Hollow Electron Beam Collimation for HL-LHC – effect on the beam core

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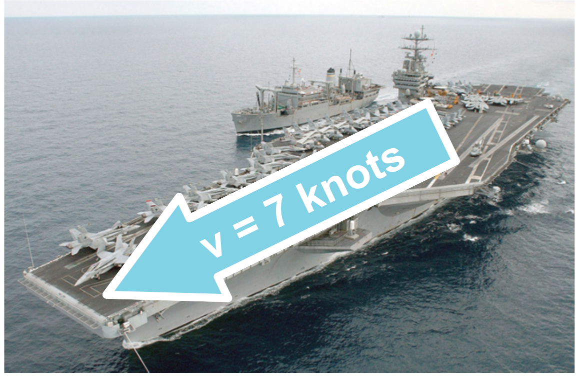
Many thanks to G. Apollinari, V. Shiltsev (Fermilab), O. Brüning, A. Rossi, L. Rossi, D. Perini (CERN)

Outline

- Introduction
  - Why do we need halo control in the LHC
  - Principle of Hollow Electron Beam Collimation (HEBC)
  - Effects of the hollow electron lens (HEL) on the beam core
- LHC experiment to determine tolerance on noise from the hollow electron lens:
  - simulations
  - first experimental results
- Conclusion and Outlook

Why do we need halo control?

- LHC: 27 km ring, 7 TeV proton beams
- nominal LHC: N_b=1.15x10^{11}, ε_N=3.75 µm
- HL-LHC: N_b=2.2x10^{11}, ε_N=2.5 µm
- leap in stored energy from LHC to HL-LHC: 362 MJ for nominal configuration, 675 MJ for planned upgrade HL-LHC

