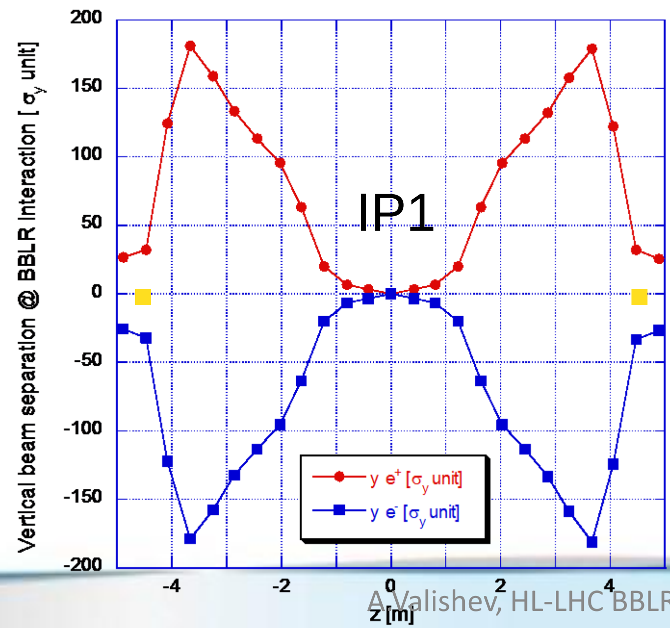
In the DAFNE IRs the beams experience 24 Long Range Beam Beam interactions

Parameters for the Pcs, one every four, in IR1 .

PC order	$Z-Z_{IP}$ [m]	b_x [m]	b_y [m]	m_x-m_P	X [s_x]	Y [s_y]
BB12L	-4.884	8.599	1.210	0.167230	26.9050	26.238
BB8L	-3.256	10.177	6.710	0.140340	22.8540	159.05
BB4L	-1.628	9.819	19.416	0.115570	19.9720	63.176
BB1L	-0.407	1.639	9.426	0.038993	7.5209	3.5649
IP1	0.000	1.709	0.018	0.000000	0.0000	0.0000
BB1S	0.407	1.966	9.381	0.035538	-6.8666	3.5734
BB4S	1.628	14.447	19.404	0.092140	-16.4650	63.196
BB8S	3.256	15.194	6.823	0.108810	-18.7050	157.74
BB12S	4.884	12.647	1.281	0.126920	-22.1880	25.505







