



# Beam dynamics simulations with hollow electron lens

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*We greatly acknowledge all BOINC volunteers who supported LHC@Home project, giving for free their CPU time and allowing these results to be produced*



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# Introduction

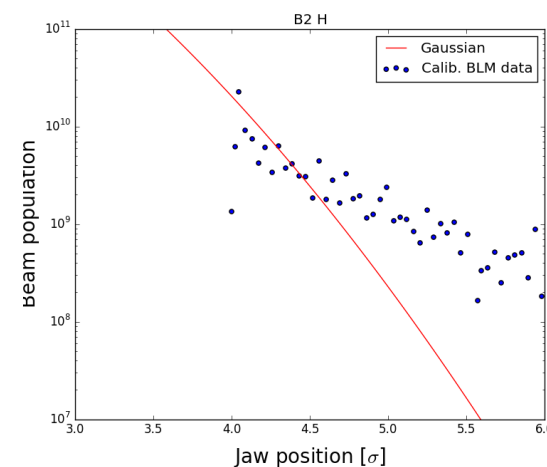
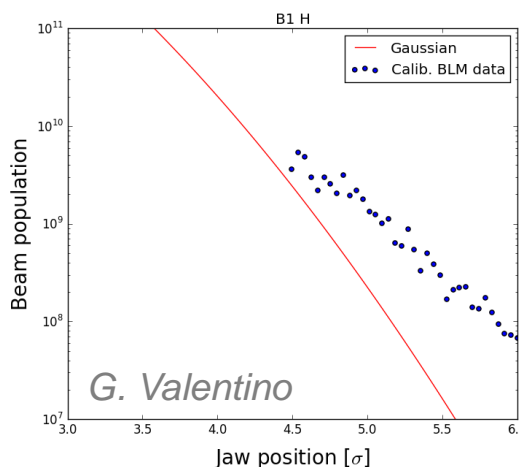
- Design **stored energy** in **HL-LHC** beams **~700 MJ**
- **How much** of this energy is **in the tails**?

→ Halo population probed by means of **collimator scans**

~5% of the beams in the tails ( $>3.5 \sigma$ )  
while 0.22% if Gaussian



**Scaling to HL-LHC parameters:**  
**~33.6 MJ in the tails!**



## Fast failure scenarios:

*Orbit jitter*  
*Crab cavity phase slip*

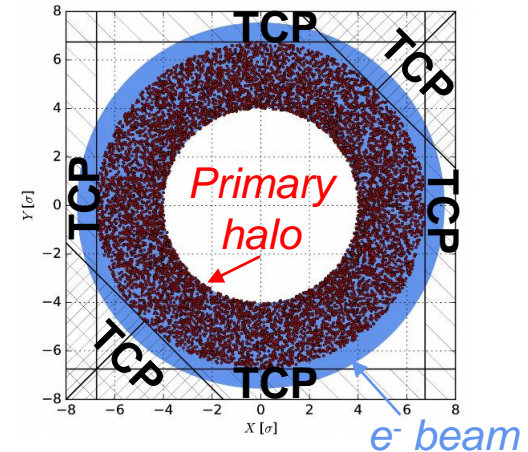
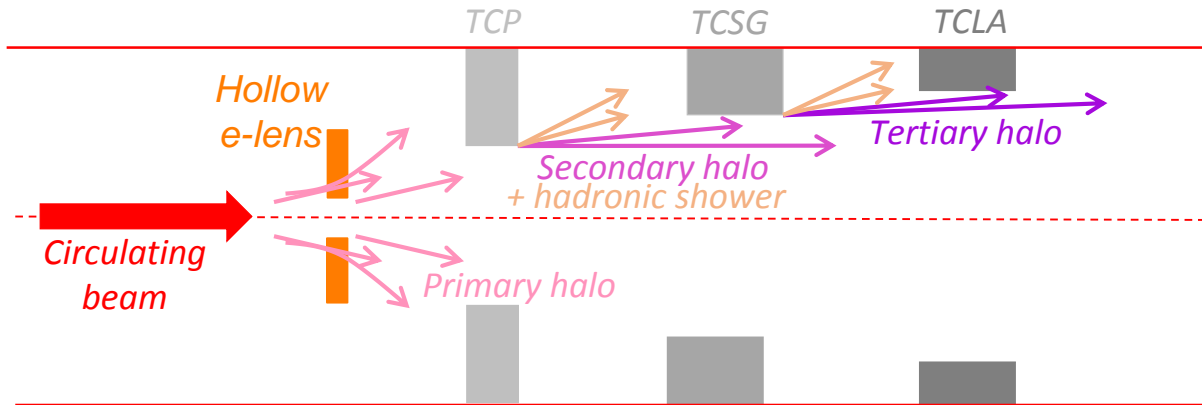


## Possible consequences:

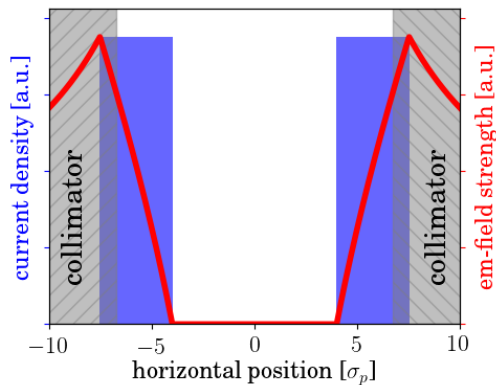
*Magnet quench*  
*Permanent damage to TCPs*

