



Update on hollow e-lens: resonant excitation MD

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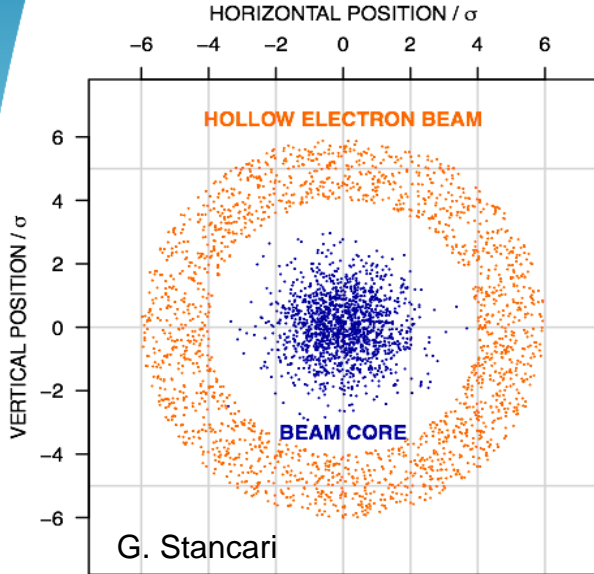
Many thanks to: G. Apollinari, D. Perini, A. Rossi, L. Valerio, all MD participants and operations!

Outline

- 1) Effects on the beam core
- 2) Simulations
- 3) LHC MDs on effects on the beam core in case of pulsed e-lens operation (resonant excitation, random)
- 4) Conclusion and Outlook

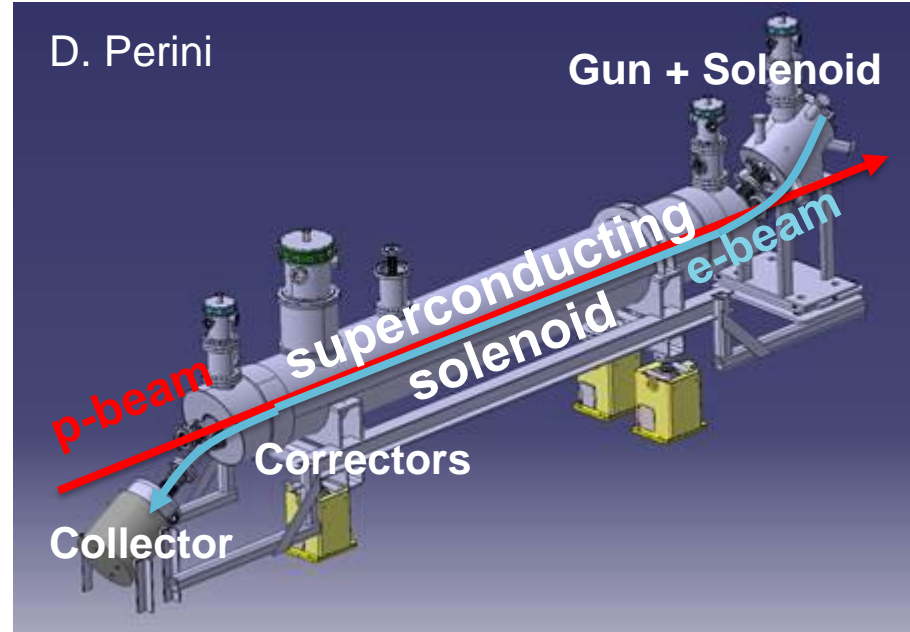
Effects on the beam core

Principle of hollow e-lens



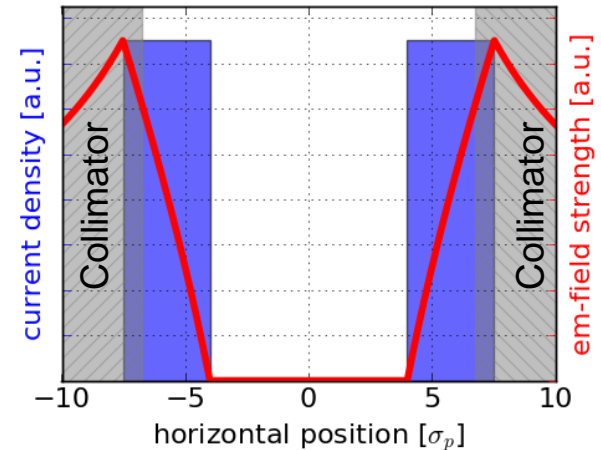
- proton beam (p-beam) traveling inside a hollow electron beam (e-beam)
- hollow profile of e-beam \Rightarrow p-beam core (ideally) not affected
- halo particles kicked to higher amplitudes by electromagnetic field of e-beam \Rightarrow cleaning of halo particles

- magnetically confined, low-energy e-beam
- tunable transverse kicks of approx. $0.3 \mu\text{rad}$



Effects of HEL on beam core

- for a perfect profile, the field at the beam core is zero => **no effect on p-beam**
 - residual field at p-beam core from **e-lens bends and profile imperfections**
 - **DC operation:** **residual fields are negligible**
 - **pulsed operation** increases diffusion in tails (fast depletion if needed):
 - random mode: uniform modulation of current
 - resonant mode: pulse e-lens every n^{th} turn -> drives n^{th} order resonances
- ⇒ **noise** is induced on the p-beam (**not negligible**)
- ⇒ approximate kick to **first order** by **dipole kick**, then we can use the **ADT** in the LHC for experimental studies and to define tolerances



Effects of HEL on beam core

Estimates for HL-LHC e-lens design parameters [3]:

$$E_{p\text{-beam}} = 7 \text{ TeV}, E_{e\text{-beam}} = 10 \text{ keV}, I_{e\text{-beam}} = 5 \text{ A}, L_{e\text{-lens}} = 3 \text{ m}, B_{\text{main solenoid}} = 5 \text{ T}$$

Noise due to uncompensated kicks from e-lens bends [4]:

estimate based on derivation of symplectic map for e-lens bends [5], scale to design parameters, assume 10% fluctuation between entrance/exit kick

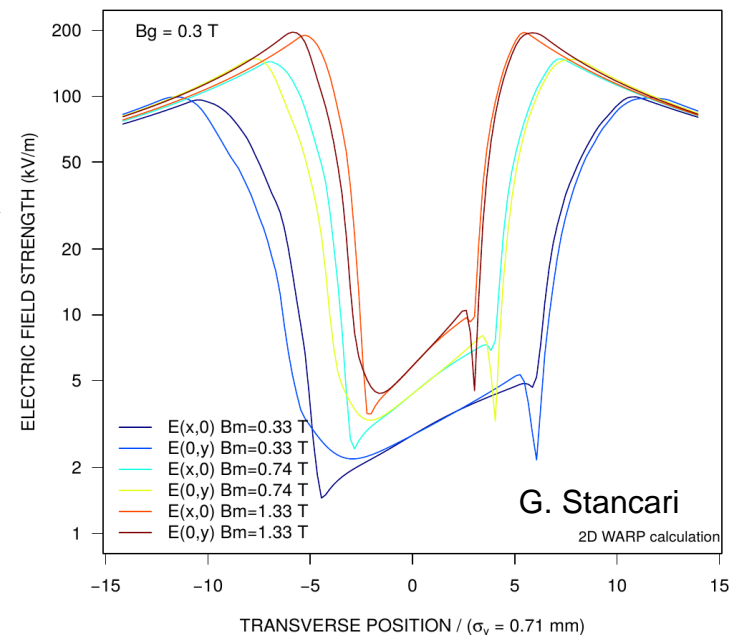
$$\Delta x' = 0.5 \text{ nrad}$$

Noise due to profile imperfections [4]:

scaled from measured profile, kick increases linearly with main solenoid field

$$\Delta x', \Delta y' = 15 \text{ nrad}$$

CALCULATED HOLLOW-BEAM FIELD
from MEASURED PROFILE at 66W 9kV 3kG 2490mA



[3] G. Stancari, V. Previtali, A. Valishev, R. Bruce, S. Redaelli, A. Rossi, B. S. Ferrando, *Conceptual design of hollow electron lenses for beam halo control in the Large Hadron Collider*, FERMILAB-TM-2572-APC, CERN-ACC-2014-0248

[4] M. Fitterer, G. Stancari, A. Valishev, *Effect of pulsed hollow electron-lens operation on the proton beam core in LHC*, FERMILAB-TM-2635-AD

[5] G. Stancari, *Calculation of the Transverse Kicks Generated by the Bends of a Hollow Electron Lens*, FERMILAB-FN-0972-APC

Simulations

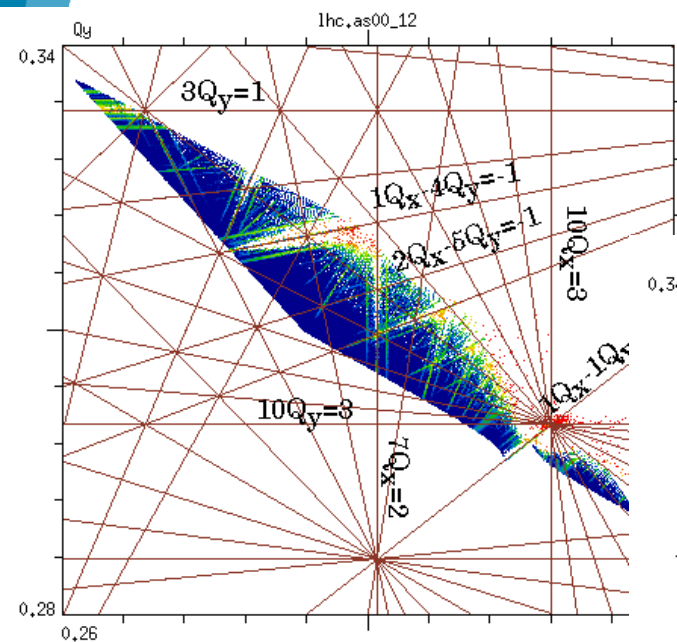
Simulations

- **FMA** to understand which resonances are excited => **most effective pulsing pattern**
- **tracking of Gaussian beam distribution** to obtain estimate for:
 - losses
 - emittance growth
 - change in shape of beam distribution
- simulation code: Lifetrac