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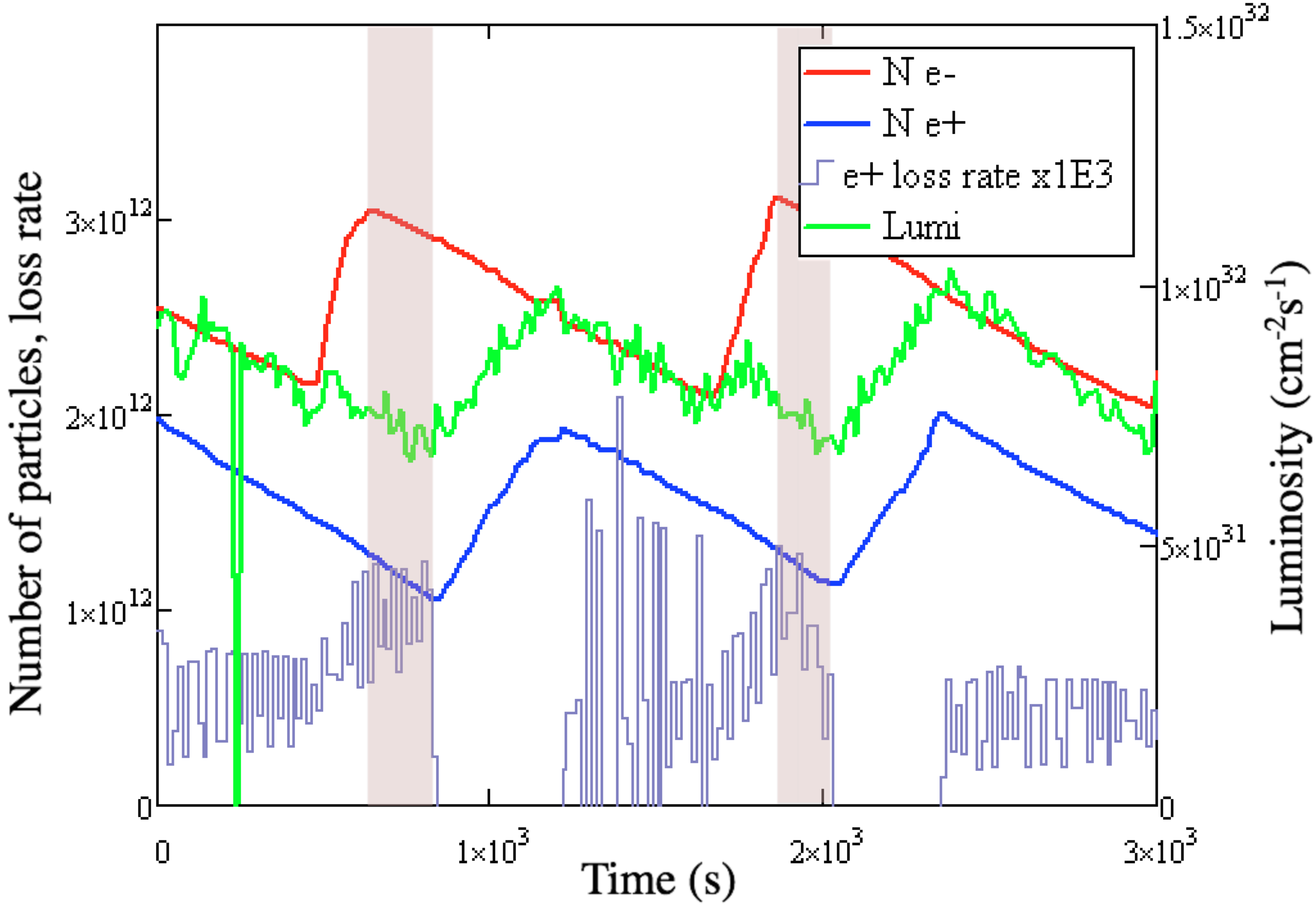
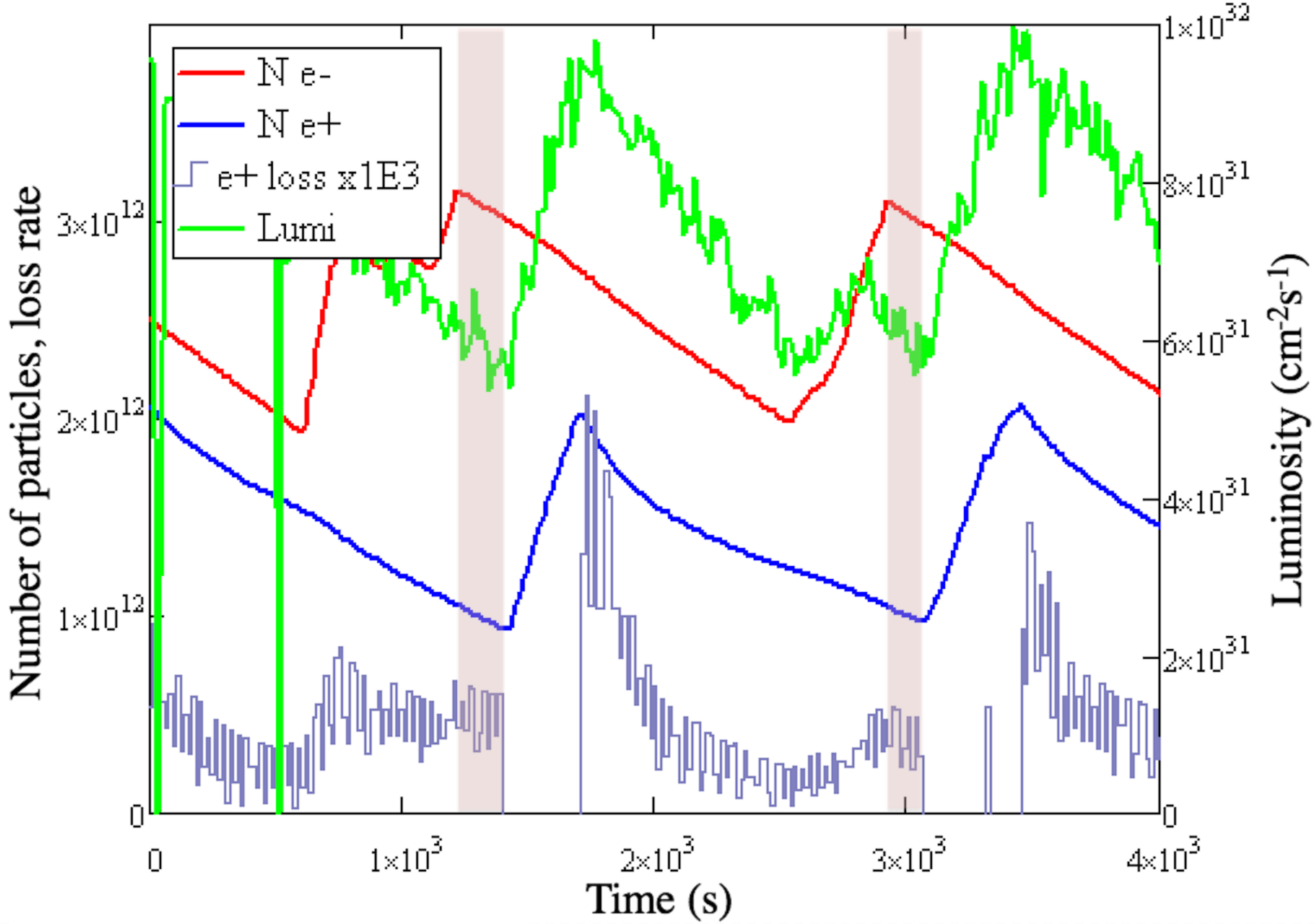
Reduction of Experimental Data