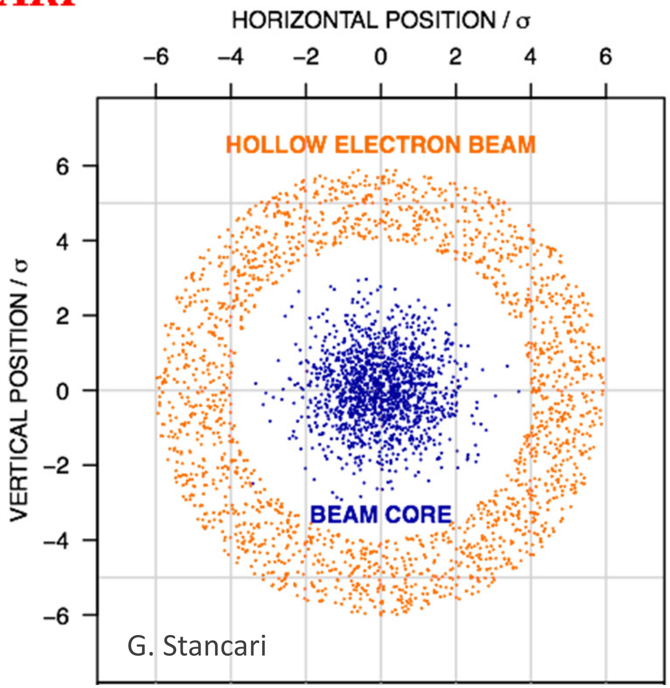


675 MJ = kinetic energy of USS Harry S. Truman cruising at 7 knots

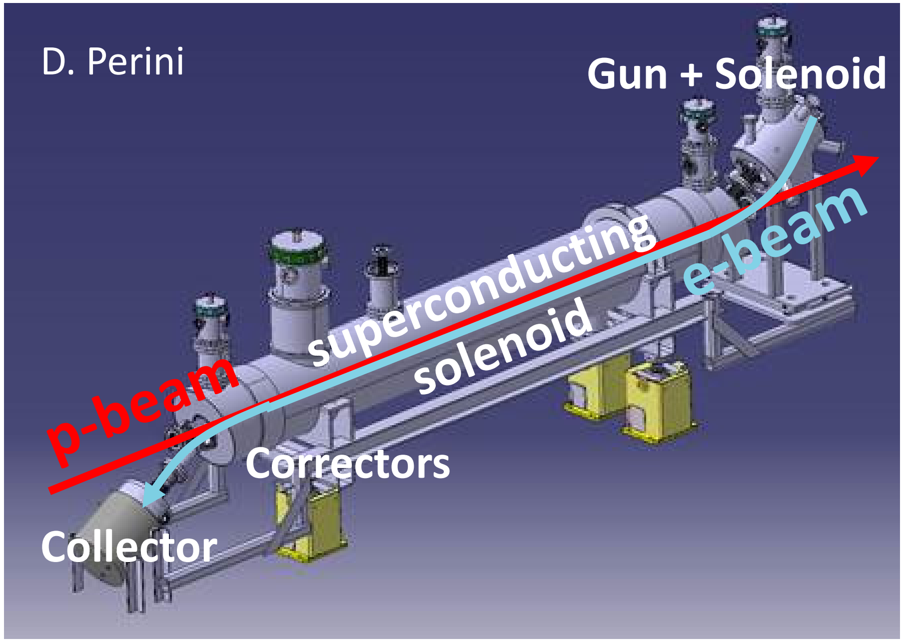
- several MJ found above 3 σ (7 MJ for Gaussian, in reality more due to overpopulated tails G. Valentino, E-lens Review 2016)

⇨ Beam losses need to be very well controlled!!!

Principle of HEBC



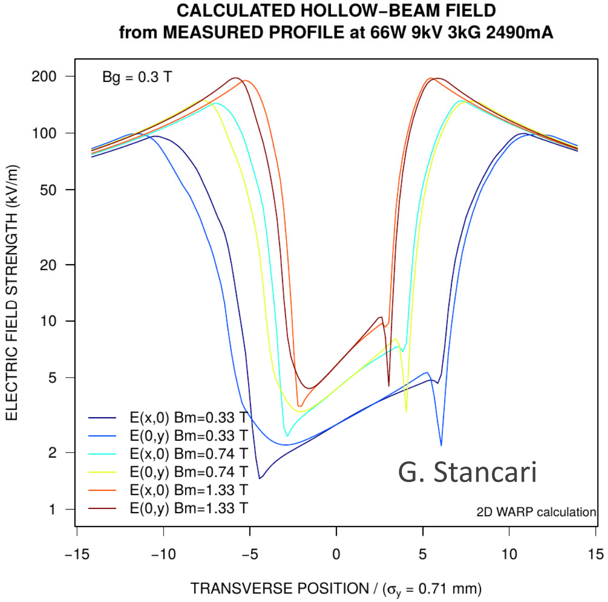
- proton beam (p-beam) traveling inside a hollow electron beam (e-beam)
- hollow profile of e-beam => p-beam core (ideally) not affected
- halo particles kicked to higher amplitudes by electromagnetic field of e-beam.



- pulsed, magnetically confined, low-energy e-beam
- tunable transverse kicks of approx. 0.3 μrad

Effects of HEL on beam core

- for a perfect uniform, radially symmetric e-beam profile, the HEL does not effect the beam core!
- effects on the beam core arise from:
  - e-lens bends (FERMILAB-FN-0972-APC, FERMILAB-TM-2635-AD):
    10% fluctuation between entrance/exit kick
    => $\Delta x' \sim 0.1$ nrad kick from bends
  - e-beam profile imperfections:
    scaled from measured profile
    => $\Delta x', \Delta y' \sim 16.0$ nrad



- pulsed operation of HEL increases diffusion in tails:
  - random mode: uniform modulation of current
  - resonant mode: pulse e-lens every nth turn -> drives nth order resonances

particularly interesting for separated beams, in which case halo removal rates are small but a fast removal is needed e.g. before the squeeze

⇨ in case of pulsed operation noise is induced on the p-beam originating from the e-lens bends and e-beam profile imperfections