# Hollow e-lens assisted collimation

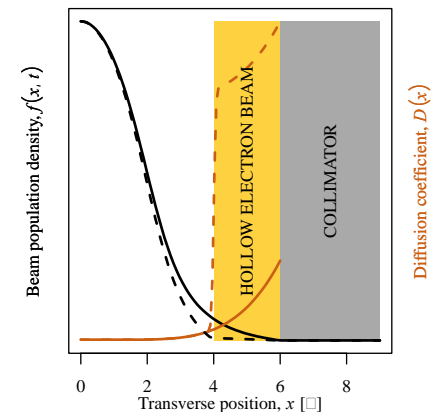
Working principle: hollow electron beam as additional hierarchy layer



em-field acting only  
on halo particles



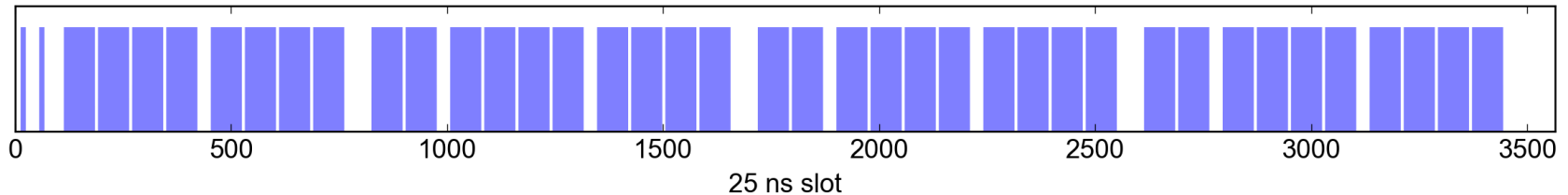
Increased diffusion speed  
and depleted halo population



# Possible working scenario

## Baseline HL-LHC filling pattern

25ns\_2760b\_2748\_2495\_2560\_288bpi\_14inj\_800ns\_bs200ns\_STD



### Machine protection constraints:

- Leave **witness trains** for an early loss detection

- ✓ **pulse rise-time** (10%-90%) of **200 ns** due to internal structure of SPS batches
- ✓ **pulse length** in the range **from 1.2  $\mu$ s to 86  $\mu$ s** (48 bunches to entire beam)
- ✓ full range of current **0 – 5 A always available**

### Main requirements on **halo depletion**:

#### Crab cavity (CC) failure

2  $\sigma$  depleted halo before TCP



**e-beam always on (DC mode) when CC on**

#### Orbit jitter

**More aggressive pulsing patterns**  
needed **before going to collision**



Compromise between removal rate  
and effects on core

# On-going studies

## Main aim:

**Define** possible **operational scenario** and **parameters** of **e-lens** in HL-LHC, that provide optimal removal rate of beam tails in each point of the cycle



**Best compromise** between **operational needs** and **hardware feasibility** to be found, parameter space diverge quickly (excitation modes, e beam current and radius, MO, Q', ...)

## Simulations approach used:

### 1. **Dynamic Aperture** simulations and **Frequency Map Analysis**



Fast simulations to **explore the parameter space** and guide the choice of a subset

### 2. **Complete tracking** simulations tacking into account **collimation**



Detailed evaluation of **beam tail depletion** and **effects on the core**

# Parameters explored

- Effect of several parameters studied:

- ✓ **Inner radius (r1):** 3, 5, 7, 9  $\sigma$
- ✓ **Pulsing pattern:** Continuous (DC), Random ON-OFF (RND), Continuous with random current between 0 A and 5A (RNDI), pulsed every 1, 2, 3, ..., 10 turns
- ✓ **e-beam current:** 1 A, 2 A, 3 A, 4 A, 5 A
- ✓ **Octupole current (MO):** -600 A, -450 A, -300 A, -150 A, 0 A, 150 A, 300 A
- ✓ **Chromaticity (Q'):** 0, 2, 5, 10, 15

- Machine optics:

- ✓ HL-LHC **v1.3**, **7 TeV**,  **$\beta^* = 15$  cm**, **separated beams**, **multipolar errors** included (completer list of machine and e-lens settings reported in backup as reference)

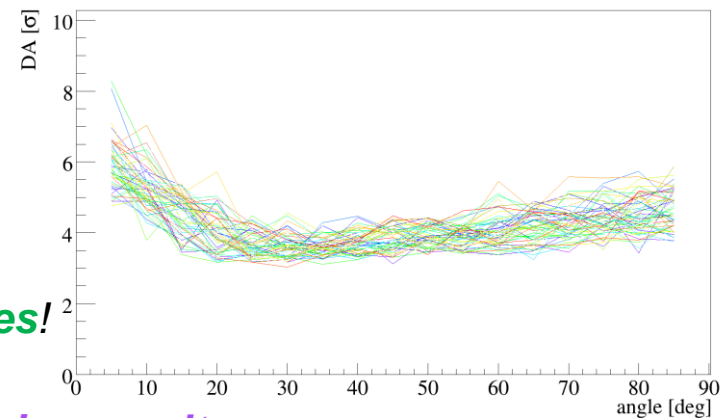
# Dynamic Aperture simulations

Simulations performed using **SixTrack**:

- **multipolar errors** (w/o beam-beam)
- **$10^6$  turns**
- **60 seeds, 17 angles, 10 amplitudes**

