Hollow Electron Beam Collimation for HL-LHC - Effects on the Beam Core

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In partnership with:

Outline

- Active halo control for collimation:
  - What is active halo control?
  - Why do we need active halo control for HL-LHC?
- Electron lenses:
  - What is an e-lens and what can it be used for?
  - Hollow electron lenses at the LHC
- Effects of the HEL on the beam core:
  - Sources
  - Experimental Results
- Summary

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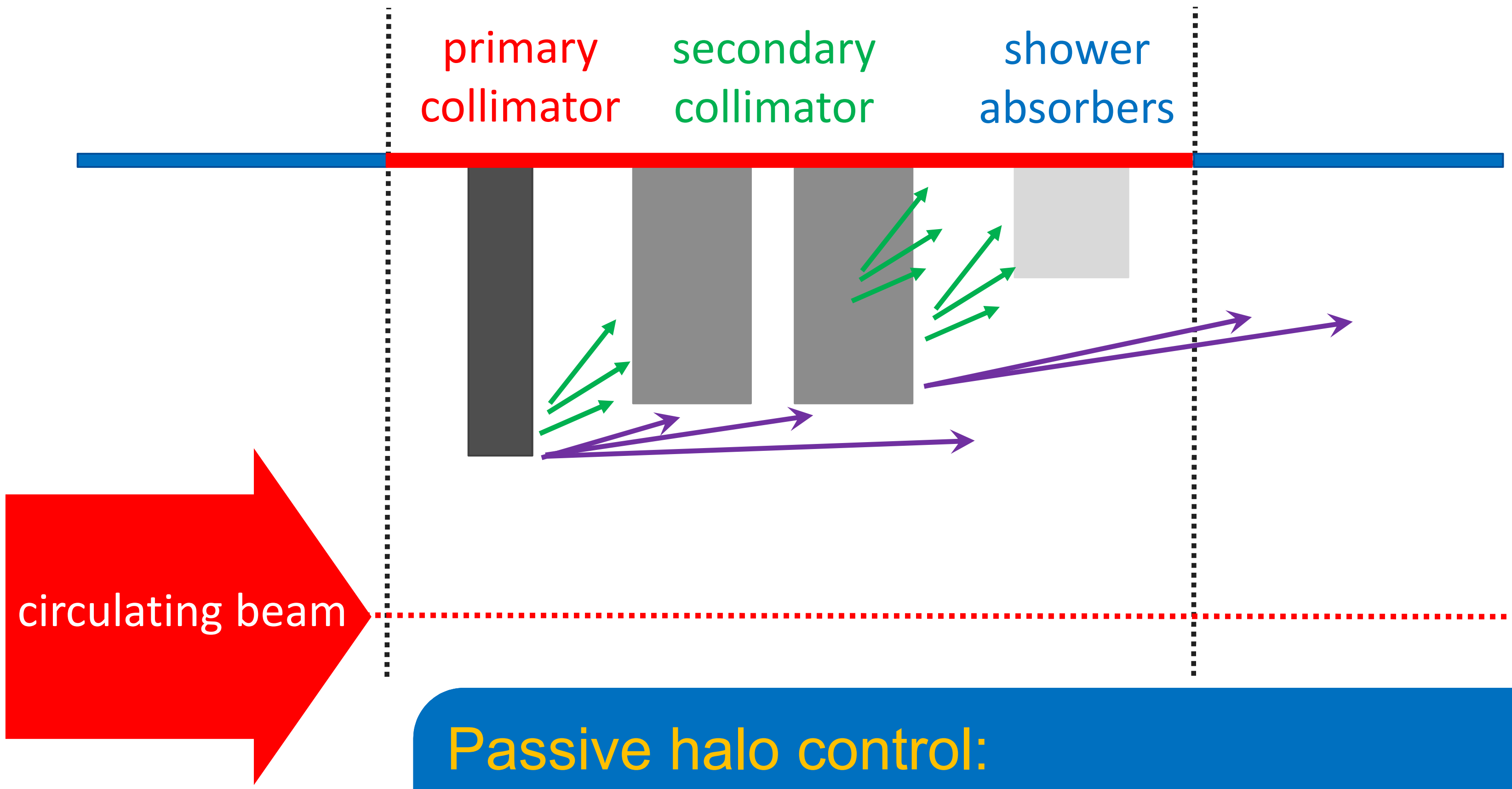
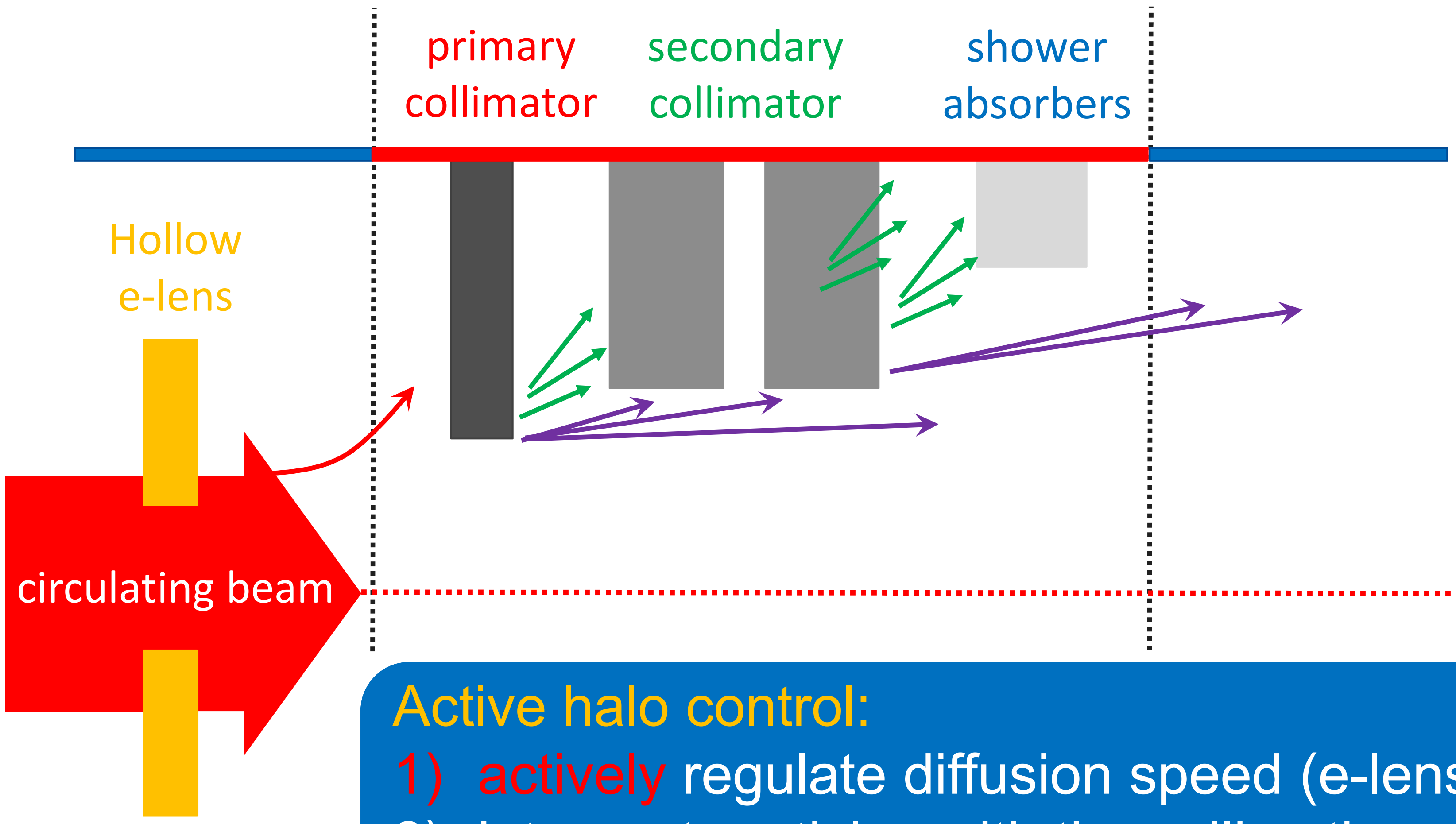
What is active halo control?