Beam Parameters	
E_{beam}	450 GeV
N_b	0.7×10^{11}
$\epsilon_{x/y}$	2.5/2.5 μm
bunch length (4σ)	1.0 ns

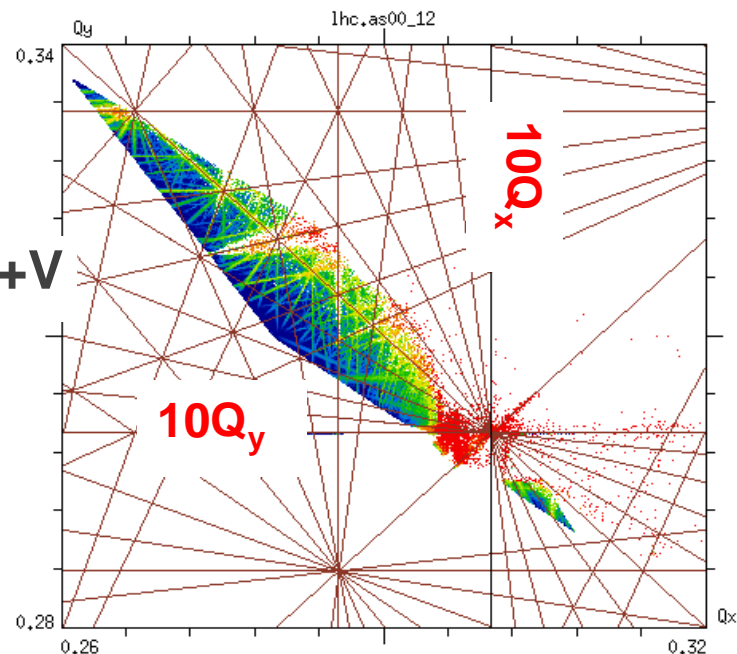
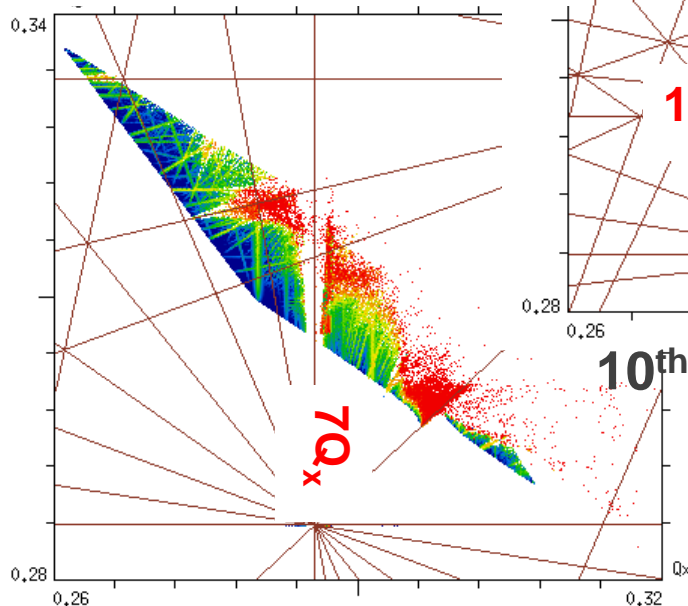
Machine Parameters	
optics	injection, $\beta^* = 11$ m
transv. aperture	5.7σ ($\epsilon_N = 3.5$ μm)
long. aperture	10σ
$Q_{x/y}$	64.28/59.31
$Q'_{x/y}$	15/15
octupoles I_{MO}	+19.6 A
a_1, b_1	avg 1 mm rms orbit
a_2, b_2 errors	avg 15% peak β -beat
$a_i, b_i, i \leq 3$	standard errors

Sensitivity to 7th and 10th order resonance (2016)



no excitation, no errors

7th turn pulsing H+V

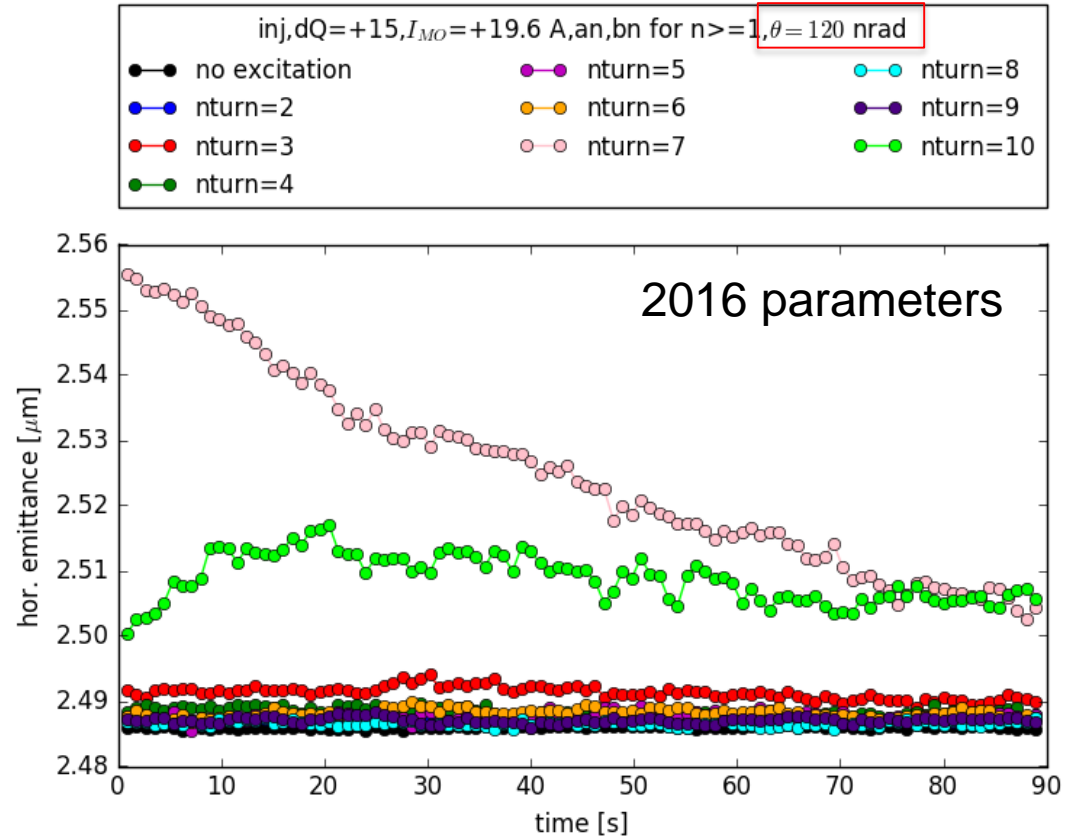


10th turn pulsing H+V

efficiency of pulsing patterns can be understood with FMA

Simulation of losses and emittances (first try)

- simulations are non-trivial as they enter deeply into the non-linear dynamics.
- simulations and experimental results of **losses** and **emittance growth** do not agree well (see :
 - emittance decrease or constant emittance instead of increase
 - losses are underestimated)
⇒ experiments can be used to benchmark simulations



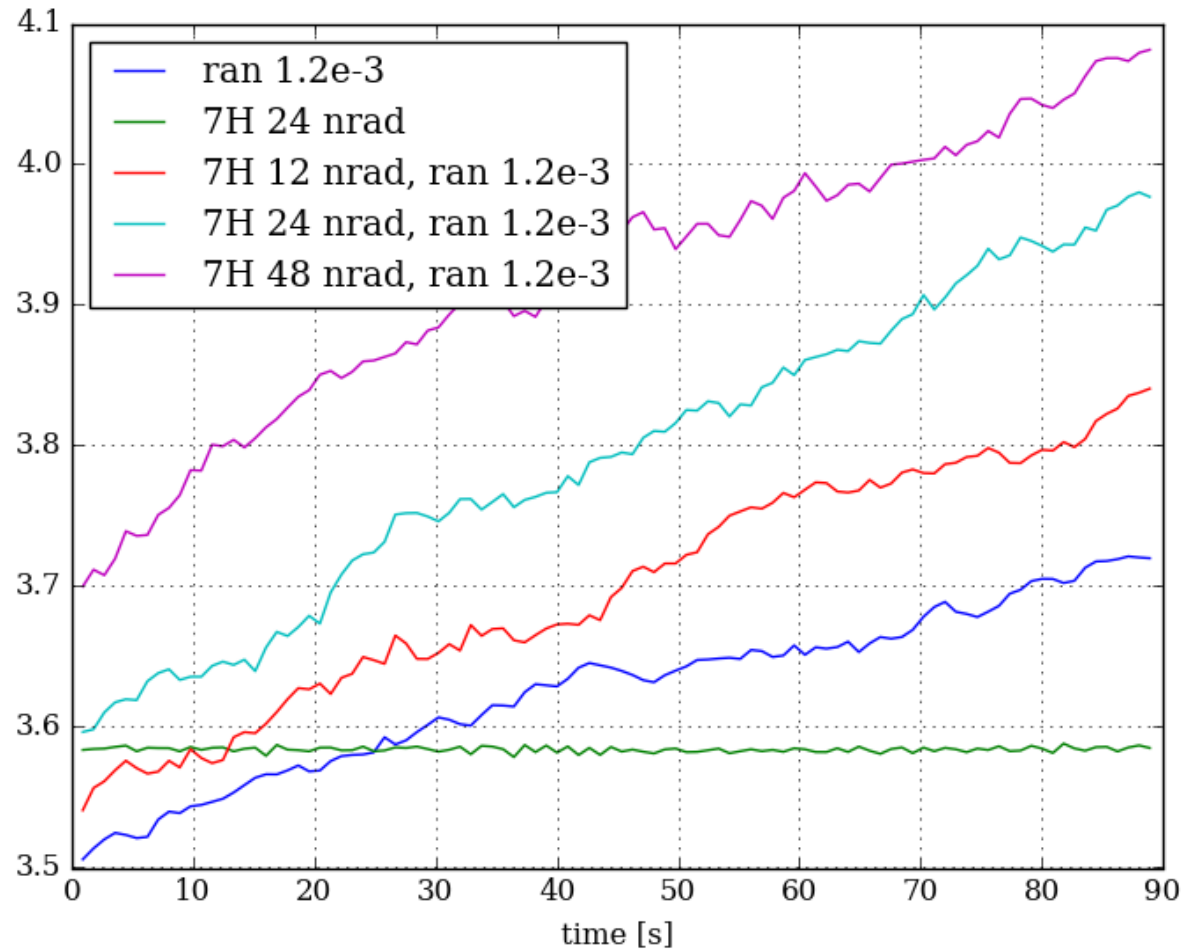
Improvement of simulations (in progress)