$$\dot{N} = \dot{N}_{Lum} + \dot{N}_{T} + \dot{N}_{BB}$$

WIRES OFF τ_{BB}=1,200 ±175 s

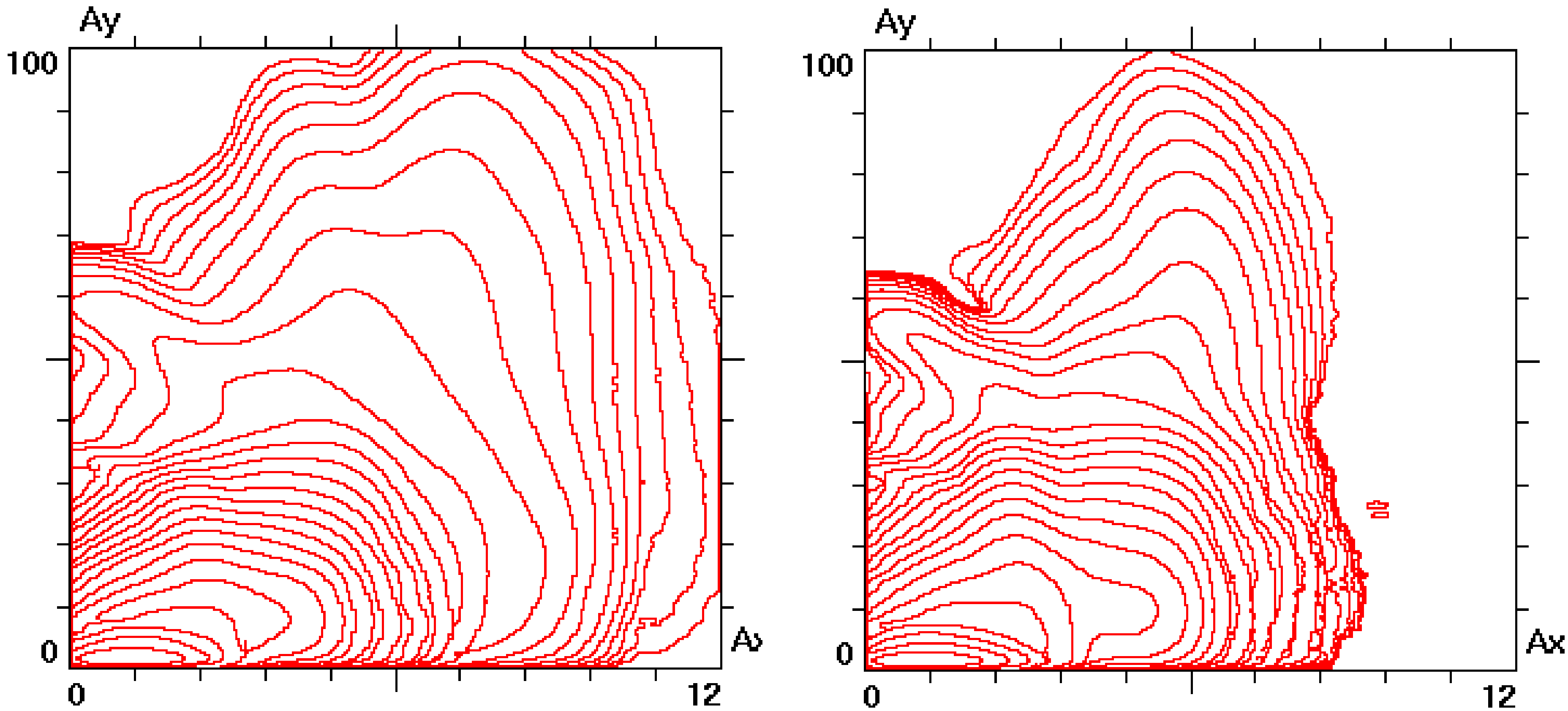
Reduction of Experimental Data



$$\dot{N} = \dot{N}_{Lum} + \dot{N}_{T} + \dot{N}_{BB}$$

WIRES ON τ_{BB}=2,000±360 s

Simulation Results

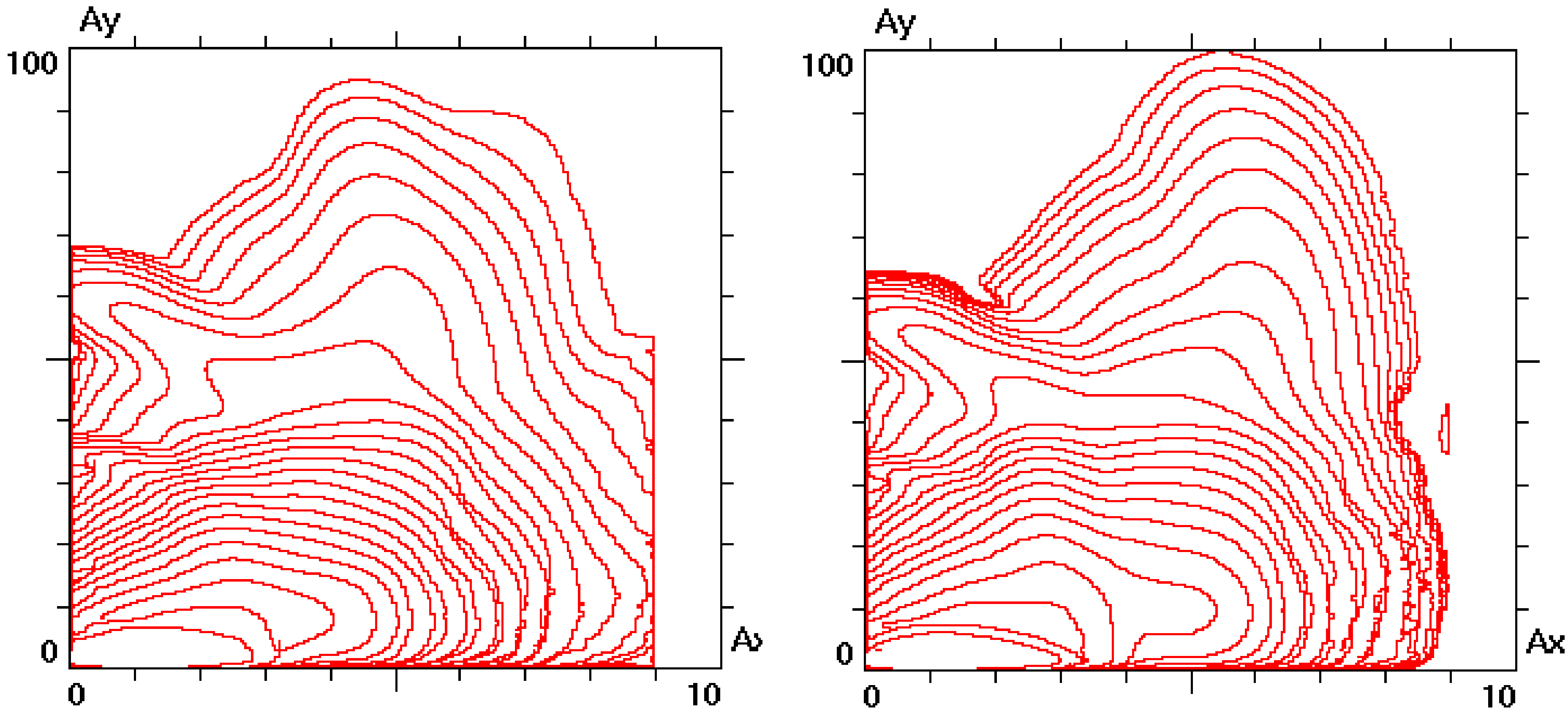


WIRES OFF

H Aperture 12σ

WIRES ON