Passive halo control:

1) intercept particles with the collimation system

What is active halo control?



Active halo control:

1) actively regulate diffusion speed (e-lens)
2) intercept particles with the collimation system

Why do we need active halo control in the HL-LHC?

=> protect the machine + gain margin and flexibility

- HL-LHC represents a leap in stored beam energy

	Tevatron	LHC 2016	LHC nominal	HL-LHC
Stored beam energy	2 MJ	250 MJ	362 MJ	692 MJ

- LHC beam tails are over-populated:
  - around 5% of the beam is in the tails (>3.5 σ) compared to 0.22% for Gaussian
  - scaling to HL-LHC parameters = **33.6 MJ vs 1.48 MJ**

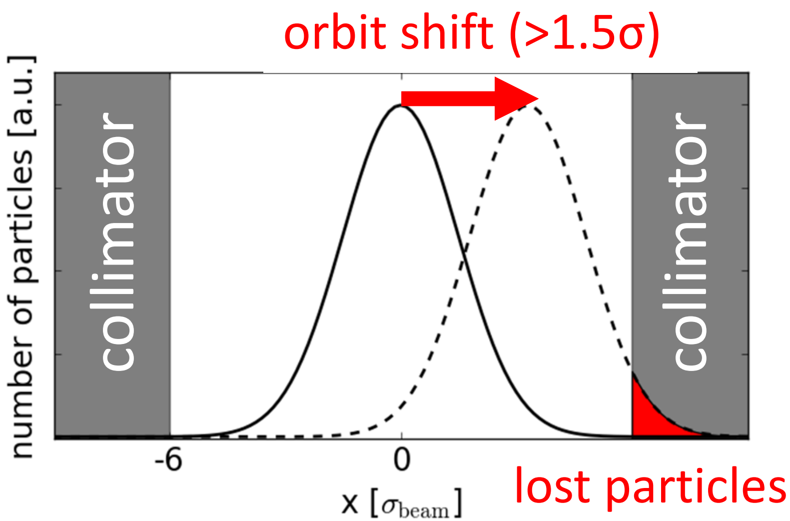
≈15 x Tevatron beam

… for more details see review on the "Needs for a hollow e-lens for the HL-LHC"

Why do we need active halo control in the LHC?