- **remove orbit error** as not modeled in the same way in SixTrack and Lifetrac => no decrease of emittance any more
- emittance varies between 2.5 and 3.5 μm => **simulate min/max emittance**
- **add random noise** \Leftrightarrow interplay between resonant excitation and random noise
 - estimate of random noise: $A_{\text{noise}} = 8.0\text{e-}5$ (from BB noise MD @ 6.5 TeV, X. Buffat)
 - scale with beam rigidity to injection : $A_{\text{noise}} = 1.2\text{e-}3$
 - apply kick at ADT:

$$z' = A_{\text{noise}} \cdot \sigma_{z'} \cdot \sin(2\pi Q_z), \quad z = x, y$$

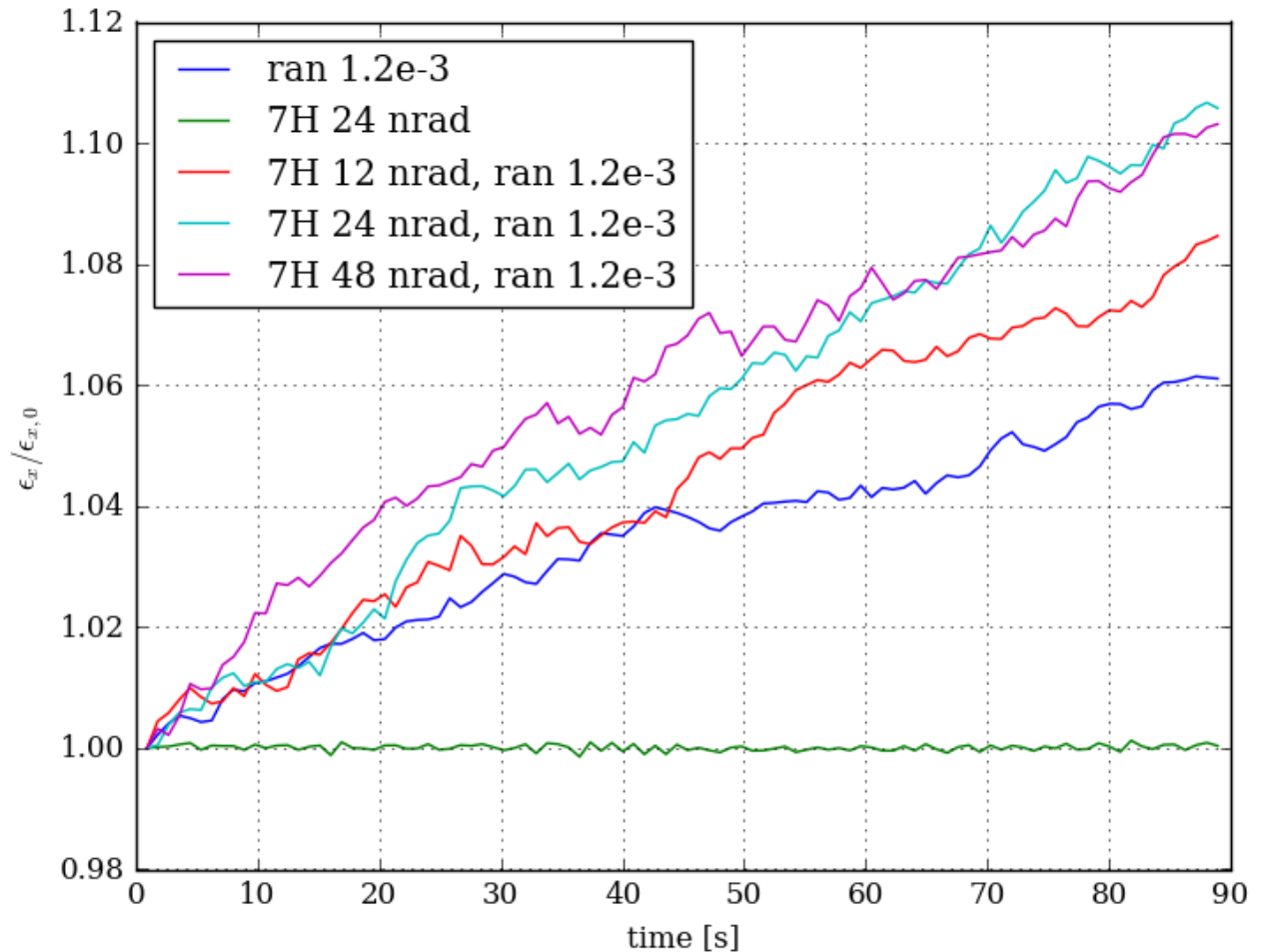
Example: 7th turn H, hor. emittance

- continuous emittance growth on top of initial change of distribution



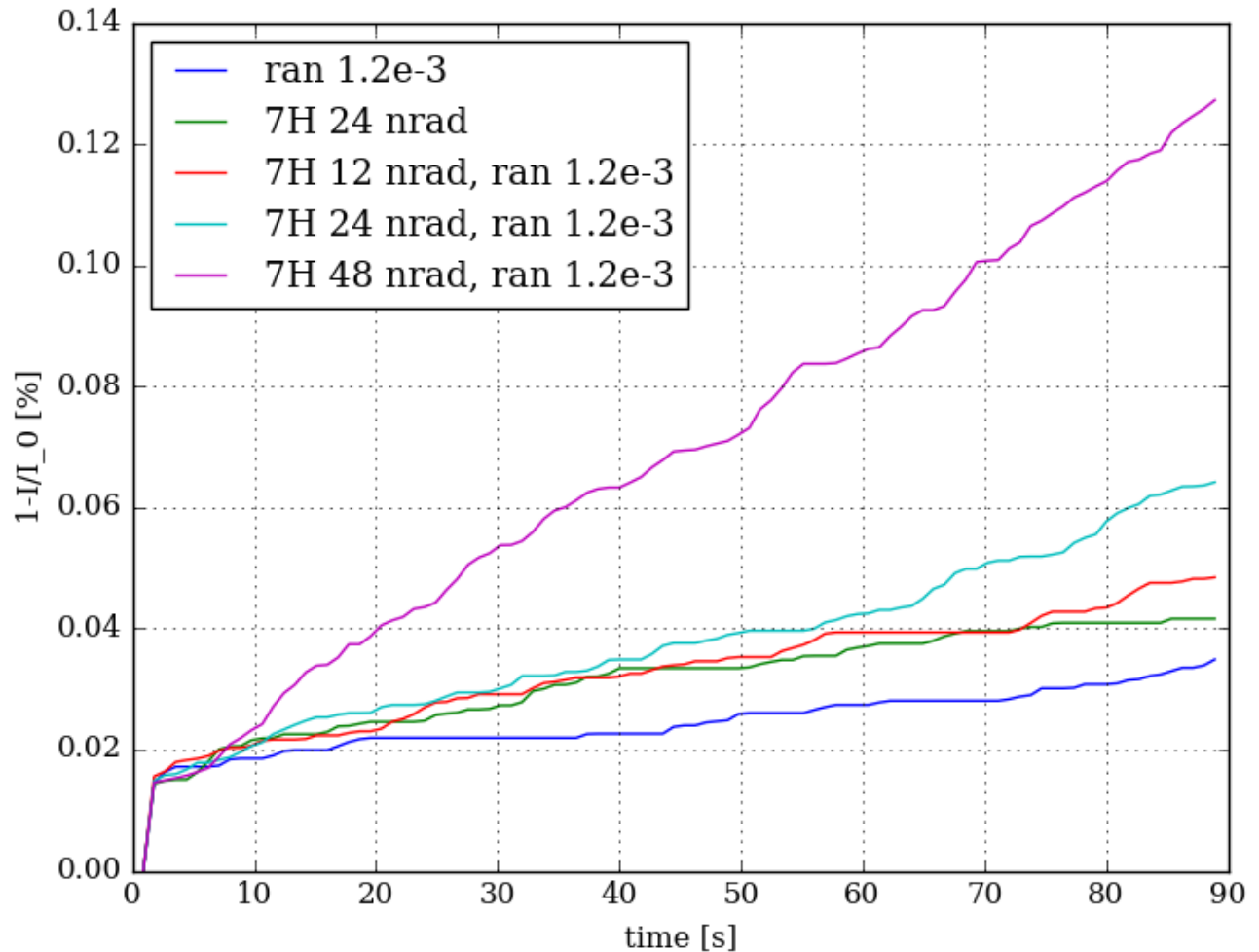
Example: 7th turn H, hor. emittance

- resonant excitation amplitude dependent emittance growth



Example: 7th turn H, relative losses

- resonant excitation amplitude dependent losses



Challenges of precise predictions from simulations

- we need the full non-linear model of the machine (tracking is CPU intensive)
 - random noise level in LHC not known at injection
 - large parameter space to scan (emittance, excitation amplitude + plane, noise level, error seeds)
 - rather large uncertainties on input (emittance, beam distribution, excitation amplitude, small number of error seeds)
 - extrapolation to larger time scales (we only simulate 90 s of the machine)
- ⇒ **saver+faster to determine tolerances experimentally and use simulations for better understanding**