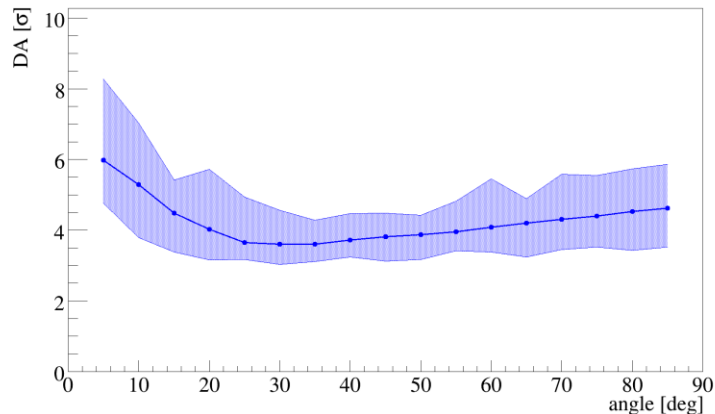


**10200 jobs** of several hours and **more than 100 cases!**  
*Impossible without combining **HTC** and **BOINC**!*



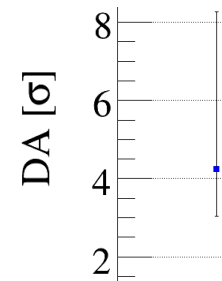
Two ways of showing results

**Average DA over all seeds**



**Envelope: absolute min and max DA**  
over all seeds

**Average DA over all seeds and angles**

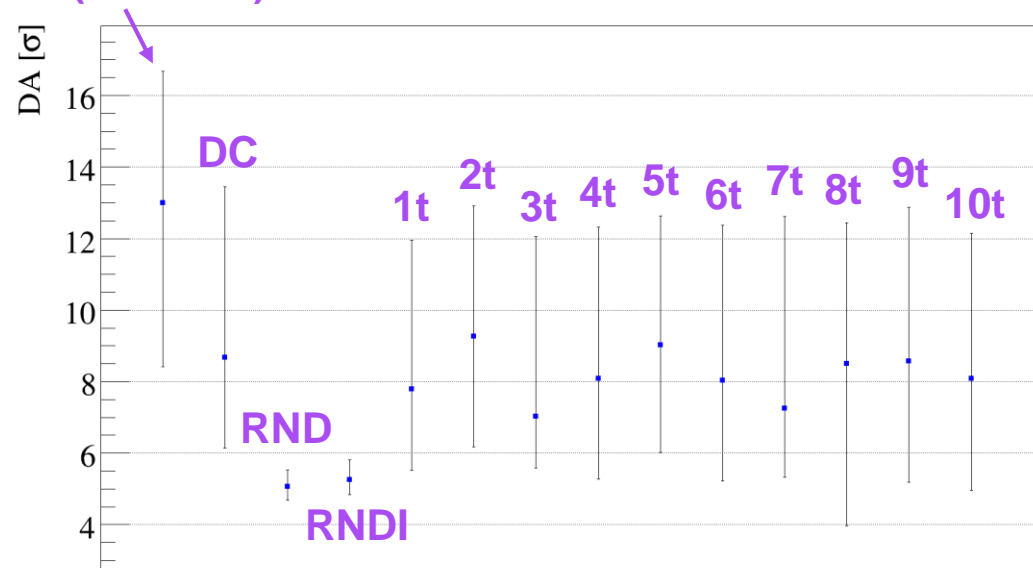


**Error bars: absolute min and max DA**  
over all seeds and angles

# Summary pulsing pattern

Example of DA for **different excitation mode** with  $r1 = 5 \sigma$ ,  $MO = 0 \text{ A}$  and  $Q' = 2$   
**(e-beam current always 5 A, except for random current modulation RNDI)**

Reference case  
 (w/o HEL)

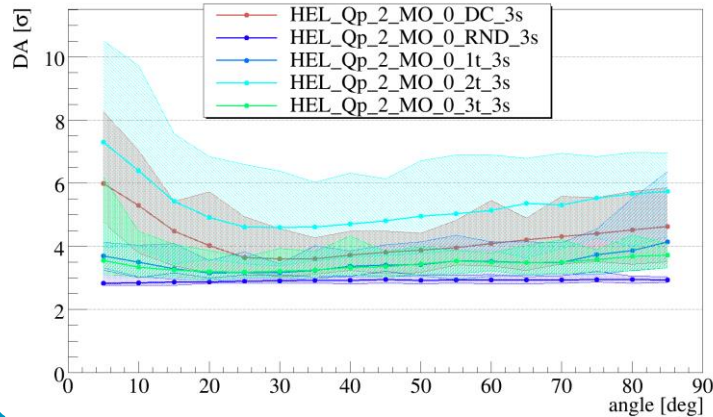


- **Clear effect of e-lens on DA:** the closer the DA to  $r1$ , the more efficient the excitation mode

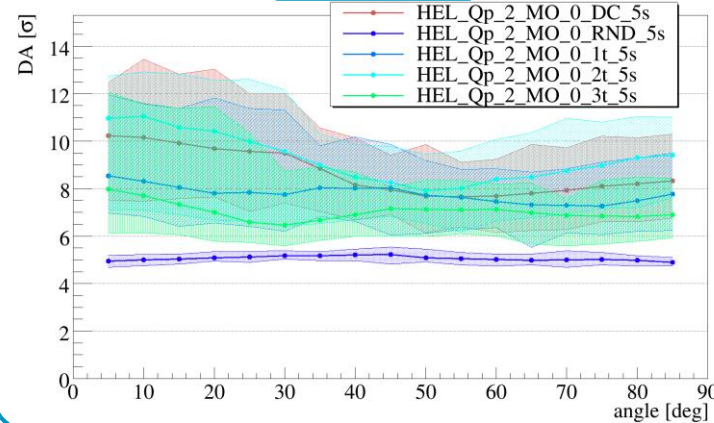
➔ Ranking of efficiency (avr DA) = **RND, RNDI, 3t, 7t, 1t, 6t, 4t, 10t, 8t, 9t, DC, 5t, 2t**