- crab cavity failure can induce fast (few turns) orbit shift

  => Quench limits, magnet damage, or even collimator deformation



- small earthquakes (Geothermie2020)
- in 2012 and 2016 LHC operation sometimes sudden beam losses occurred => beam dumps in HL-LHC?

  => shorter fill length => less integrated luminosity

- increase of operational margin (e.g. less sensitive to transients)

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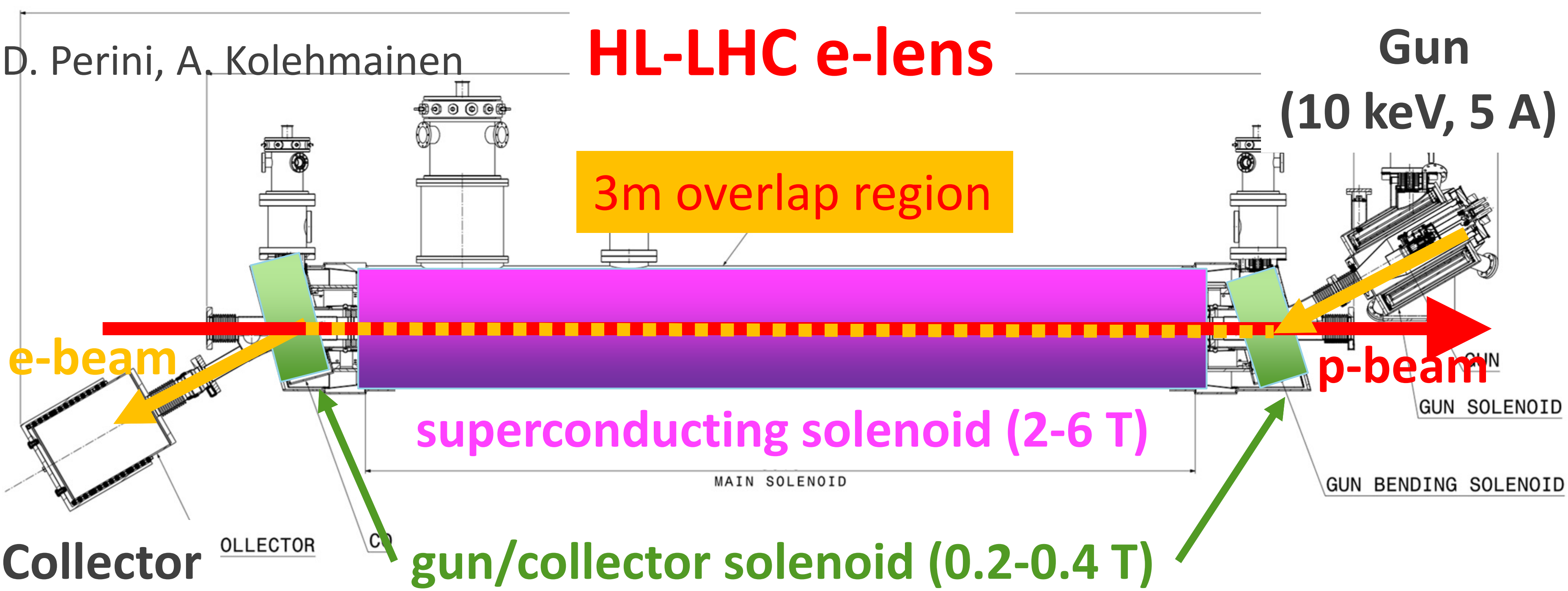
What is an electron lenses?

- DC or pulsed low-energy e-beam
- circulating beam affected by electromagnetic field of e-beam
- e-beam confined and guided by strong solenoids



C. Zanoni, WEPVA117

What are electron lenses used for?

In the Fermilab Tevatron Collider:

- **long-range beam-beam** compensation (tune shift of individual bunches);
  Shiltsev et al., Phys. Rev. Lett. ***99****, 244801 (2007)*
- studies of **head-on beam-beam** compensation;
  V. Shiltsev et al., New J. Phys. 10, 043042 (2008), Stancari and Valishev, FERMILAB-CONF-13-046-APC
- demonstration of **halo scraping with hollow electron beams**;
  Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)
- **abort gap cleaning** (for years in regular operation);
  Zhang et al., Phys. Rev. ST Accel. Beams ***11****, 051002 (2008)*

PAST

Presently used in RHIC at BNL for **head-on beam-beam compensation** with significant luminosity improvements
Fischer et al., Phys. Rev. Lett. 115, 264801 (2015)

W. Fischer, TUPVA045

PRESENT

Current areas of research:

- **hollow electron beam collimation** of protons in the LHC;
  Conceptional Design Report, CERN-ACC-2014-0248, FERMILAB-TM-2572-APC
- generation of **nonlinear integrable lattices** in the Fermilab Integrable Optics Test Accelerator
  Nagaitsev, Valishev et al., IPAC'12; Stancari, arXiv:1409.3615, Stancari et al., IPAC'15
- **long-range beam-beam compensation** as current-bearing "wires" in the LHC
  Valishev and Stancari, arXiv:1312.5006; Fartoukh et al., PRSTAB ***18****, 121001 (2015)*
- to **generate tune spread for Landau damping** of instabilities before collisions in the LHC and for the Fermilab Recycler