resonant excitation MDs 2016 + 2017

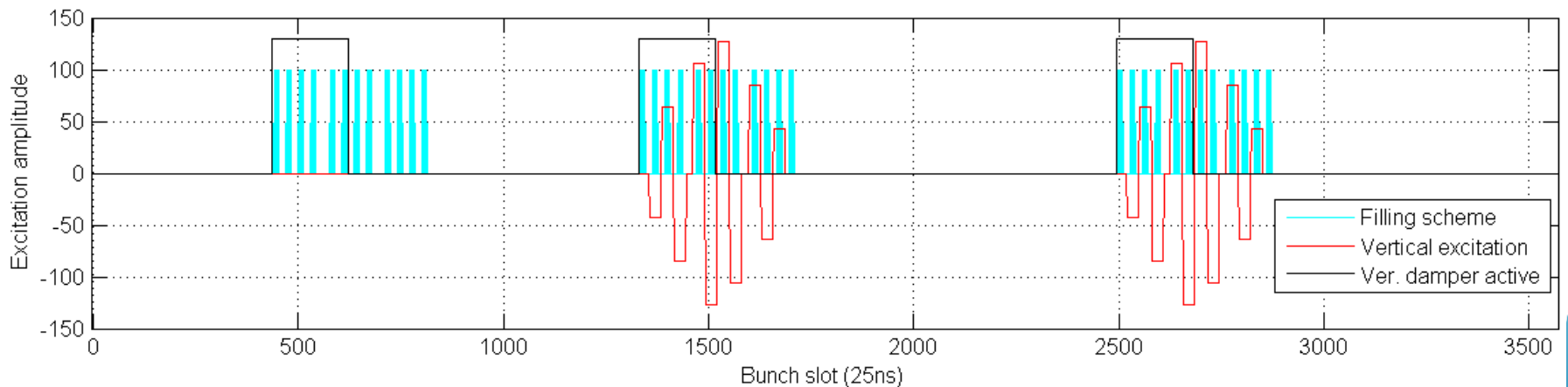
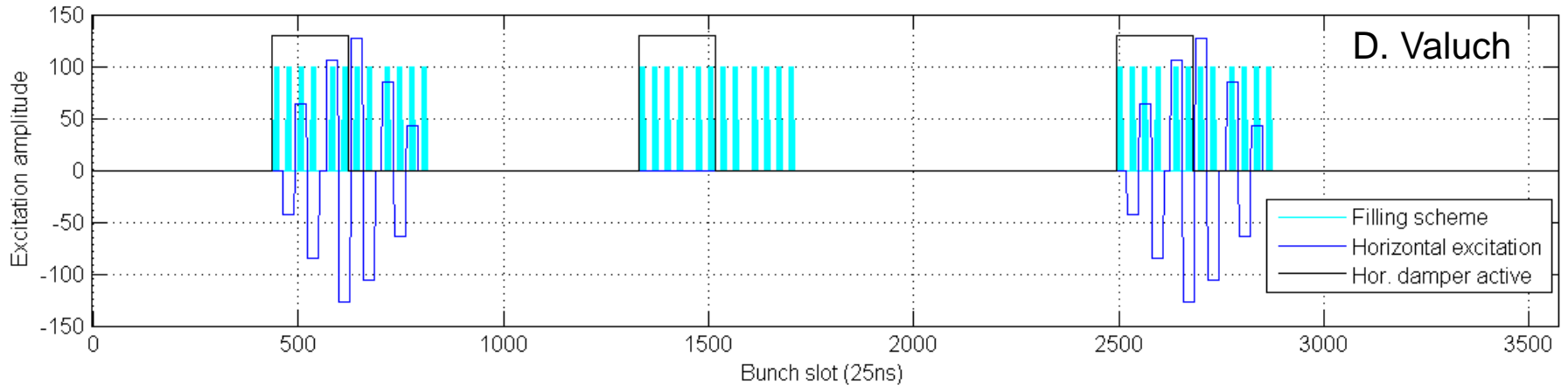
Experiments at the LHC (resonant excitation MDs)

- in total 2 experiments (one in 2016 + one in 2017)
- Excitation:
 - e-lens field approximated by dipole kick
 - dipole kick is applied with ADT with either resonant or random pulsing pattern, one pattern per fill
 - **2016:** patterns **7th H, 10th V** turn pulsing
 - **2017:** patterns **7th, 8th** turn pulsing, **random**

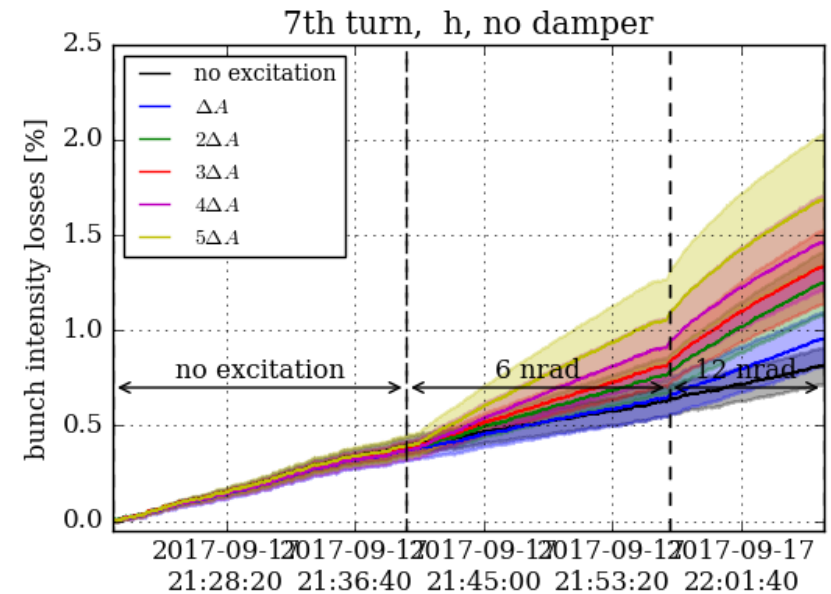
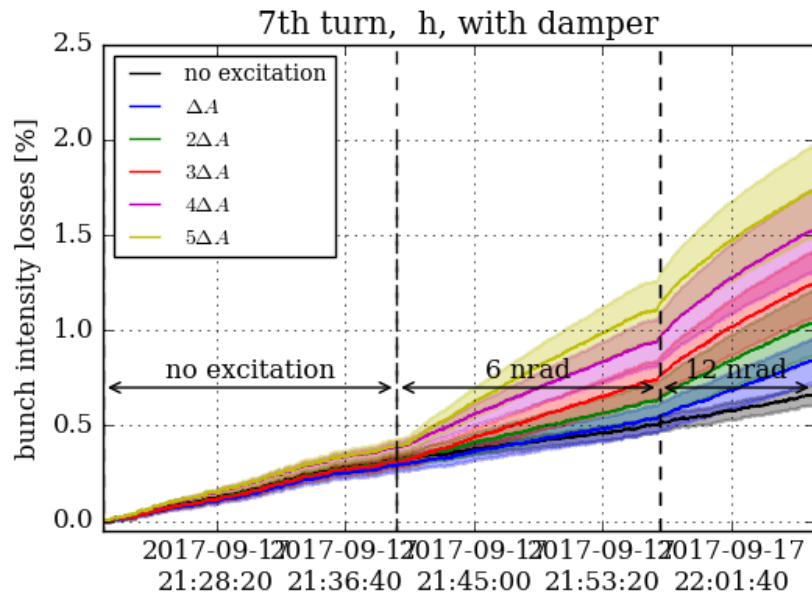
Parameter	MD 2167 (17./18.09.2017)	MD 1415 (23./24.08.2016)
Beam	Beam 1	
beam energy	injection energy, 450 GeV	
single bunch intensity	0.7×10^{11}	
normalized emittance	2.5 – 3.5 μm	
number of bunches	3 × 72 = 216 bunches (+ 1 pilot + 12 nominal)	12 × 4 = 48 single bunches
injection optics, $\beta^* = 11$ m	standard optics 2017	standard optics 2016
working point (Q_x, Q_y)	(62.27,60.295)	(64.28,59.31)
chromaticity (Q'_x, Q'_y)	(+15,+15)	
Landau damping octupoles	$I_{\text{MO}} = \pm 19.6$ A, explicitly +19.6 A for MOF circuit and -19.6 A for MOD circuit (standard 2016 settings)	

Example filling scheme 2017

we have to test: pattern + plane + effect of transverse damper

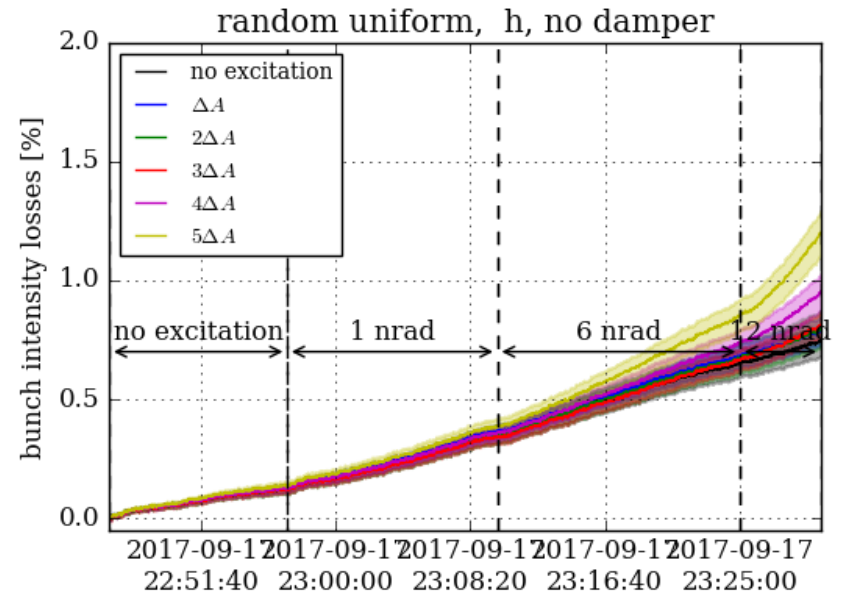
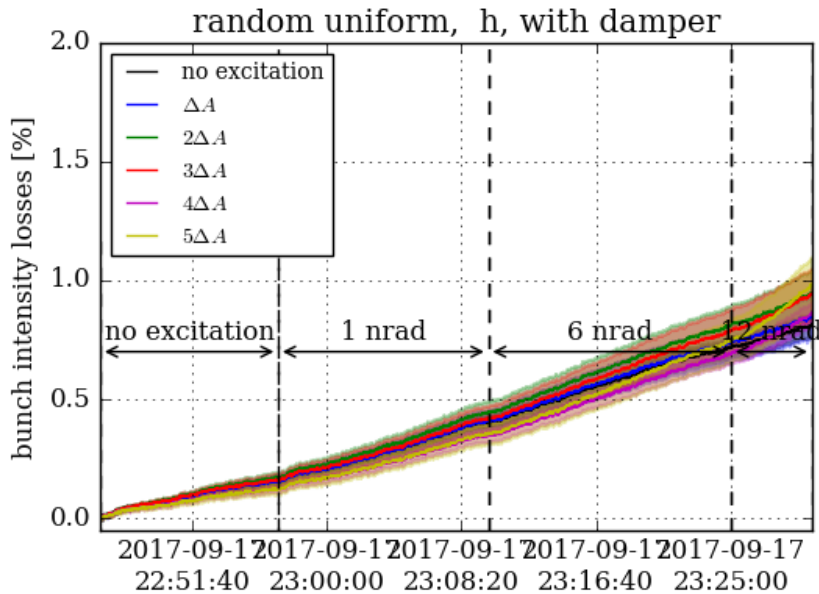