# Summary r1 scan

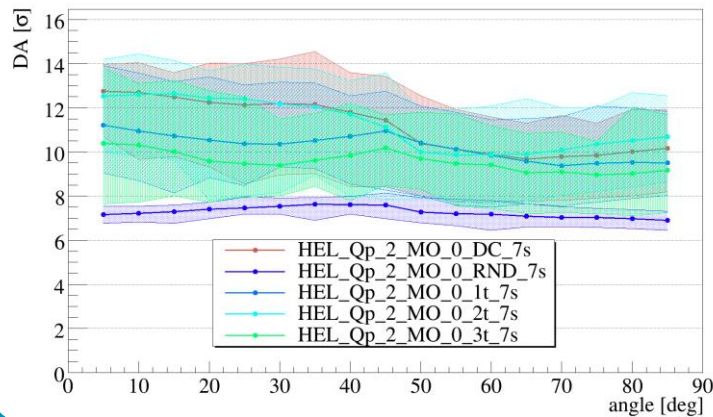
**$r1 = 3 \sigma$**



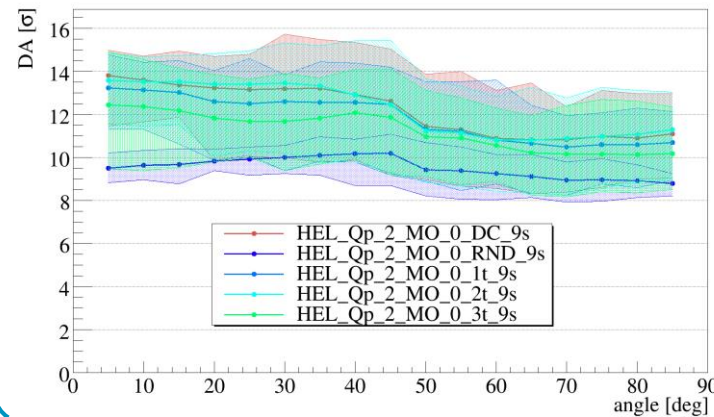
**$r1 = 5 \sigma$**



**$r1 = 7 \sigma$**



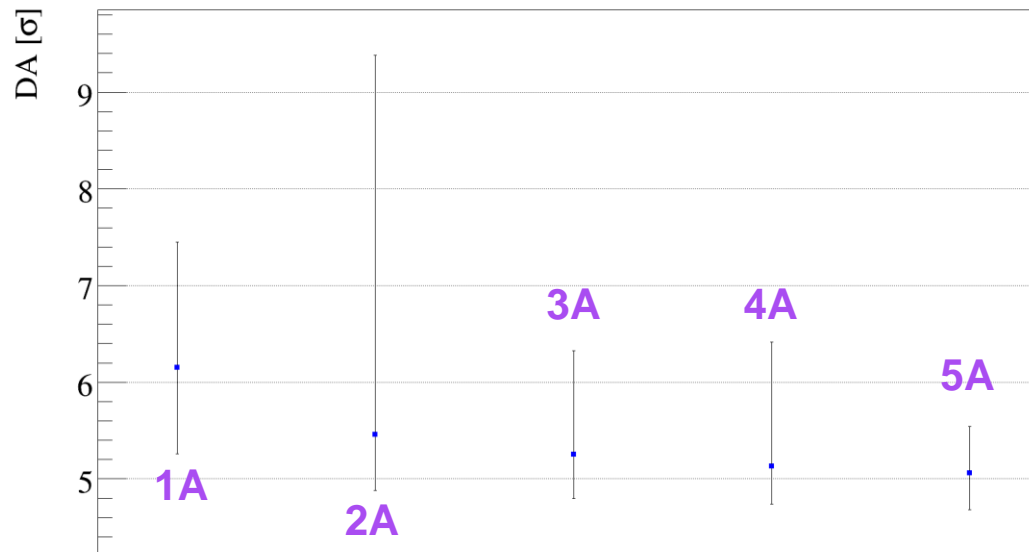
**$r1 = 9 \sigma$**



The **larger  $r1$** , the worse the **magnetic field quality** and smaller the **e-beam density** ➡  
➡ **Reduced difference** of efficiency for between **pulsing patterns**

# Summary e-beam current scan

Example for *random ON-OFF excitation with  $r1 = 5 \sigma$ ,  $MO = 0$  A and  $Q' = 2$*