A. Rossi, TUPVA115

FUTURE

versatile applications depending on e-beam profile + pulsing

Project Status of hollow electron lens for HL-LHC

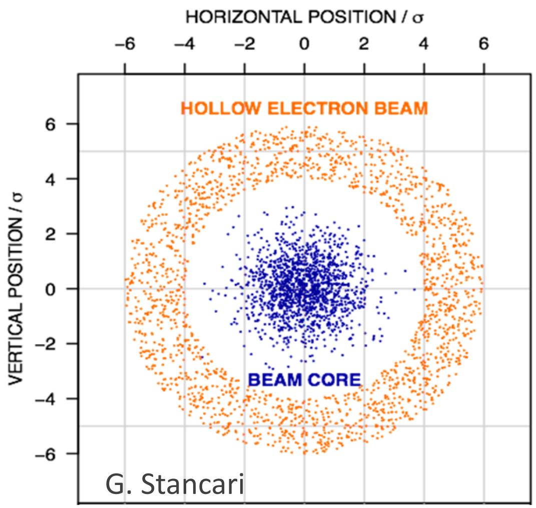
- 2010-2011: first successful experiments with hollow-beam collimation for antiprotons conducted in the Fermilab Tevatron collider
- 2014: conceptual design report for 2 electron lenses (1 per beam) for LHC based on Tevatron TEL2 in 2014 (see CDR [1])
- 2015-now: study of alternative methods for active halo control mostly in experiments at the LHC (transverse damper excitation, tune modulation)
- 2016: Review on the needs of a hollow electron lens for HL-LHC based on operational experience in LHC Run 1 and Run 2 [2]
  - ⇒ clear message that active halo control is needed for HL-LHC
  - ⇒ e-lens is by far the best technology compared to alternative methods
  - ⇒ in process to add hollow electron lens to HL-LHC Baseline

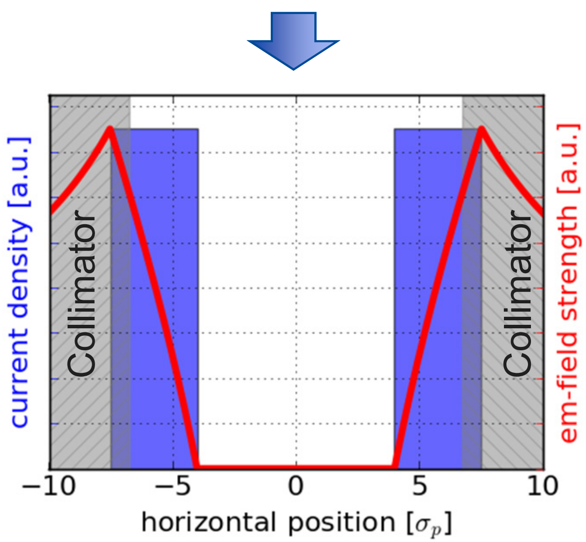
Next steps:

- end of 2017: technical design report (detailed technical design, new hollow e-gun built + tested, study halo/core effects of HEL in detail)
- spring 2018: hollow beam collimation experiments at RHIC with ions
- 2018 Cost&Schedule Review : assessment of cost and decision to add to HL-LHC Baseline

[1] *CDR*, CERN-ACC-2014-0248, FERMILAB-TM-2572-APC, [2] see Indico page "Needs for a hollow e-lens for the HL-LHC"

Hollow electron lenses at the LHC





Principle of hollow e-lens:

- increase of **diffusion** for **halo particles**
- **no effect on core** as HEL acts in amplitude space

⇒ ***active halo control***

Modes of operation:

- DC as ***standard operation*** mode

⇒ *negligible effect on the beam core (to be confirmed)*

- pulsed operation to ***further increase diffusion***:
  - random current modulation
  - switch e-lens on/off every n^{th} turn (drives n^{th} order resonances)

⇒ *e-lens could introduce noise on the p-beam core*

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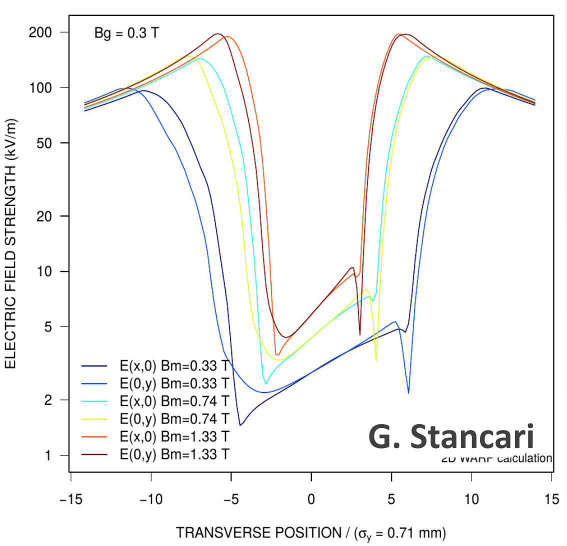
Sources of electromagnetic field at p-beam core:

- imperfections in the e-beam profile
- e-lens bends

⇒ *non-linear kick on beam core*

- kick amplitudes are negligible in DC mode
- are they negligible in pulsed operation (noise)?