Experiment at the LHC

Motivation:

- derive limits on tolerable kick from profile imperfections and e-lens bends
- effects depending on non-linear dynamics in general difficult to predict precisely in simulations -> verify simulations with experimental results
- first test of resonant mode as random mode is to first order white dipole noise (known from analytical formulas and other experiments at the LHC)

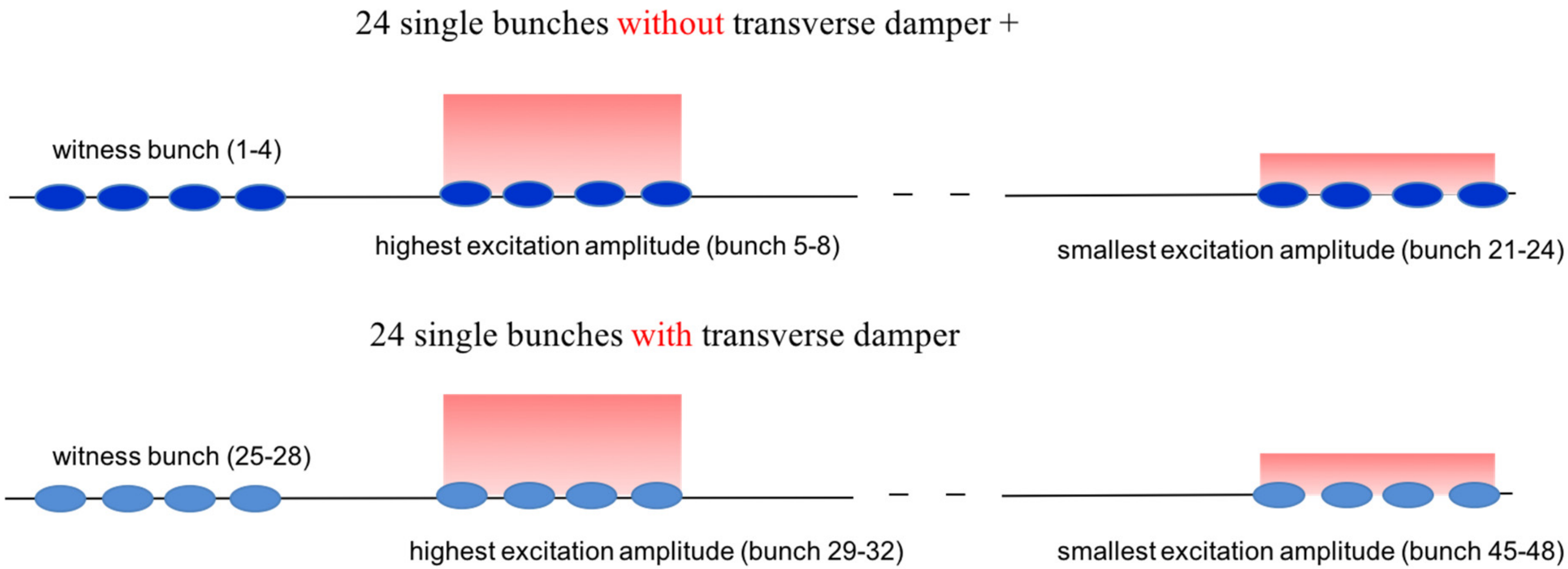
LHC experiment - resonant mode:

- kick in first order can be modeled as dipole kick
- dipole kick with almost arbitrary frequency spectrum can be applied bunch-by-bunch with the kickers of the LHC transverse damper (ADT), H and V not synchronized
- experiments at top energy always inefficient due to long recovery time in case of beam losses -> first test at injection
- use low intensity bunches in order to reduce emittance growth due to IBS ($N_b=0.7\times10^{11}$, $\varepsilon_N=2.5$ μm => 4.6 %/h emittance growth)

Experiment at the LHC

LHC experiment – resonant mode:

- filling scheme to test different excitation amplitudes and effect of transverse damper



Simulation setup

- simulation code: Lifetrac
- "realistic" machine model:
  - LHC at injection
  - focusing octupole family with I_{MO}=+19.6 A
  - chromaticity of 15
  - standard error tables + a_1,b_1,a_2,b_2 scaled to obtain around 1 mm rms orbit and 15% average peak beta-beat (note only one seed simulated)
- Gaussian 6D distribution, 10^4 particles, 10^6 turns
- kick amplitude: 120 nrad and 12 nrad
- pulsing patterns: 2nd up to 10th turn

Simulation results

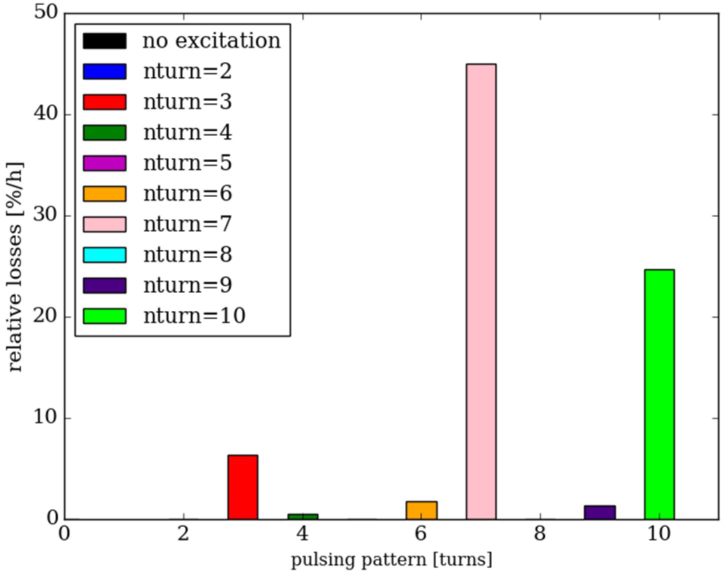
120 nrad, pulsing every 7th and 10th turn:

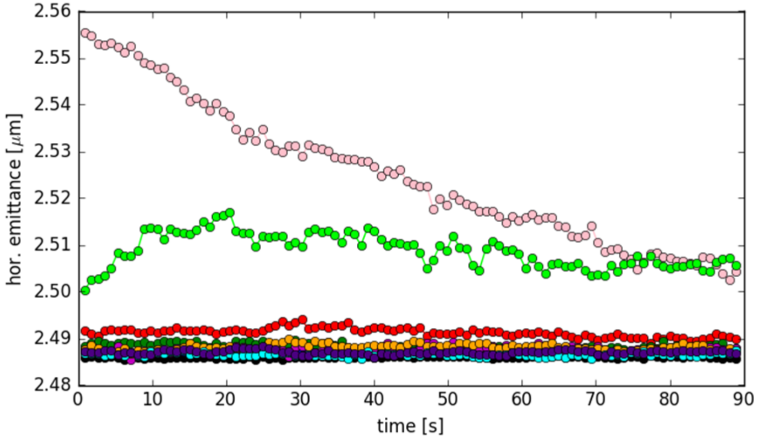
- large losses + decrease of bunch length
  -> mainly longitudinal losses
- adjustment of beam distribution over first 10^4 turns
  -> emittance growth
- similar observation also without magnet errors
  -> losses and emittance behavior driven by sextupoles, octupoles and high chromaticity

120 nrad, other pulsing patterns:

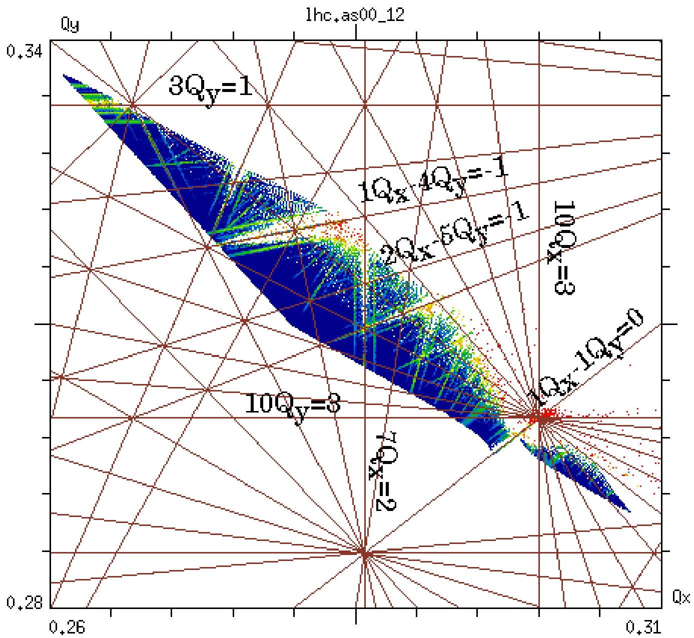
- small or no losses
- no change of emittance