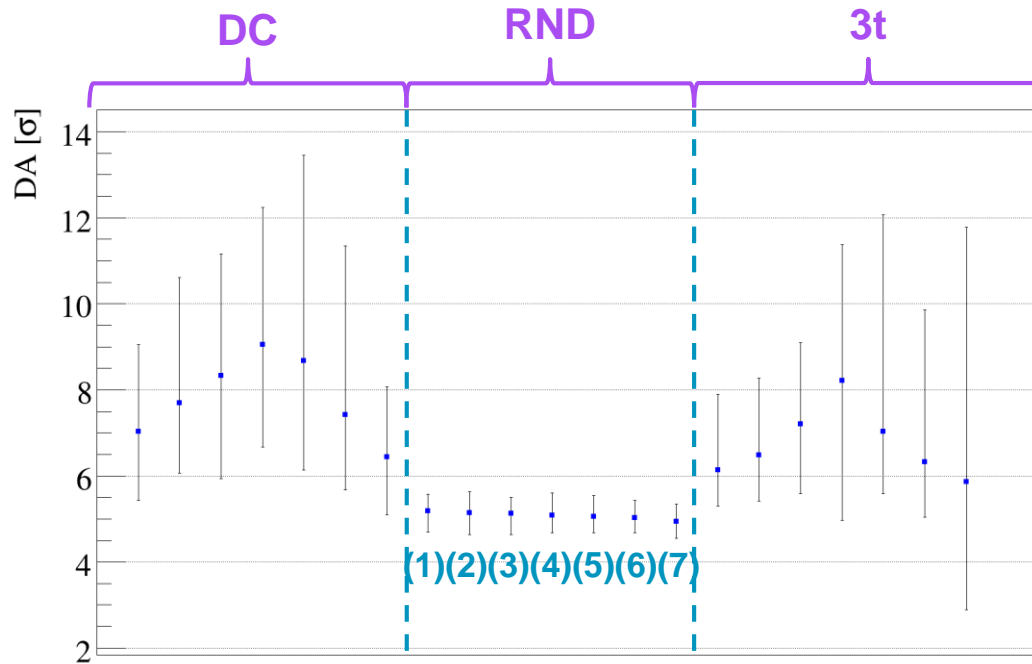
- **Very similar** average DA with  $I > 3A$



Significant operational **margins on e-beam current**

# Summary MO current scan

Example for **DC, RND and 3t excitations** with  $r1 = 5 \sigma$  and  $Q' = 2$

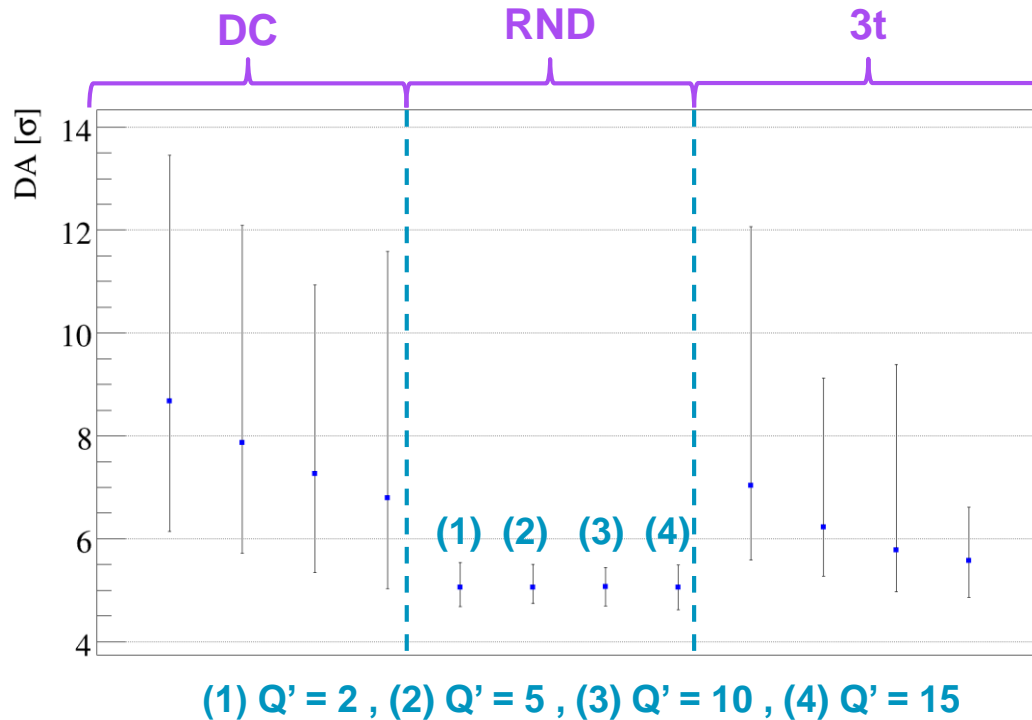


(1) MO = -600 A , (2) MO = -450 A , (3) MO = -300 A , (4) MO = -150 A , (5) MO = 0 A ,  
(6) MO = 150 A , (7) MO = 300 A

- **All** excitation **modes strongly affected** by MO current, **except RND**
- **Positive MO current beneficial** for e-lens efficiency

# Summary Q' scan

Example for **DC, RND and 3t excitations** with  $r1 = 5 \sigma$  and  $MO = 0 A$



- **All** excitation **modes strongly affected** by chromaticity, **except RND**
- **Monotonic increase of e-lens efficiency** as a function of Q'

# Dynamic Aperture Vs Turns

## Main aims:

1. Study the behaviour of **DA as a function of the simulated turns**
2. Use parametric fit to **extrapolate DA at much larger turns**
3. Use fit parameters to perform **predictions on optimal pulsing pattern**

$$DA(N) = b \left[ \ln \frac{N}{N_0} \right]^{-\kappa}$$

- **Two models used to describe DA evolution:**  
(arXiv:1909.09516)