⇒ *experiment at LHC (only dipole kick) to derive tolerances in case of pulsed operation*



No HEL installed in LHC, approximate with **dipole kick** for HEL design parameters [1,2,3]:

- imperfections: 15 nrad @ 7TeV
- e-lens bends: 0.5 nrad @ 7TeV

[1] *CDR*, CERN-ACC-2014-0248, FERMILAB-TM-2572-APC , [2] M. Fitterer et al., FERMILAB-TM-2635-AD [3] G. Stancari, FERMILAB-FN-0972-APC

Experiment at the LHC – beam parameters

- first experiment at injection (450 GeV)
- use low intensity bunches in order to reduce emittance growth due to IBS (N_b=0.7x10^{11}, ε_N=2.5 μm => 4.6 %/h emittance growth)
- 48 single bunches:
  - 2x4 references bunches (with+without transverse damper)
  - 5x4 bunches with excitation (with+without transverse damper)
- standard chromaticity and octupole settings to stabilize bunches (I_{oct} = +19.6 A, Q'=15)

- dipole excitation can be applied bunch by bunch with different amplitudes using the transverse damper (ADT)

⇒ *in this first experiment only n^{th} turn pulsing*

… for more details see ColUSM#82

Experiment at the LHC – simulation parameters

- simulation code: Lifetrac

- Gaussian distribution (10^4 macro-particles)
- number of turns = 10^6 (90s real time)
- non-linear machine model (standard machine errors, 1 mm rms orbit, 15 % avg. peak beta-beat)

- excitation amplitude: 120 nrad and 12 nrad

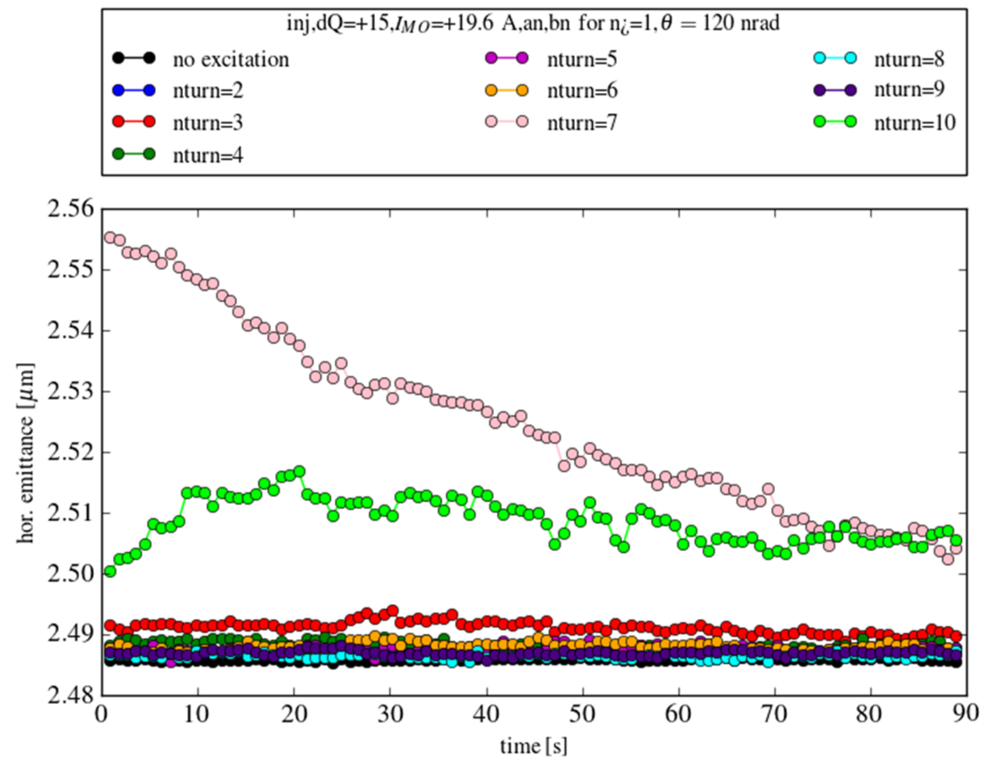
Experiment at the LHC – simulation results

expected kick from HEL: 15 nrad

12 nrad H+V: no effect

120 nrad H+V: strongest effect for 7th and 10th turn pulsing

- losses
- constant or decreasing emittance due to change of transverse distribution over 10^4 turns caused by excitation of resonances