12 nard: no visible effect



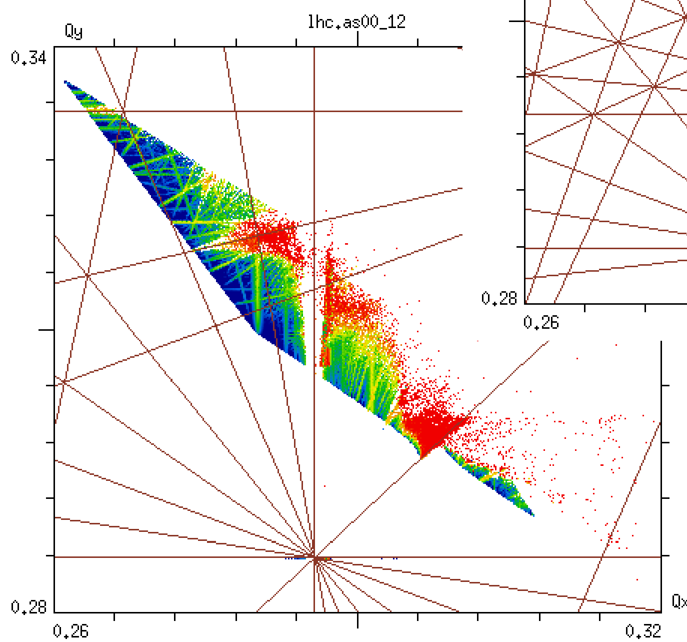


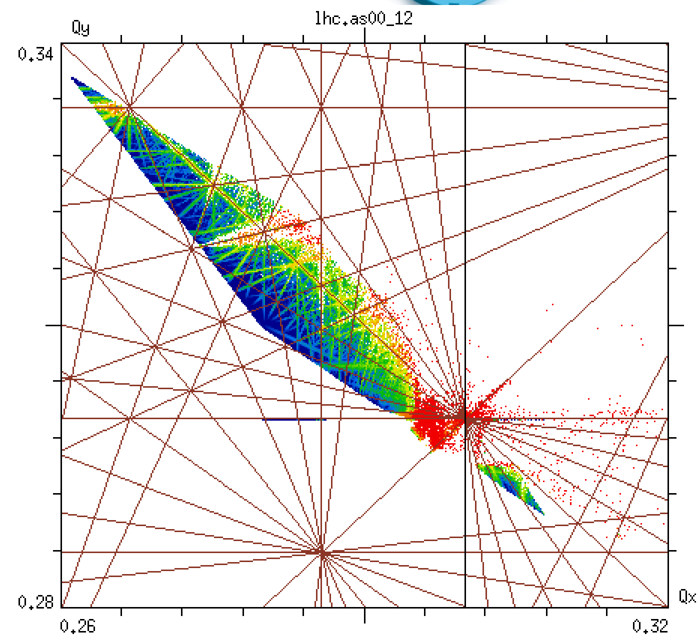
Simulation results - FMA



no excitation, no errors

7th turn pulsing



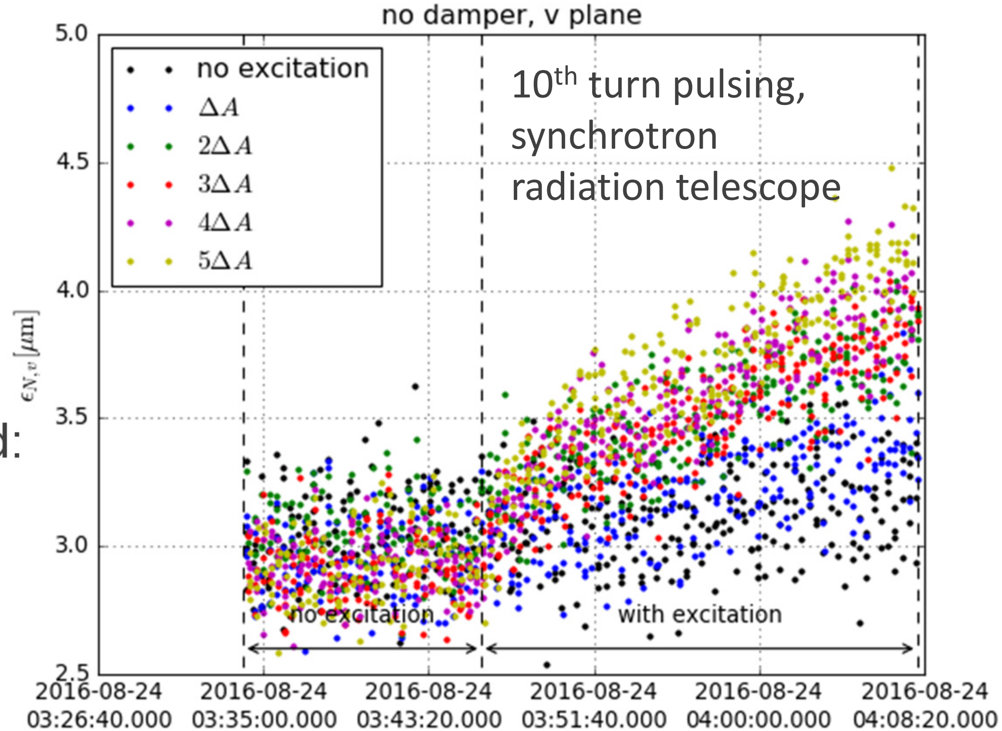


10th turn pulsing

- 7th turn pulsing drives $7Q_x$ resonance
- 10th turn pulsing drives $10Q_y$ resonance