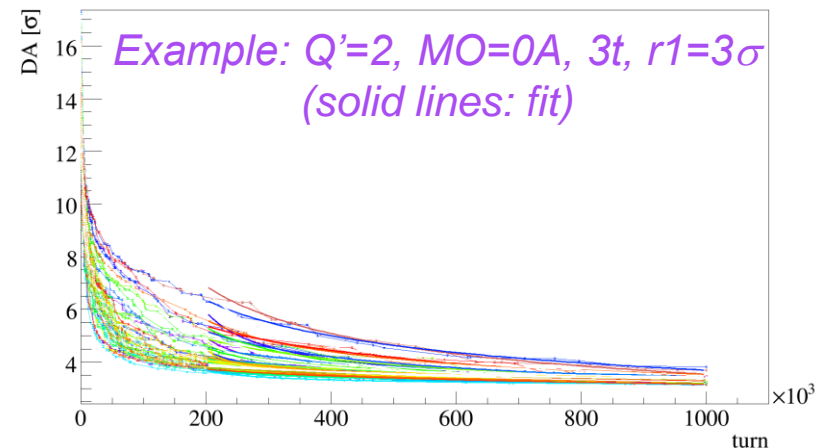
$$DA(N) = b \left[ \ln \mu N + \frac{\kappa}{2} \ln \left( \frac{2}{\kappa} \ln \mu N \right) \right]^{-\kappa}$$

- **Models** valid for **natural diffusive mechanisms**

→ **e-lens additional factor** → **Parametric study** to define minimum turn for the fit

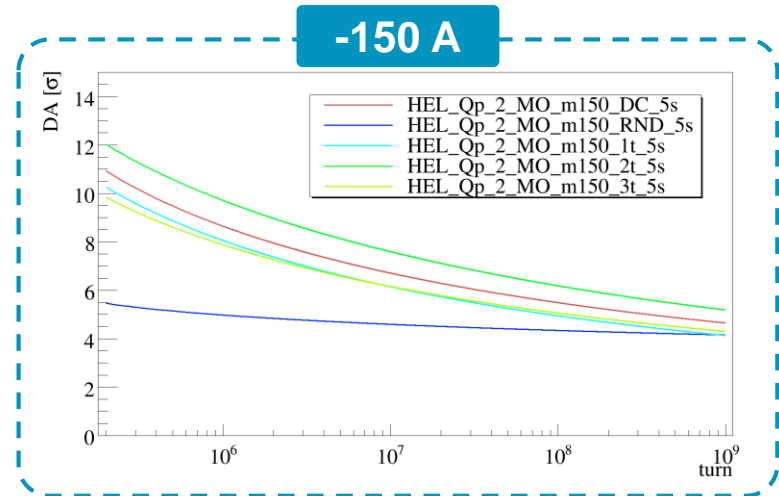
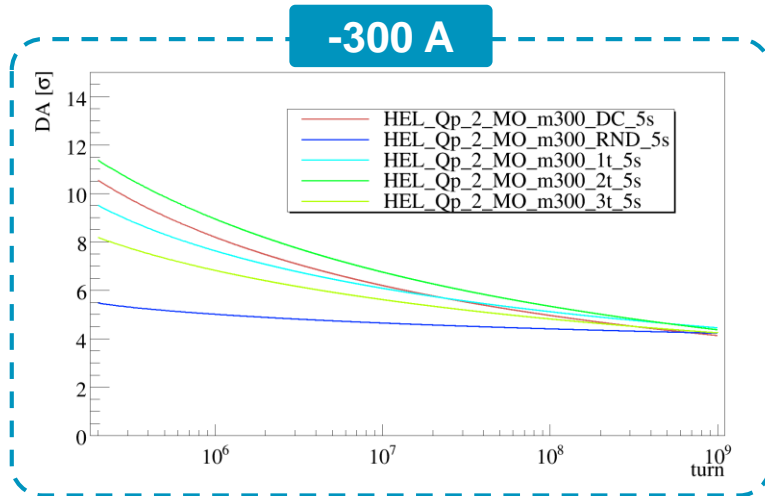
**Average DA vs Turns over 60 seeds**  
evaluated and **extended to  $10^9$  turns** (~24h)

Checked **difference between two models:**  
**below 4%** along the  $10^9$  turns



# Dynamic Aperture Vs Turns and MO current

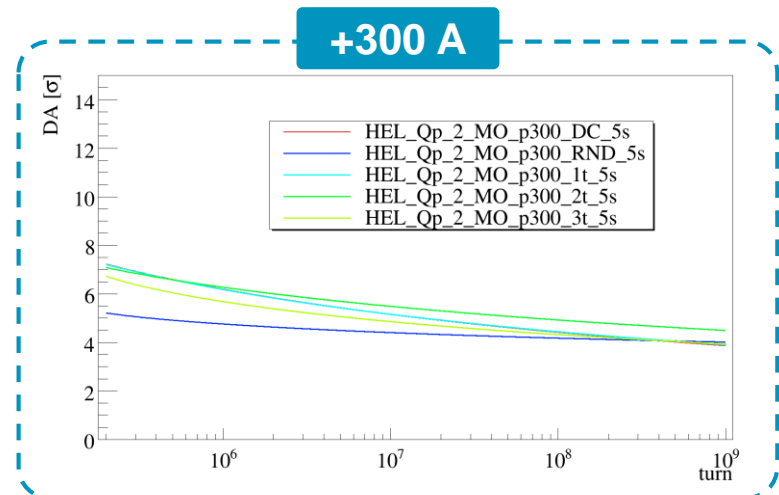
Example for **different excitations modes with  $r1 = 5 \sigma$  and  $Q' = 2$**