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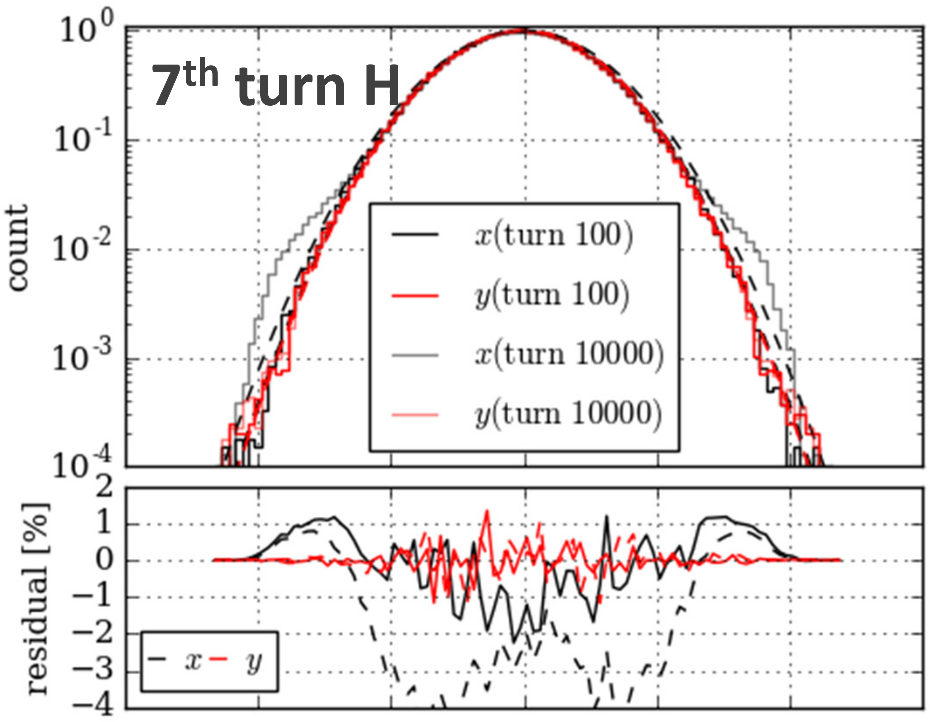
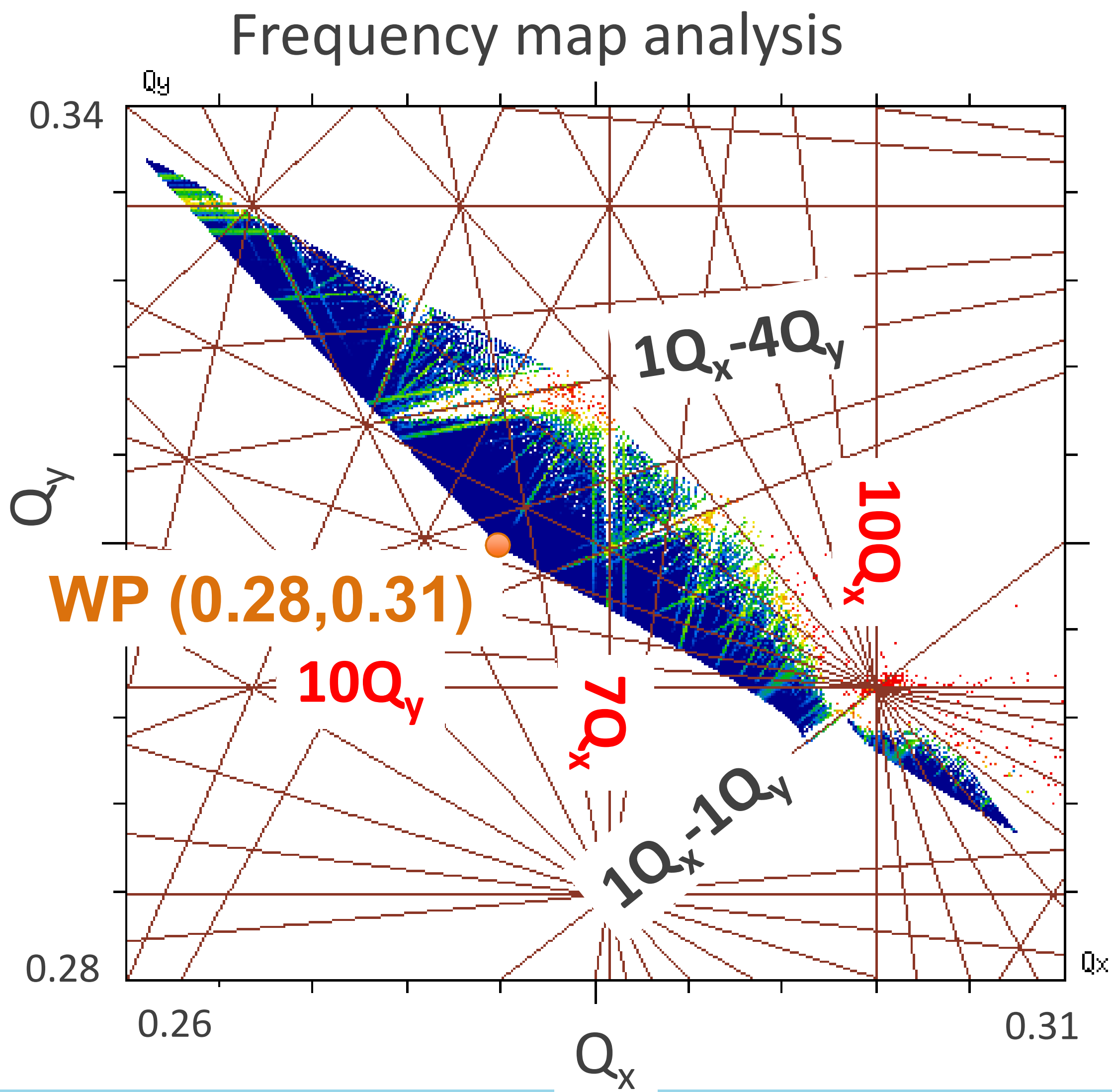