Example FBCT losses 2017 – 7th



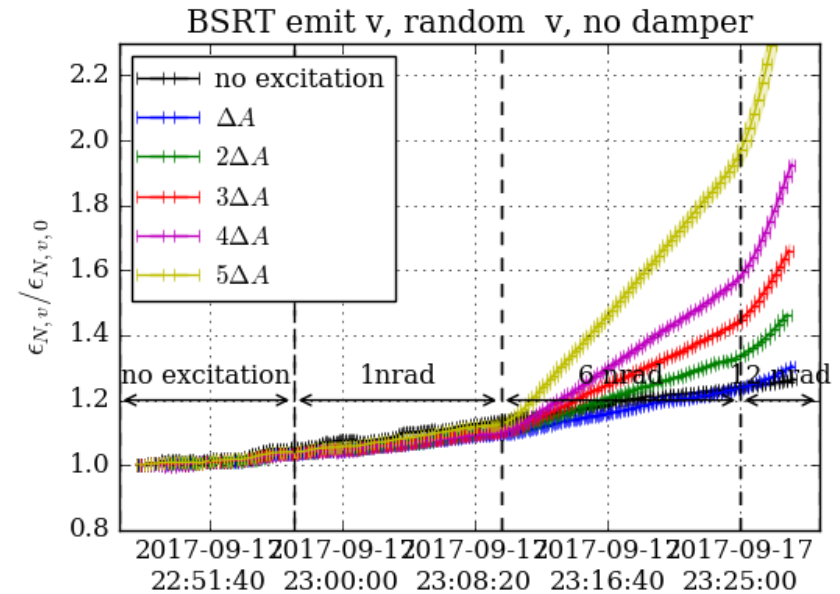
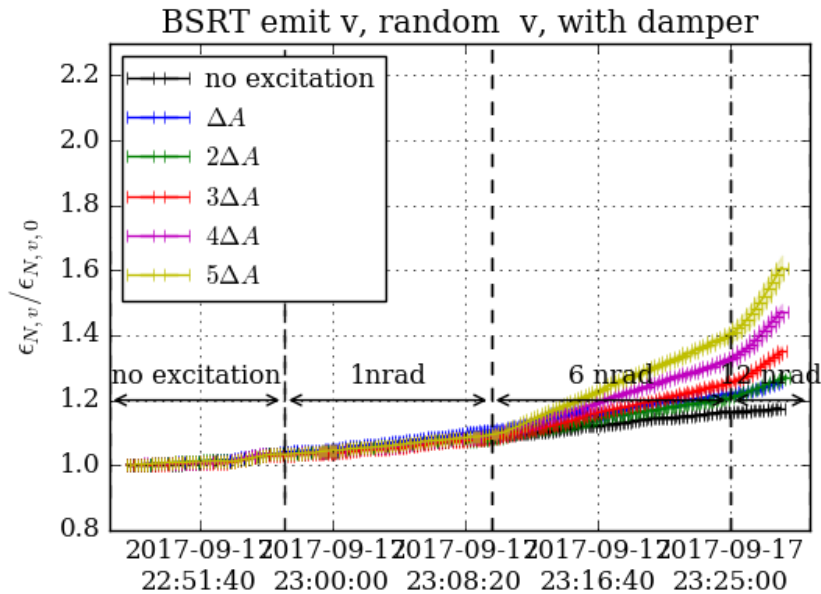
- excitation amplitude dependent losses
- no reduction of losses by transverse damper

Example FBCT losses 2017 – random



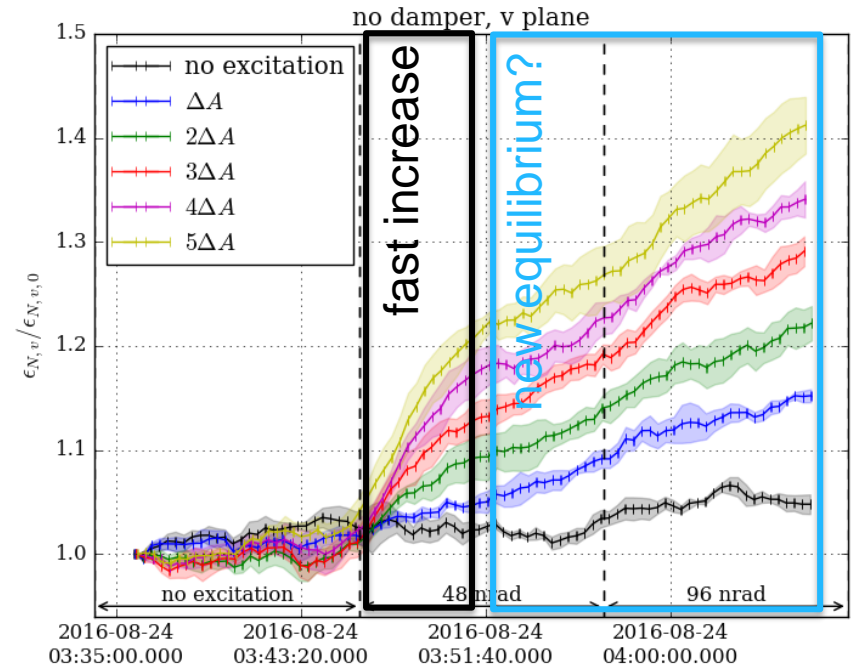
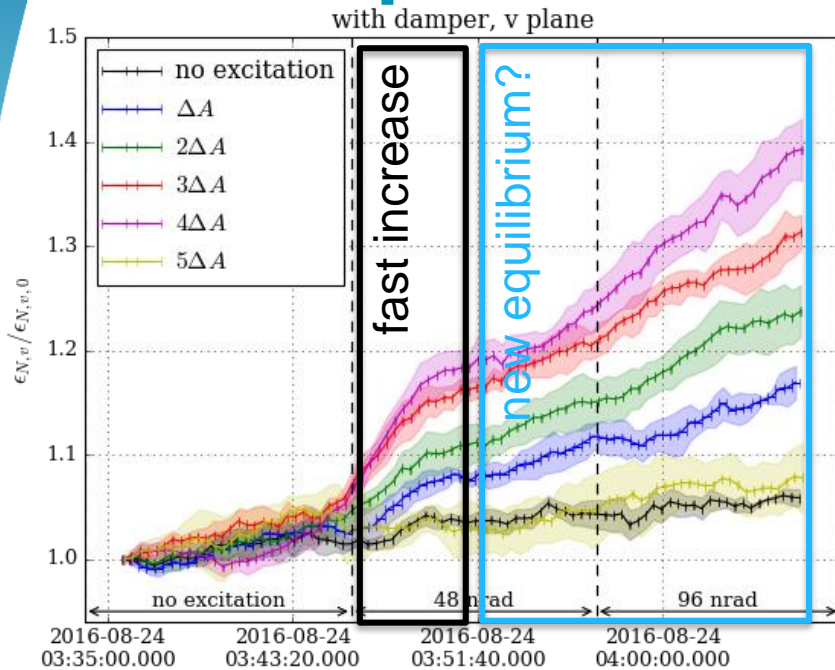
- excitation amplitude dependent losses
- reduction of losses by transverse damper

Example BSRT emittance 2017 – random



- excitation amplitude dependent losses
- constant amplitude dependent growth rate of emittance
- reduction of emittance growth by transverse damper