The larger the MO current



The smaller the initial DA and decay rate  
(Similar behaviour as a function of  $Q'$ )

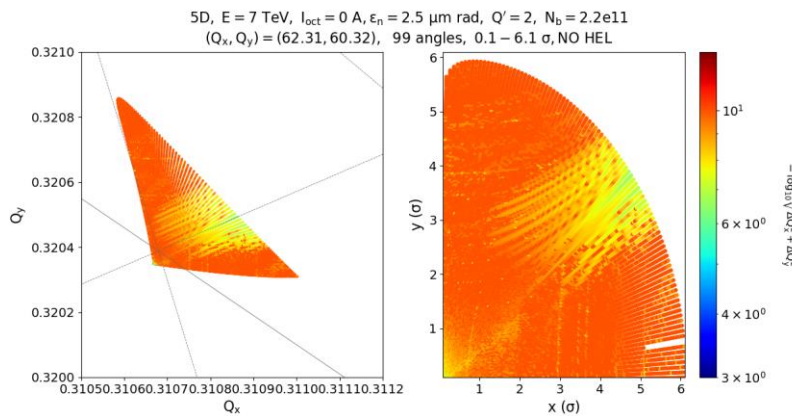


# Frequency Map Analysis

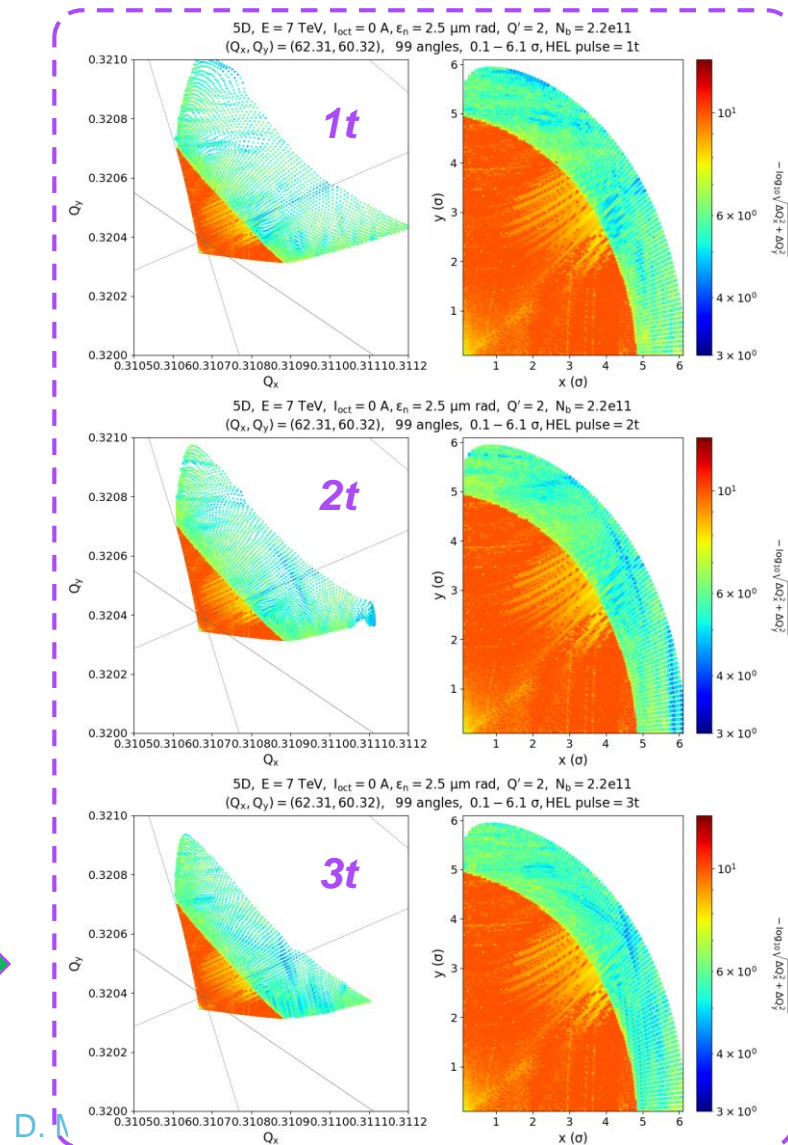
**Main aim:** understand driving terms to enhance halo diffusion speed

- 10000 turns simulated:
  - **Initial Q** calculated over the **first 3000 turns**
  - **Final Q** calculated over the **last 3000 turns**

**Example of FMA w/o e-lens**  
 $I_{MO} = 0$  A,  $Q' = 2$



*Ideal case to study e-lens effect*  
 $(r1 = 5 \sigma)$

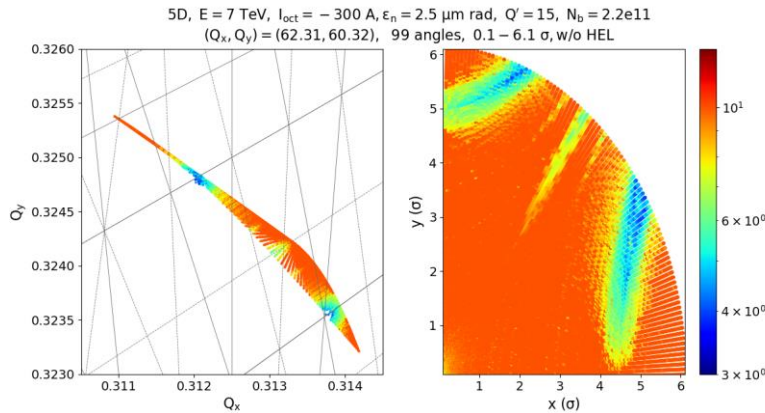


D.