Sensitivity to 7th and 10th order resonances:



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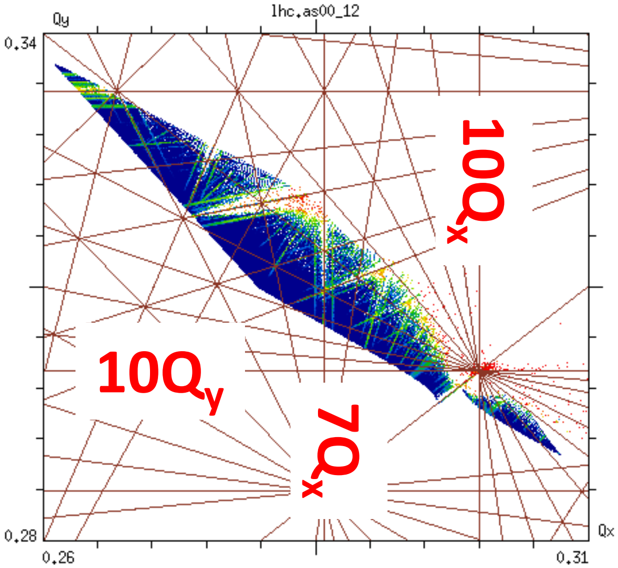
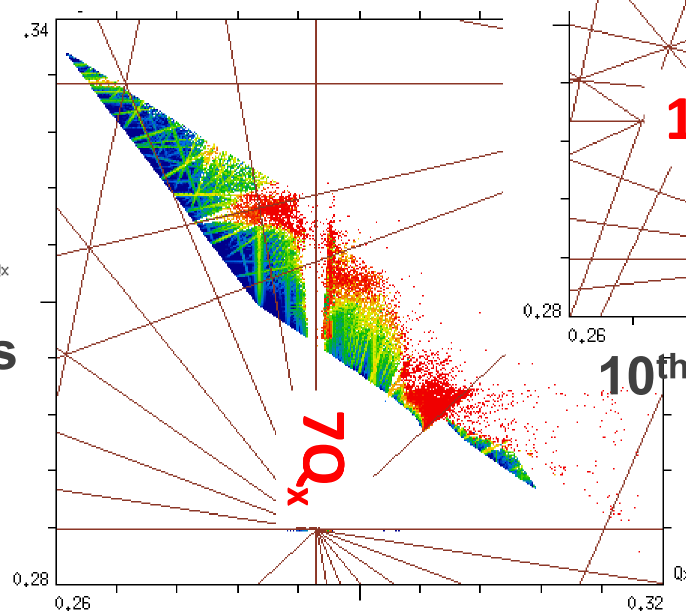
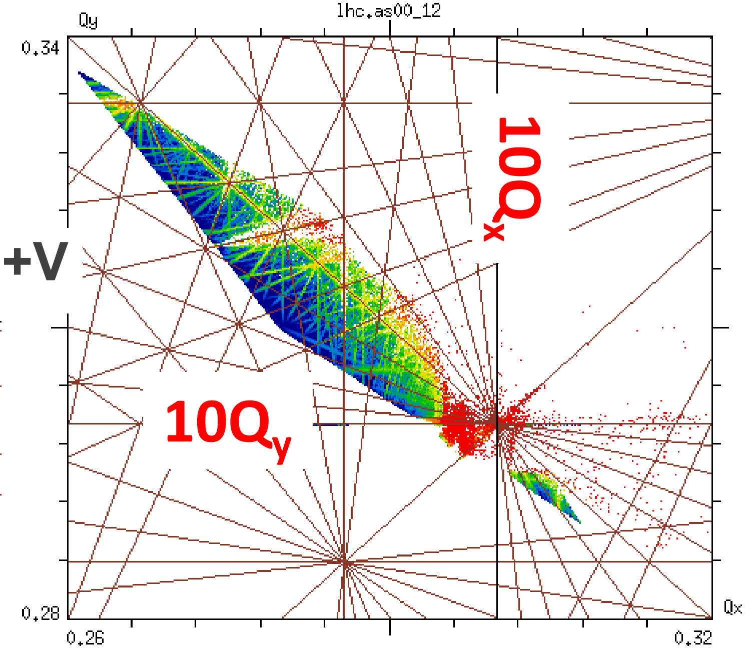


no excitation, no errors

7th turn pulsing H+V





10th turn pulsing H+V

=> efficiency of pulsing patterns can be understood with FMA

Experimental results

expected kick from HEL: 15 nrad

- **10^{th} V pulsing:**
  - small losses (3%/h for 15 nrad)
  - strong emittance growth (43%/h for 15 nrad)
  - change of distribution
- **7^{th} H pulsing:**
  - high losses (10-20%/h for 15 nrad)
  - very small emittance growth (few %/h for 15 nrad)
  - change of distribution (depletion of tails)
- **8^{th} H, 3^{rd} H, 3^{rd} V:** no effect, **but** no conclusion can be drawn as distribution was already too perturbed

