What can be gained with a HEL in terms of increased diffusion for HL-LHC

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CERN, Review of Hollow E-Lens Needs for HL-LHC
October 6th, 2016

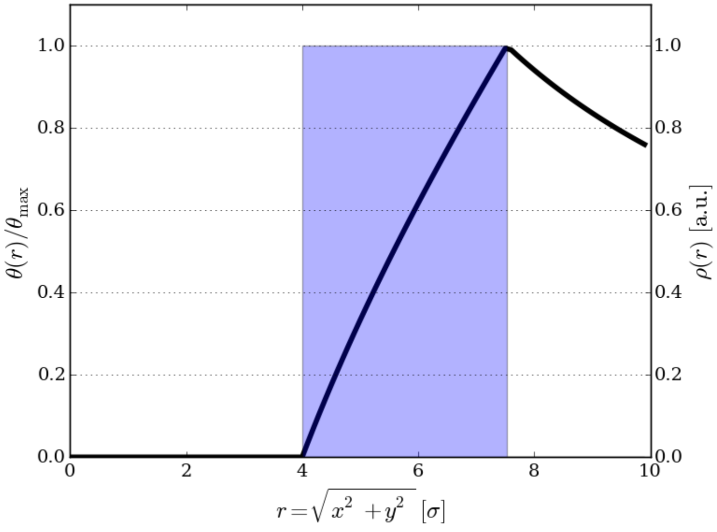
Literature HEL simulations

- simulations for LHC:
  - V. Previtali, G. Stancari, A. Valishev , S. Redaelli, FERMILAB-TM-2560-APC
  - A. Valishev, FERMILAB-TM-2584-APC
- HL-LHC simulations and experimental results (first drafts published):
  - HL-LHC: M. Fitterer, G. Stancari, A. Valishev, S. Redaelli: FERMILAB-TM-2636-AD
  - LHC experiment: M. Fitterer, G. Stancari, A. Valishev FERMILAB-TM-2635-AD

- modeling of e-lens:
  - kick from ideal uniform profile:

$$\theta_{\max} = \theta(r_2) = \frac{2LI_T(1 \pm \beta_e\beta_p)}{4\pi\epsilon_0 \left(B\rho\right)_p \beta_e\beta_p c^2} \cdot \frac{1}{r_2}$$

  - e-lens bends:
    G. Stancari, FERMILAB-FN-0972-APC
  - multipole expansion to model realistic profiles: I. Morzov, G. Stancari, A. Valishev, D. Shatilov, FERMILAB-CONF-12-126-APC



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Simulations

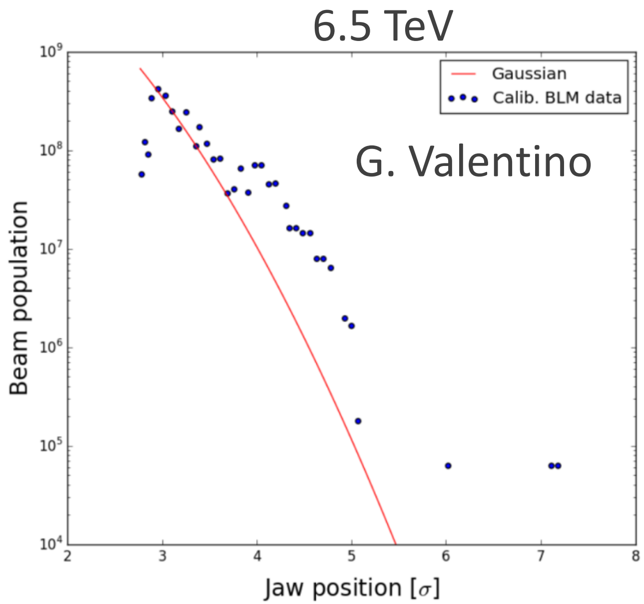
available codes: SixTrack, LifeTrac and Merlin

main objectives:

- effect of HEL on:
  - halo -> compare halo removal rates := $\Delta I_{halo}/\Delta t$
    - halo removal rates for different scenarios with and without HEL
    - obtain halo removal rates vs amplitude
    - study effect of influence of longitudinal plane
  - beam core -> emittance + losses

strong dependence on beam distribution model:

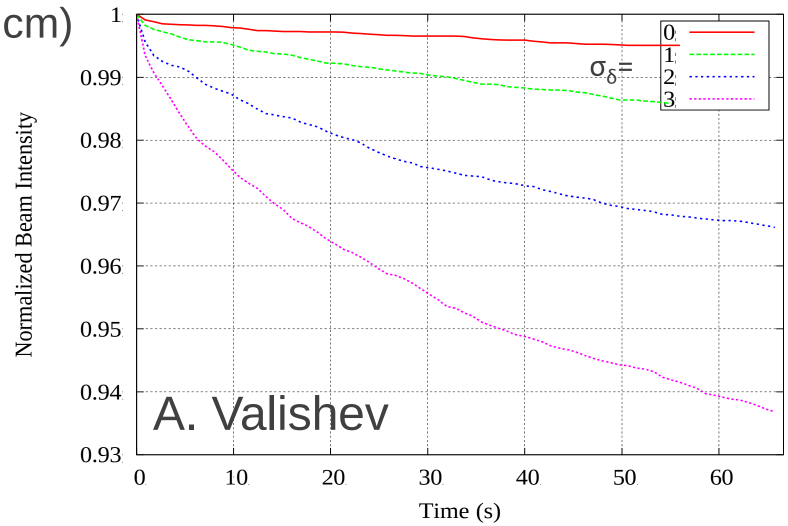
- beam core: 6D Gaussian distribution cut at 6 σ
- halo:
  - to predict the true losses a good knowledge of halo population and diffusion is needed (see Gianluca's, Yanni's and Fanouria's talks) -> in general very difficult task!
  - instead use uniform transverse distribution between 4 and 6 σ and with δp=0 and Gaussian in (z-δp/p) cut at 6σ



LHC HEL simulations

simulation parameters:

- nominal LHC V6.503 collision optics ($\beta^*_{IP1/5}$=55 cm)
- beam parameters: N_p=1.15x10^{11}, ε_N=3.75 µm, σ_E=1.1x10^{-4}, σ_z=7.5 cm
- HEL in IR4 with $\beta_x = \beta_y$



main results for halo:

- no HEL: minimal losses with beam-beam (0.002%/s = 0.12%/min = 8%/h)
- with HEL, DC mode, I_{HEL} = 3.6 A:
  - halo removal rates much smaller without beam-beam than with beam-beam
  - strong dependence on momentum
- random mode (current modulation): HEL becomes dominant loss mechanism

HEL mode	beam-beam	long. distr.	halo removal rate	
			%/s	%/h
DC, 3.6 A	no	Gaussian	0.01	40
	yes		0.07	250
random 3.6 A	no	Gaussian	0.33	1180
	yes		0.35	1267

for details: V. Previtali, G. Stancari, A. Valishev , S. Redaelli, FERMILAB-TM-2560-APC, FERMILAB-TM-2584-APC

LHC HEL simulations

main results for core:

- HEL bends: in DC mode no effect
- random mode (current modulation): HEL bends induce emittance growth for U-shape, not for S-shape due to uncompensated kicks for U-shape (without beam-beam + 10% modulation: S-shape - 0 %/h, U-shape - 38 %/h)

HL-LHC simulations + experiments

Simulation studies and experiments:

- beam core (for details see FERMILAB-TM-2635-AD):
  - in DC mode no emittance growth is expected from the HEL
  - in pulsed mode the HEL can induce noise on the beam core -> emittance growth
  - experiment this September at the LHC at injection + simulations in order to estimate tolerance on noise (in progress), see LSWG meeting.

- halo (for details see FERMILAB-TM-2636-AD):
  - comparison of halo removal rates without and with HEL for different key scenarios in order to evaluate of HEL performance at top energy
  - impact of a pulsed operation. Option for pulsing/modulating are currently:
    - random: random modulation of the e-lens current (white noise)
    - resonant: switching the e-lens on/off every nth turn (drives nth order resonances)

HL-LHC HEL halo simulations

HL-LHC scenarios:

LHC cycle	$\beta^*_{x,y}$ [m] IP1/5	β^* [m] IP2/8	x-angle [μrad] (IP1/2/5/8)	spectrometer polarity (IP2/8)	separation [mm] IP1/2/5/8	$Q'_{x/y}$	I_{MO} [A]
flat top	6.0,6.0	10.0/3.0	295/170/295/220	1/1	0.75/2.0/0.75/2.0	15	-550
						3	-550
						3	0
start leveling	0.7,0.7	10.0/3.0	295/170/295/220	1/1	0/0/0/0	3	-550
squeezed round	0.15,0.15	10.0/3.0	295/170/295/220	1/1	0/0/0/0	3	-550
squeezed flat	0.075,0.30	10.0/3.0	275/170/275/220	1/1	0/0/0/0	3	-550

beta* leveling:

$\beta_{x,y}$(IP1/5) [m]	bunch intensity [10^{11}]
0.70,0.70	2.2
0.42,0.42	1.7
0.30,0.30	1.5
0.15,0.15	1.1

HL-LHC HEL halo simulations

simulation parameters:

- code: LifeTrac
- HL-LHC layout V1.0
- HEL in IR4 with $\beta_x = \beta_{y,}$ inner radius 4 σ (=beam sigma with 2.5 µm emittance)
- HEL current of 3.6 A (CDR value), 5.0 A (maximum of current gun)
- halo distribution: uniform transverse distribution between 4 and 6 σ with δp/p=0 or Gaussian in (z-δp/p) cut at 6 σ (σ = beam sigma)

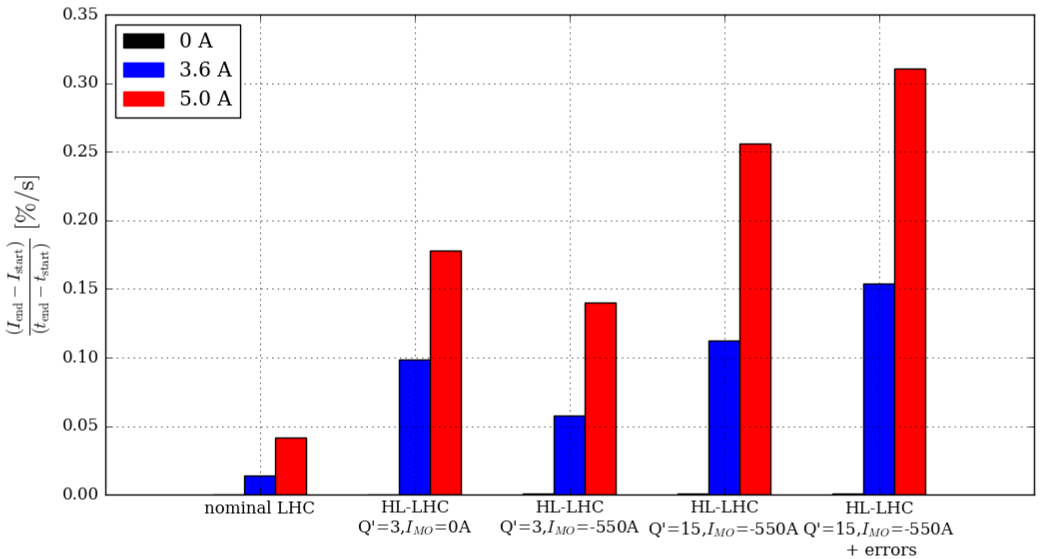
main observations (details see next slides):

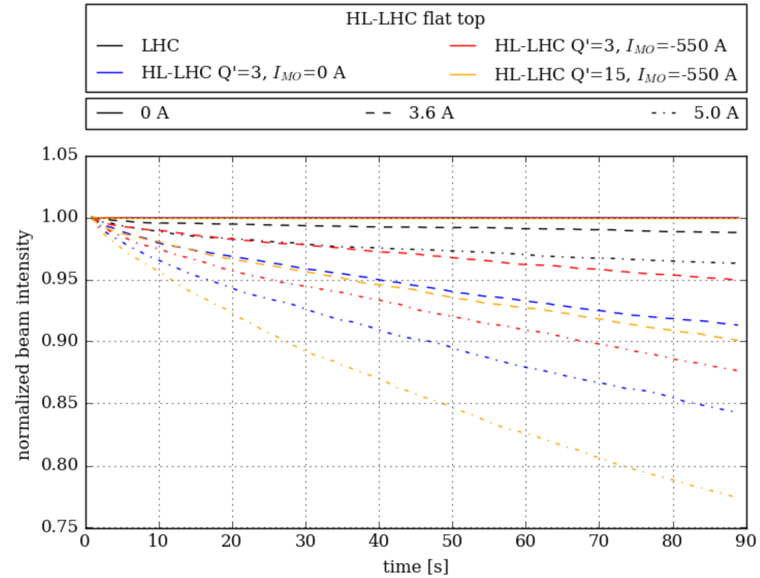
- halo removal rates depend on:
  - δp/p, smallest rates for δp/p=0 (strong dependence, up to x100 or more)