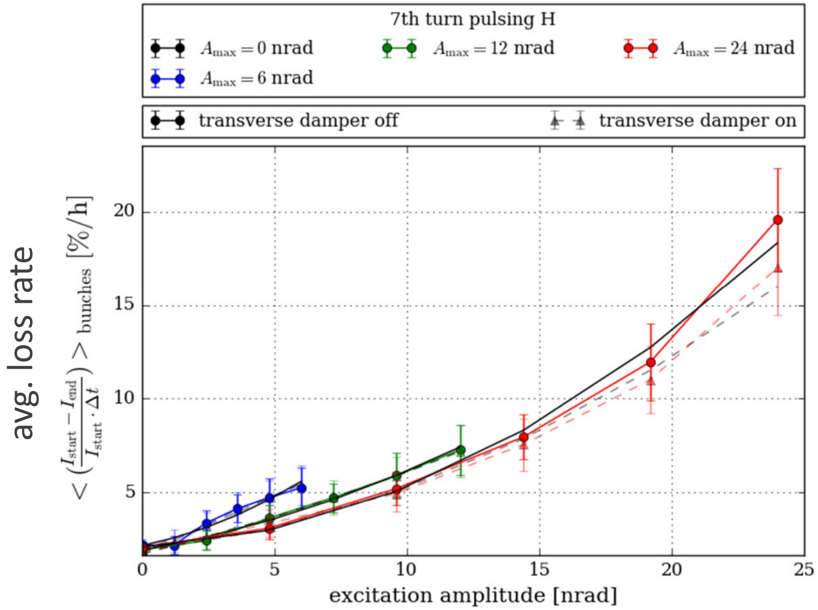
First experimental results

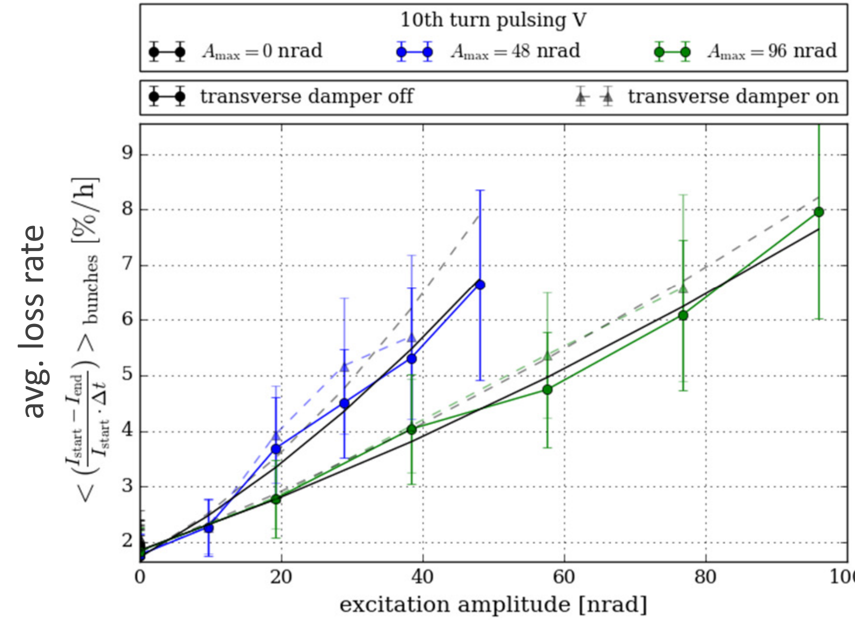
- 7^{th} turn H ($7Q_x$ resonance), up to 24 nrad:
  - losses
  - very small emittance growth
- 10^{th} turn V ($10Q_y$ resonance), up to 96 nrad:
  - losses
  - emittance growth
- 8^{th} turn H, 3^{rd} turn H and V, 24 nrad:
  - losses within the noise
  - no emittance growth



⇨ reproduce sensitivity to pulsing patterns! Good qualitative agreement of measurements and simulations!

First experimental results





Scaling of losses from fast beam current transformers with excitation amplitude:

- scale approx. quadratically
- no real difference with or without transverse damper
- comparison simulations and experiment:

pulsing pattern	exp. losses (120 nrad) [%/h]	sim. losses (120 nrad) [%/h]
7th turn	280 – 720	45
10th turn	10 – 20	25

Conclusion

- DC operation: no effect on the beam core is expected from the hollow electron lens
- pulsed operation (random, resonant): due to e-lens bends and profile imperfections noise can be introduced

- experiment at LHC to test resonant mode:
  - sensitivity to pulsing patterns in terms of losses could be reproduced in experiment
  - scaling with amplitude agrees for 10th turn pulsing, but not for 7th turn pulsing
  - emittance growth observed for 7th and 10th turn pulsing

- if the kick at injection can be directly translated to top energy, we get:

pulsing pattern	exp. losses (16 nrad) [%/h]	exp. losses (32 nrad) [%/h]
7th turn	10 – 19	30 – 60
10th turn	3	3 – 5

- next steps: detailed analysis + experimental test of remaining pulsing patterns and random mode

Thank you for your attention!