Simulation Results



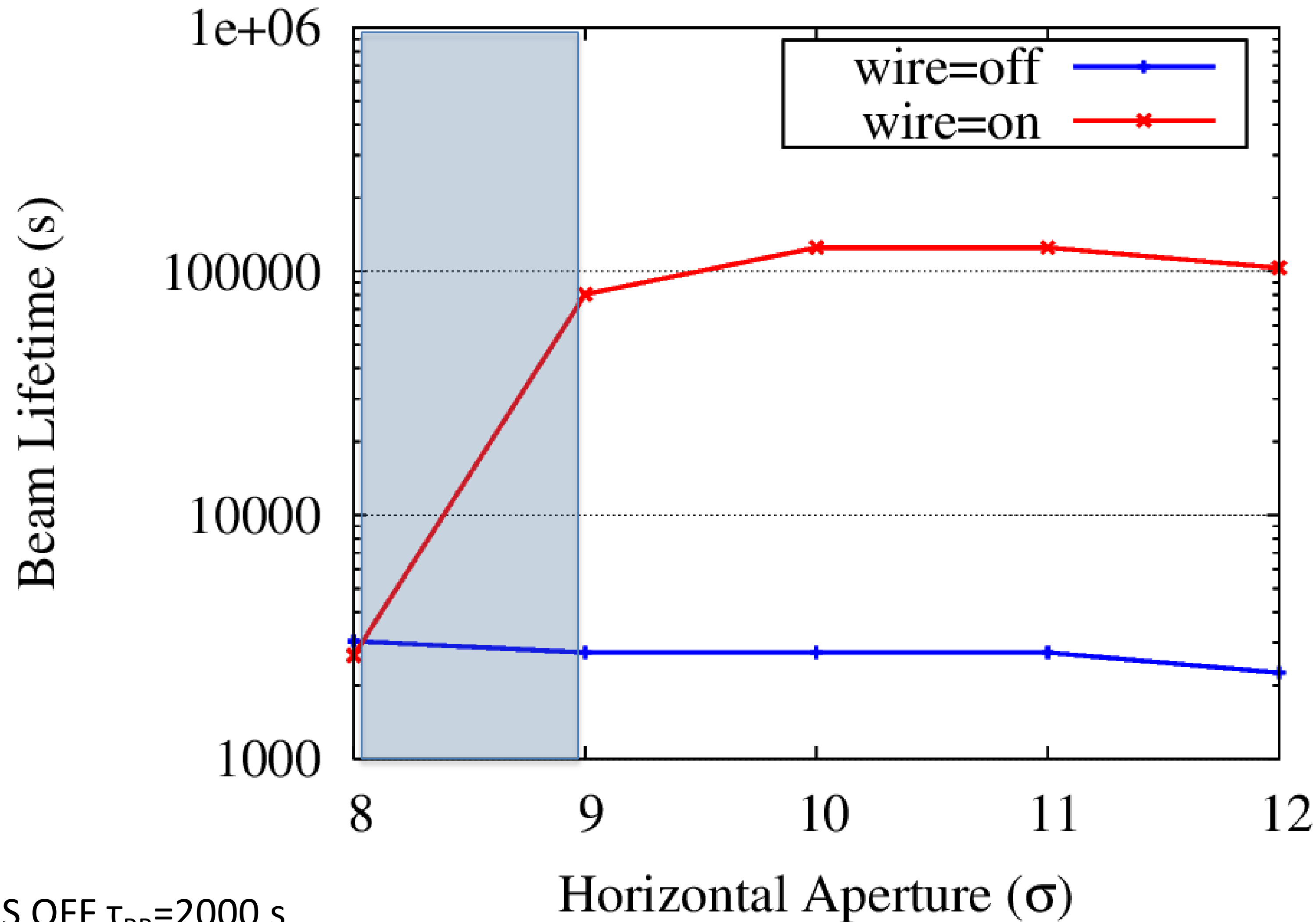
WIRES OFF H Aperture 9σ WIRES ON

LARP

High Luminosity LHC

30 Nov 2015

Simulation Results



WIRES OFF τ_{BB}=2000 s

Lifetrac Simulation Summary

The general conclusions of 2005-2006 campaign have been reproduced

1. Full machine detail does not change the results
   - in particular strong coupling in the IR due to experimental solenoid
   - sextupoles
2. No effect on specific luminosity from BBLR – in quantitative agreement with experiment
3. Aperture model implemented and lifetime effect reproduced quantitatively

In April 2015, Lifetrac simulation was used to guide machine development, which resulted in performance increase

(M.Zobov et al., IPAC-2015)