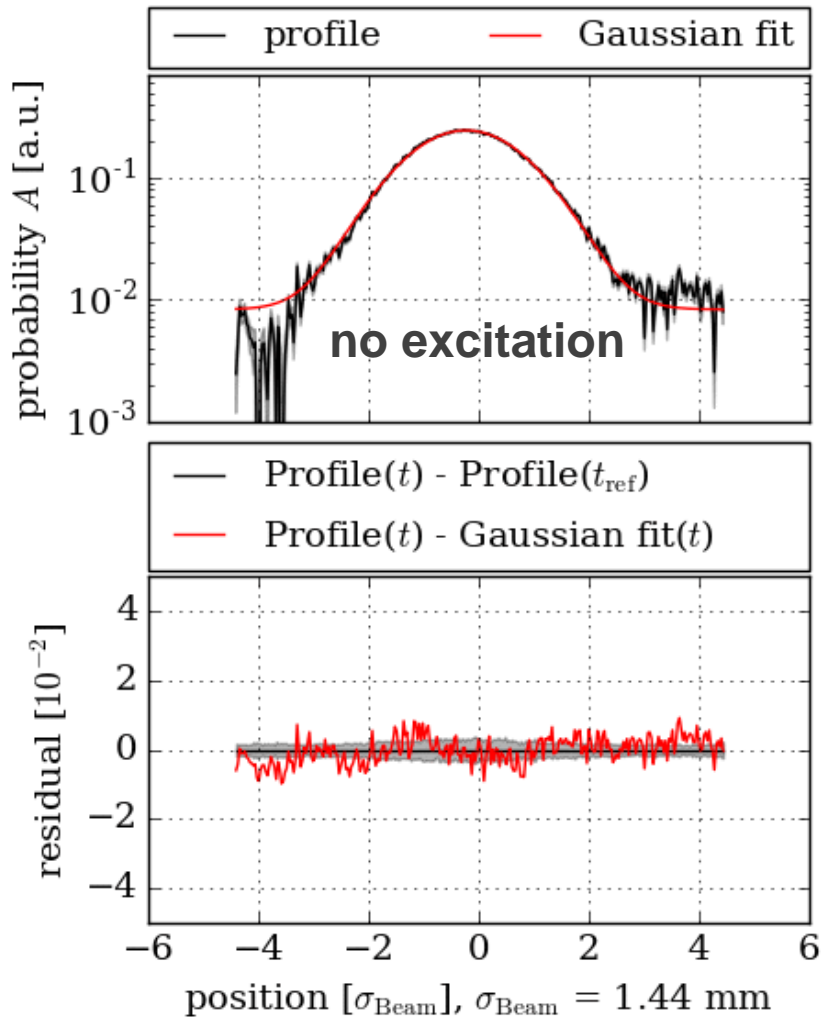
Example BSRT emittance 2016 – 10th



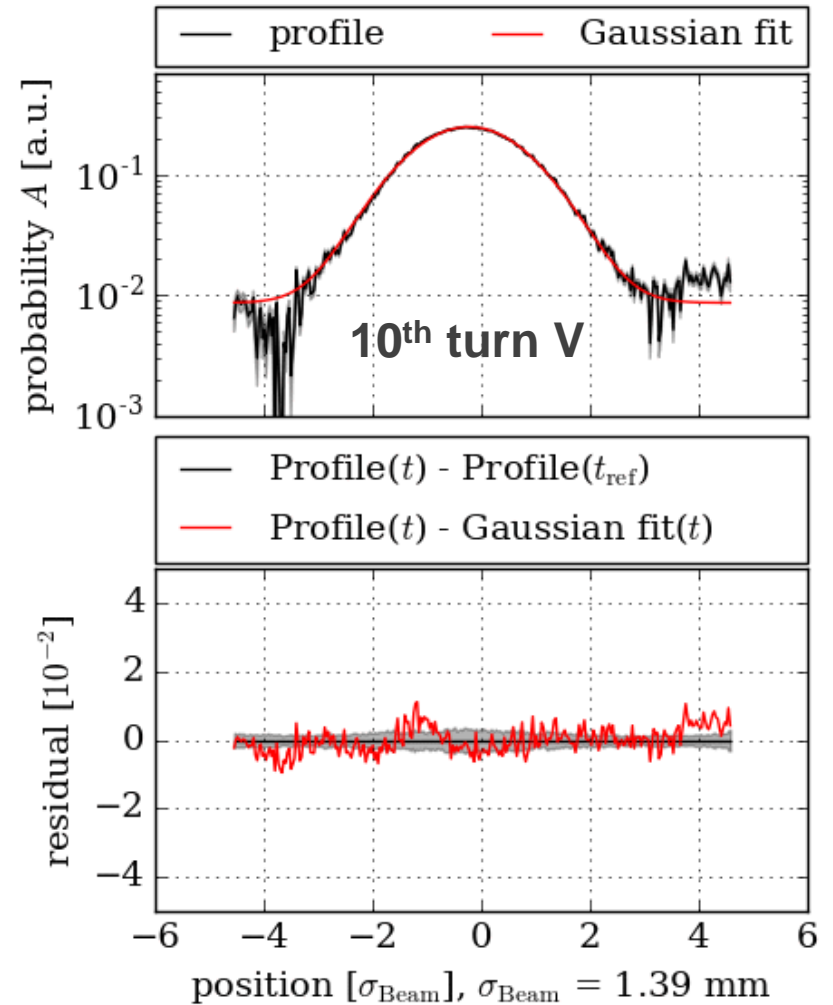
- excitation amplitude dependent emittance growth
- strong increase followed by constant growth (adjustment of beam distribution to new equilibrium state?)
- no reduction of emittance growth by transverse damper

Example BSRT profiles 2016 – 10th

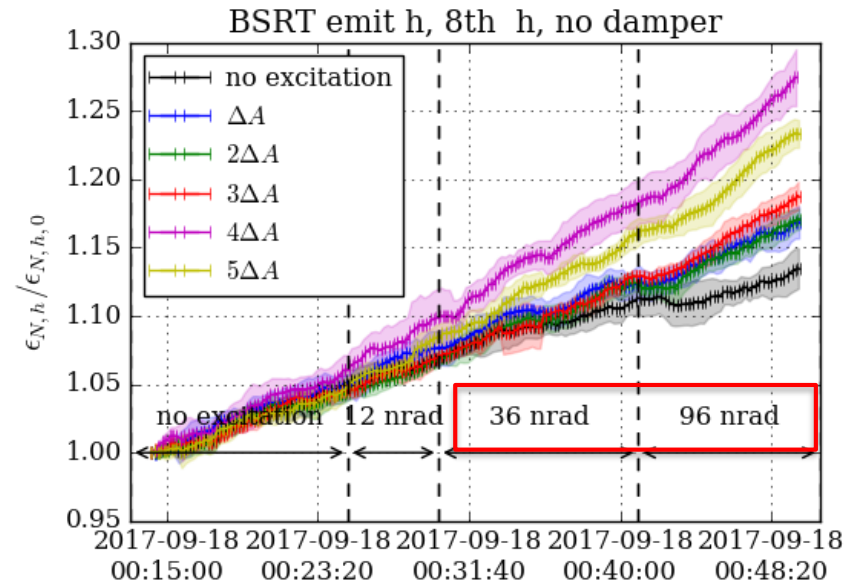
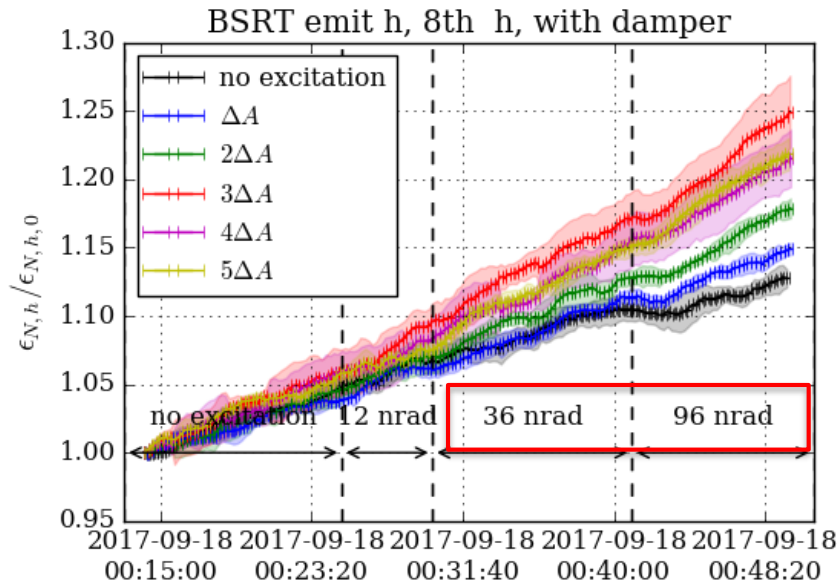
V plane, slot 50, $t=03:34:07$, $t_{\text{ref}} = 03:34:07$



V plane, slot 1300, $t=03:34:17$, $t_{\text{ref}} = 03:34:17$

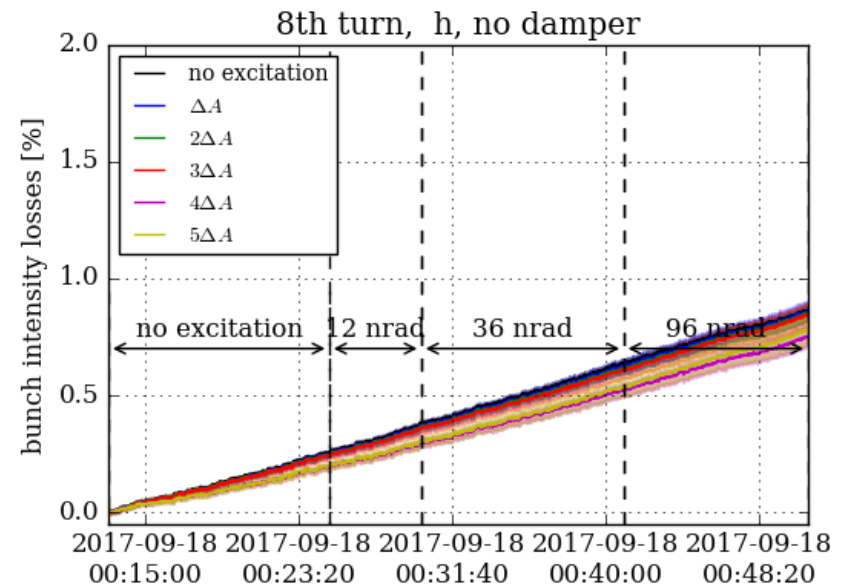
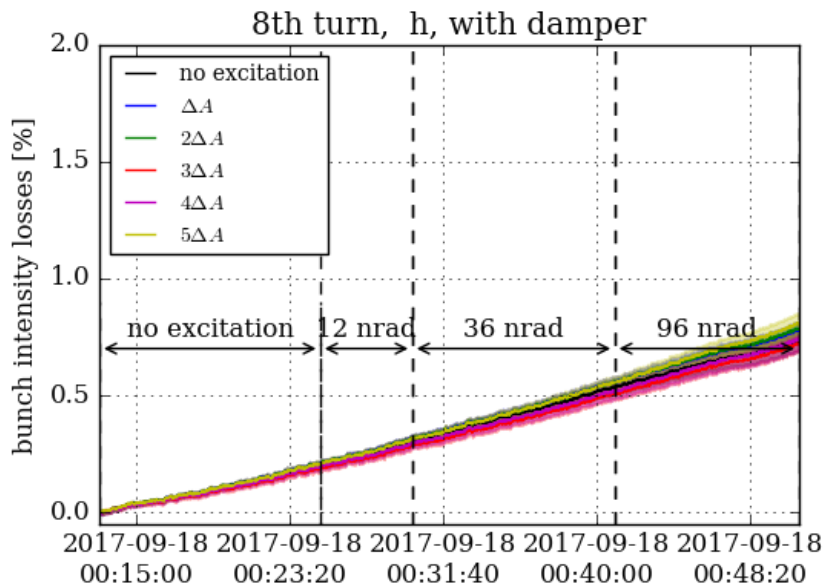