# Coupling with non linearity

## Example of FMA w/o e-lens

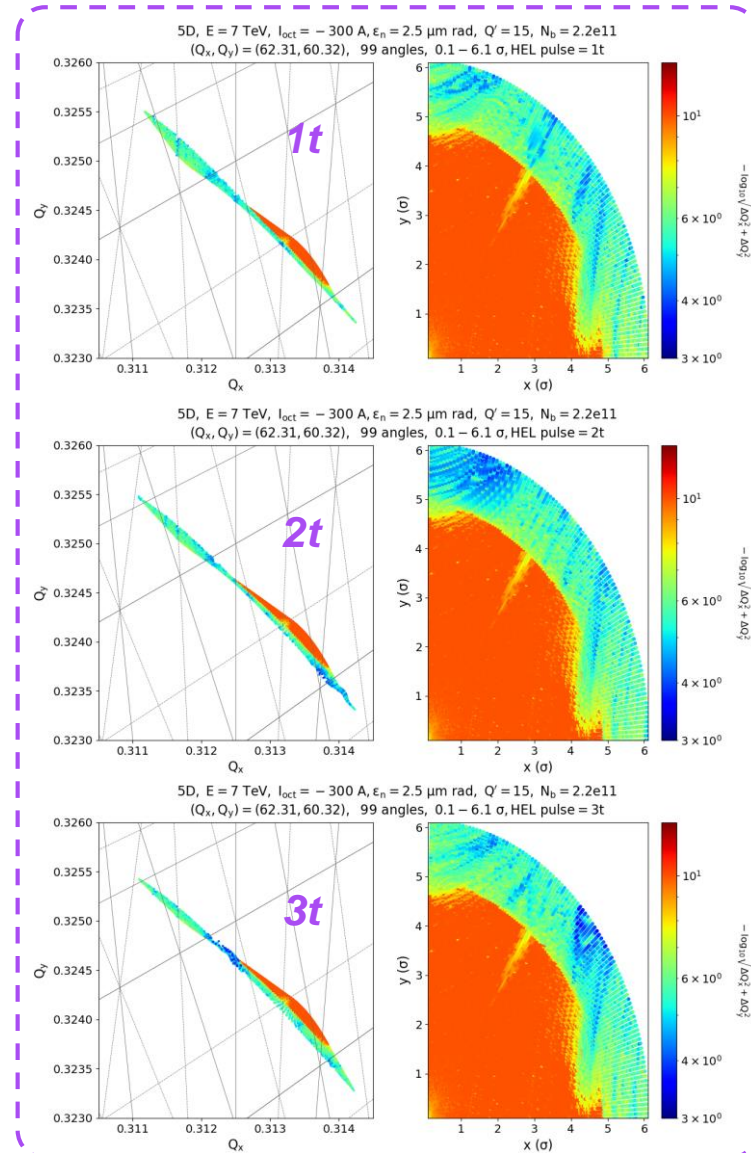
$I_{MO} = -300$  A,  $Q' = 15$



## Main qualitative observations:

- Clear distortion of Q phase space
- **e-lens enhances** effects due to **non linearity**

Crucial for **DC** mode with **beam-beam**



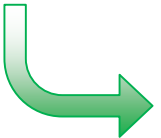
# Conclusions

- **Simulation studies** on-going taking into account **several parameters**:



- ✓ Inner radius, current and pulsing pattern of the e-beam
- ✓ Octupole current and chromaticity

- **Interesting results** obtained



- ❖ **RND** pulsing pattern sets **DA at e-lens inner radius**  
(complete **tails removal** on the scale of **few s**, also at **low current**)
- ❖ **First steps** to study **correlation between DA and tail depletion rate**  
(link DA with time needed for tail depletion as a function of pulsing pattern)

Key ingredients to define **operational parameters** and **tolerances at each point of the cycle**

- **Next steps/on-going studies:**



- **Halo depletion** simulations
- Introduction of **residual field** to study effects on the **beam core**  
(**field maps from BINP just arrived**)



***Thank you for your attention!***



# Outline

## *Backup*

# Machine settings

- Optics = HL-LHC v1.3
- BP = collision (but still separated beams)
- Beam-beam = NO
- Field errors = MBRB, MBRC, MBRS, MBX, MBW, MQW, MQTL, MQMC, MQX, MQY, MQM, MQML, MQ, MQXF
- Turns =  $1e6$
- Angles = 17
- Aperture steps = 10 (from  $2\sigma$  to  $22\sigma$  with  $2\sigma$  step)
- Seeds = 60

# e-lens settings

- Length = 3 m
- e-beam current = 5 A
- e- kinetic energy = 10 keV
- e- distribution = UNIFORM
- Pulsing patterns = DC, RANDOM on-off, RANDOM current, 1 turn, 2 turns, ..., 10 turns (i.e. 1 turn ON and 1 turn OFF, 1 turn ON and 2 turns OFF , ... , 1 turn ON and 10 turns OFF)
- $r1 = 3, 5, 7, 9 \sigma$
- $r2$  = given by magnetic compression using real e-gun dimension ( $r1=4.025\text{mm}$ ,  $r2=8.05\text{mm}$ )
- Bending solenoids = NO