Comparison of Simulations and Experiments

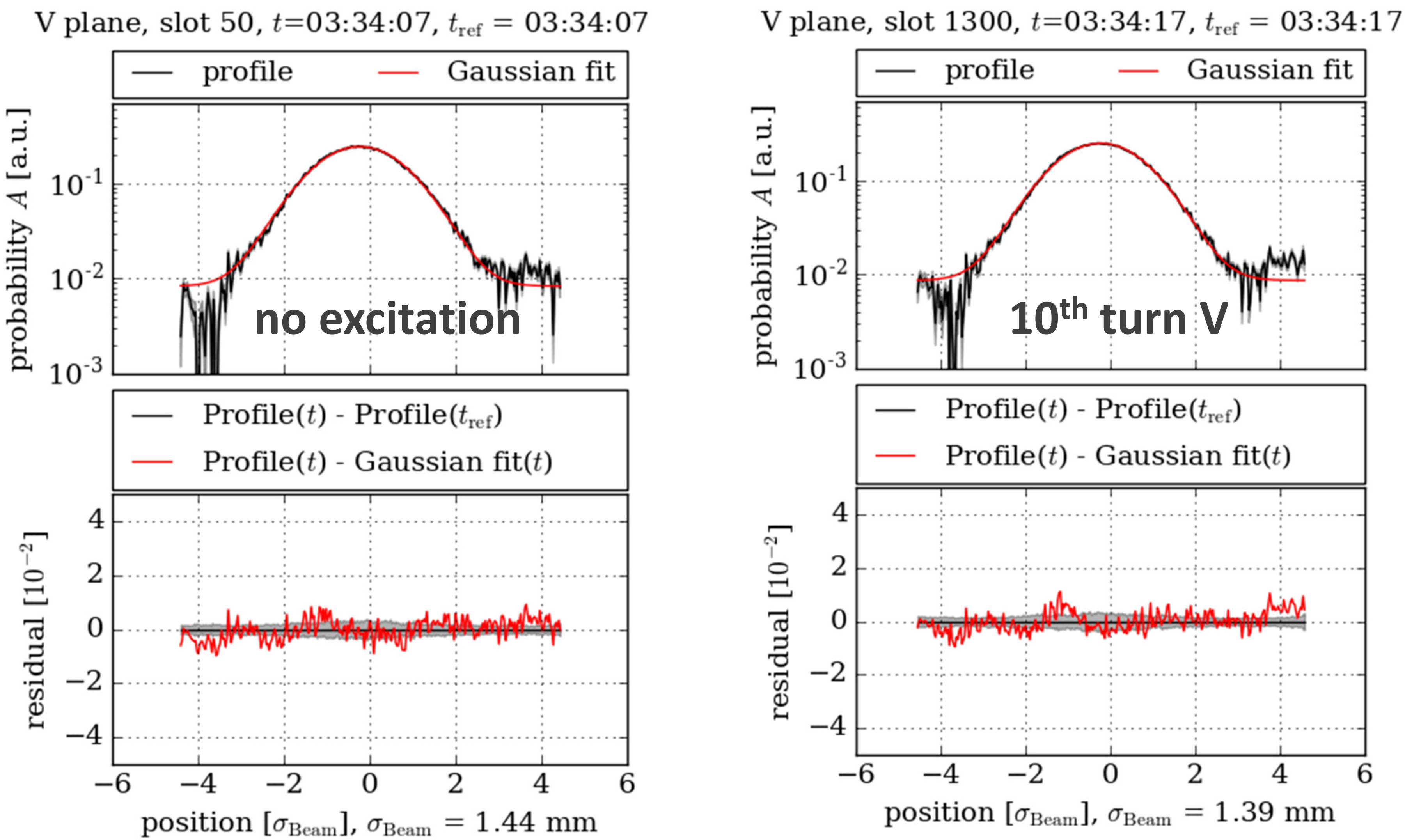
- visible effects for 7th and 10th turn pulsing in simulations and experiments

=> we can predict the relative effectiveness of pulsing patterns

- losses in general underestimated in simulations
- change of beam distribution in simulation and experiment leading to:
  - experiment: emittance growth + higher diffusion (increased losses)
  - simulation: constant emittance or decreasing after initial adjustment

=> quantitative comparisons of simulation and experiment are challenging as we enter here non-linear dynamics

Synchrotron Radiation Telescope profiles



Summary

- electron lenses are very flexible device with a wide range of applications

- active halo control is required for HL-LHC in order to reach the full performance
- compared to other active halo control methods, the hollow electron lens presents the best technology
- CDR completed in 2014 proving the feasibility, detailed TDR foreseen for end 2017, decision to add to HL-LHC Baseline in 2018

- Effects on the beam core:
  - DC operation (standard): no adverse effects expected
  - pulsed operation (optional, higher diffusion): residual e-beam field introduces noise on the beam core

  ⇒ first estimates+experiments at the LHC show that effect is not negligible
  - work ongoing to refine simulations+measurements for a better specification:
    - ➢ better measurements of new hollow e-gun (currently done at Fermilab)
    - ➢ experiments at LHC
    - ➢ improvement of simulations in terms of models + understanding

Thank you for your attention!