8th turn BSRT emittance (2017)



- effect on beam only for much higher amplitudes
- 96 nrad = maximum amplitude without saturation

8th turn FBCT losses (2017)



- no effect on losses even for maximum amplitude of 96 nrad

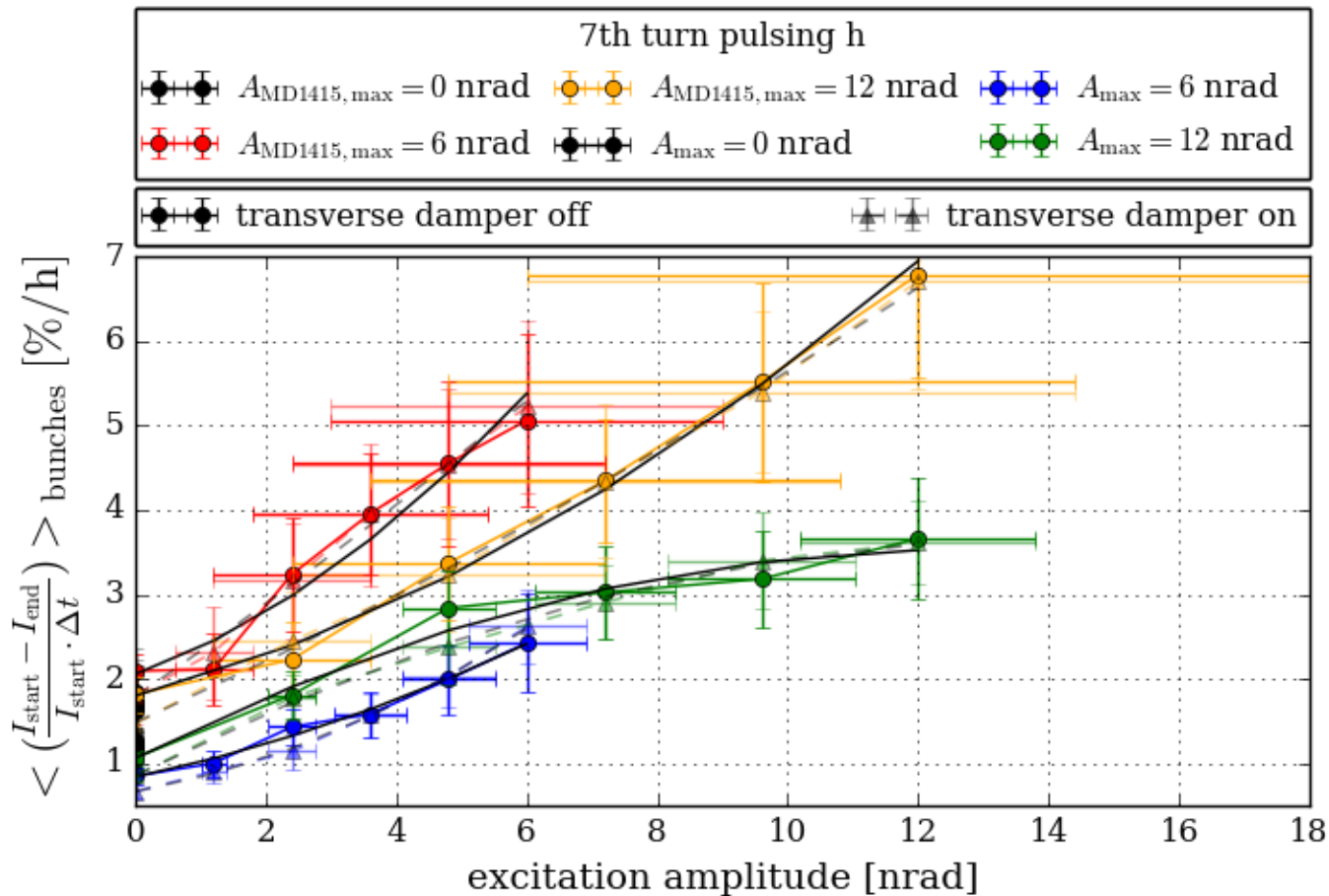
Summary of experiments in 2016 and 2017

- **7th turn pulsing (6 and 12 nrad):**
 - high losses
 - small emittance growth
- **10th turn pulsing (48 and 96 nrad):**
 - small losses
 - large emittance growth
- **8th turn pulsing (12, 36 and 96 nrad):**
 - no losses
 - small emittance growth
- **random (1, 6 and 12 nrad):**
 - small losses
 - strong emittance growth

no reduction of
losses/emittance growth if
transverse damper active

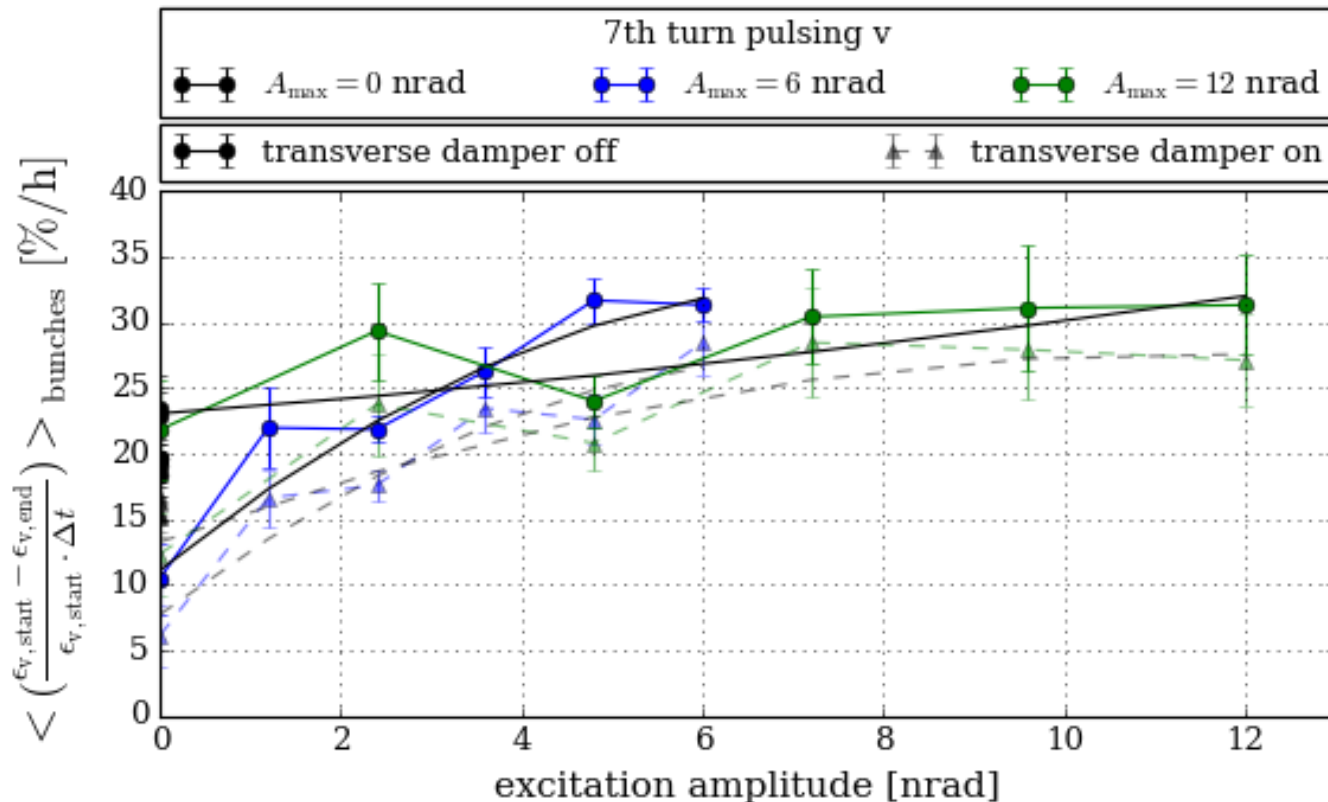
reduction of losses/emittance
growth if transverse damper
active

Scaling FBCT losses 7th (2016+2017)



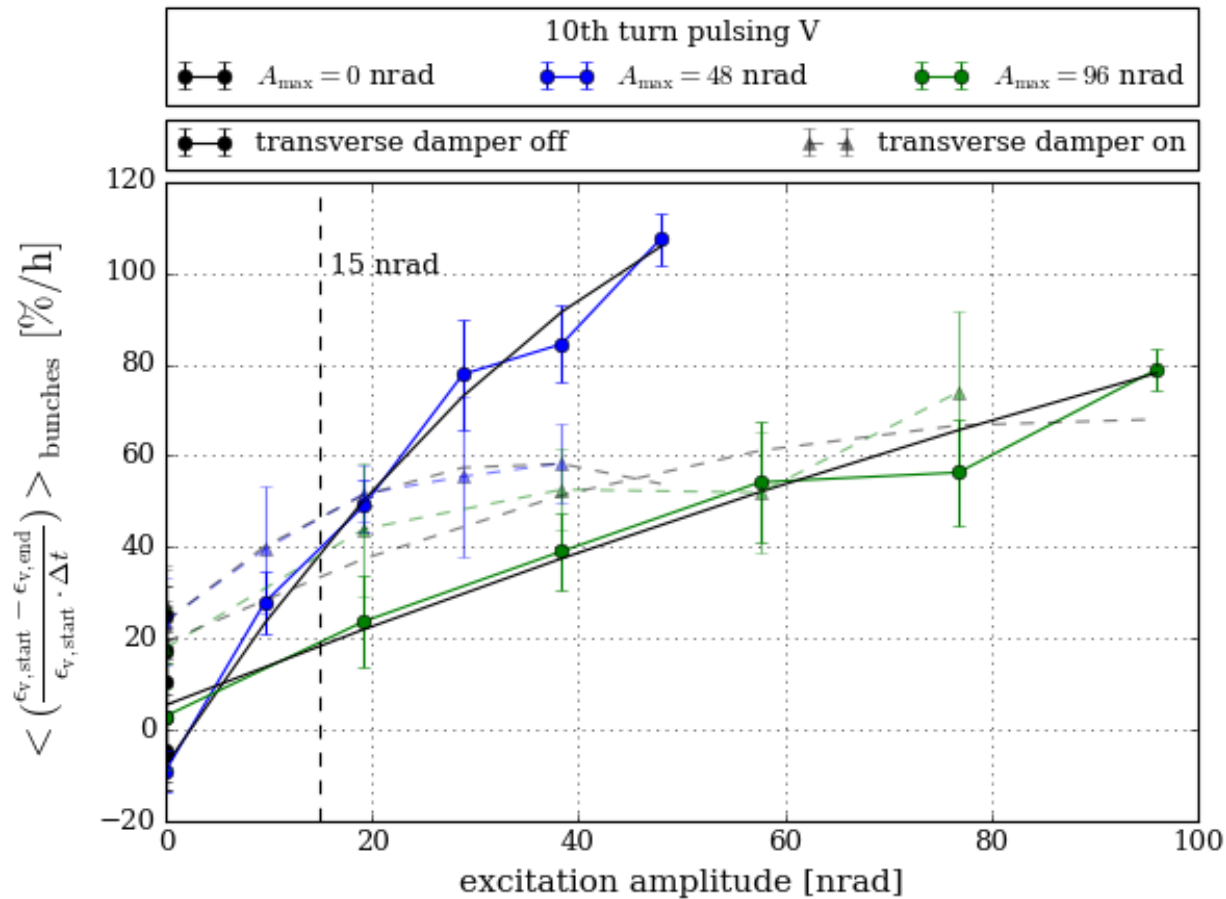
- **different tune in 2016 than in 2017**
- similar results in both MDs

Scaling BSRT losses 7th (2016+2017)



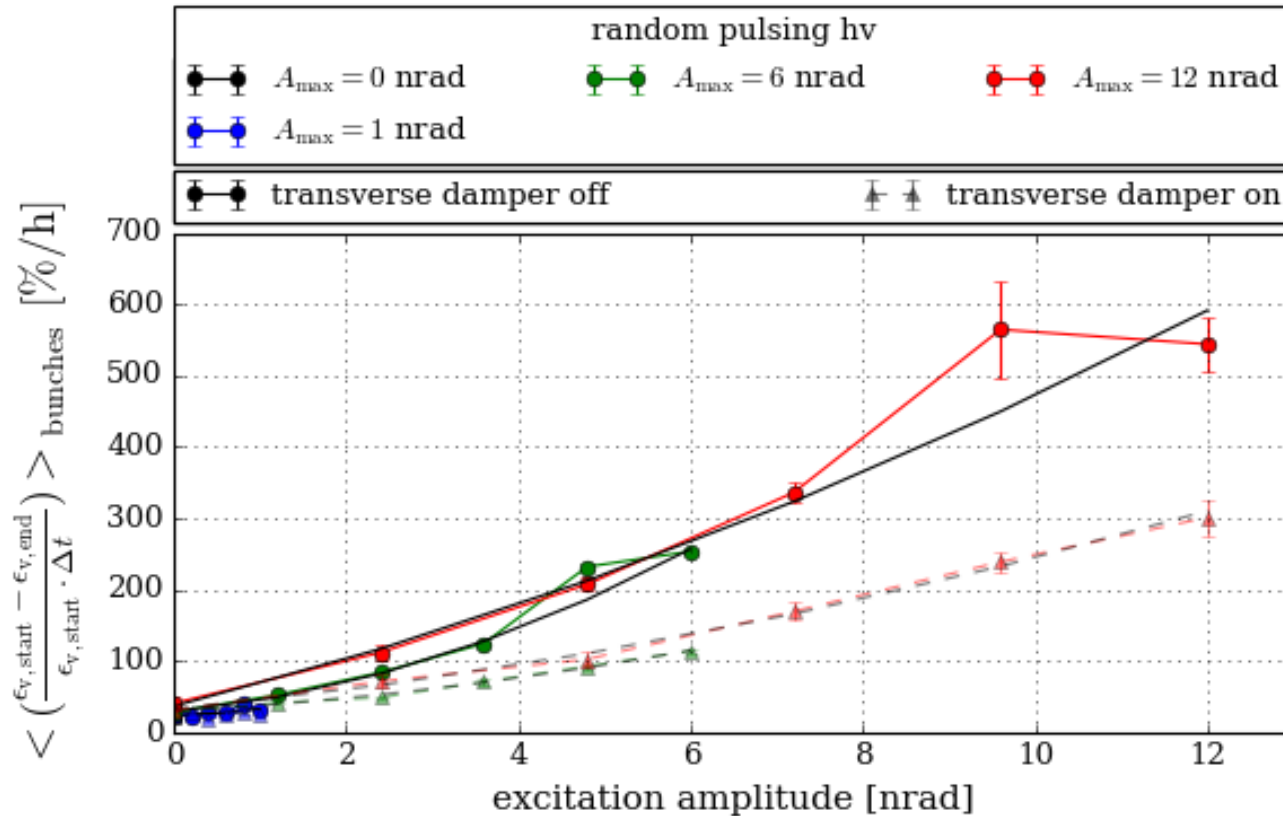
- small emittance growth
- emittance growth in V for pulsing in V (and H+V) (different tune)
- no horizontal emittance growth

Scaling BSRT emittance 10th 2016



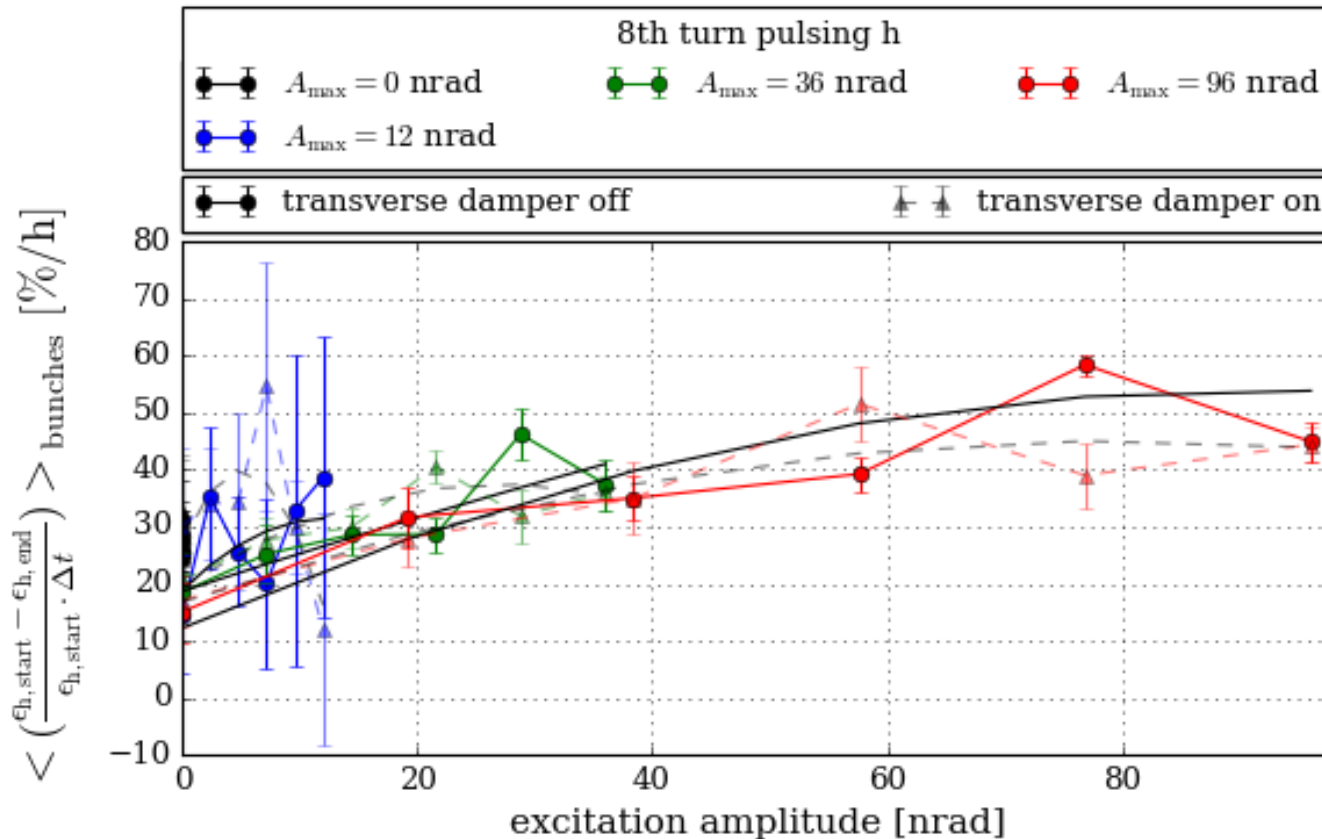
- strong emittance growth in the plane of excitation

Scaling BSRT emittance random (2017)



- very strong emittance growth
- strong effect of the transverse damper

Scaling BSRT emittance 8th (2017)



- noisy
- small emittance growth visible

Summary

- effects of e-lens on beam core are **negligible in DC operation**
 - ⇒ **the e-lens does work in DC mode**
- for the optional **pulsed operation** (nth turn + random) mode, the e-lens induces noise
 - ⇒ **effects on beam core not negligible** for current estimate of **15 nrad dipole field**
- experiments in 2016 and 2017 to determine tolerances on residual e-lens field in core region
- relative effectiveness of pulsing patterns can be predicted in simulations and understood with FMA
- quantitative simulation of losses and emittance non trivial
 - ⇒ better to determine tolerances experimentally and use simulations for better understanding

Summary

- **all pulsing patterns** for which an effect is predicted in simulations show **high losses** and/or **high emittance growth** for 15 nrad
 - ⇒ improve the residual e-lens field in the core region (better e-gun)
 - ⇒ find a pulsing patterns that effects the halo, but not the core (dependent on machine + beam configuration)
- effect of transverse damper:
 - nth turn pulsing: no effect
 - random: reduction of emittance growth and losses
- in all experiments we only excited for max. 15 min during injection
 - ⇒ this is "a good case scenario"
 - ⇒ for more precise values we would need to measure also at collision energy and for a longer time

Questions?