    -> in the following only removal rates for Gaussian in (z,δp/p)
  - non-linearities: the “stronger” the non-linearity the higher the halo removal rate
- non linearities considered:
  - chromaticity and Landau damping octupoles needed for beam stability in particular for separated beams (flat top)
  - beam-beam (full crabbing + long-range)
  - magnetic errors (”standard” errors from latest error tables as used for dynamic aperture simulations)
- pulsing considerably increases the halo removal rates. Random pulsing is most efficient.

HL-LHC HEL halo simulations

Flat top – dependency on chromaticity and octupole current:

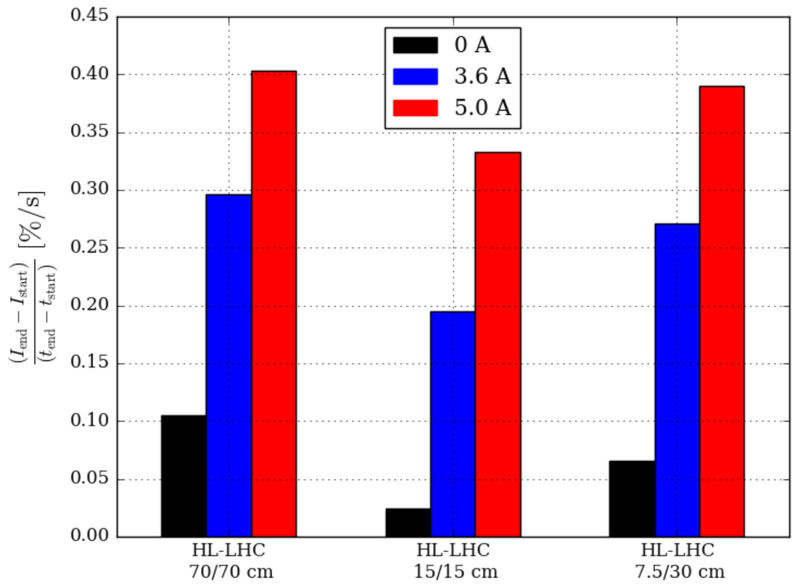


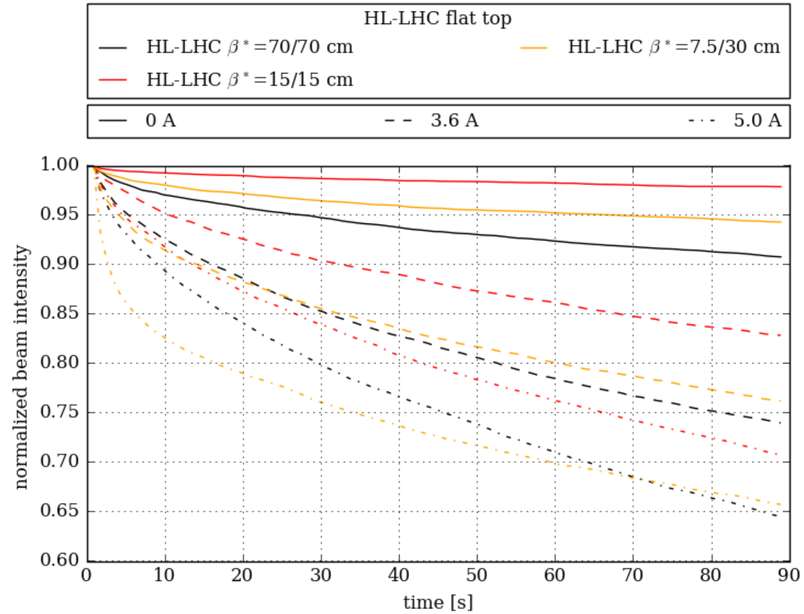


- halo removal rates for Q'=3, I_{MO}=0 could be very dependent on working point due to small tune spread
- highest halo removal rate for high chroma + octupoles + further increase with errors
- halo removal rates for 3.6 A between 0.06 %s (= 3.45 %/min = 207 %/h) and 0.15 %/s (= 9.25 %/min = 555 %/h)

HL-LHC HEL halo simulations

Leveling – dependency on β* and beam intensity (see leveling scenario):

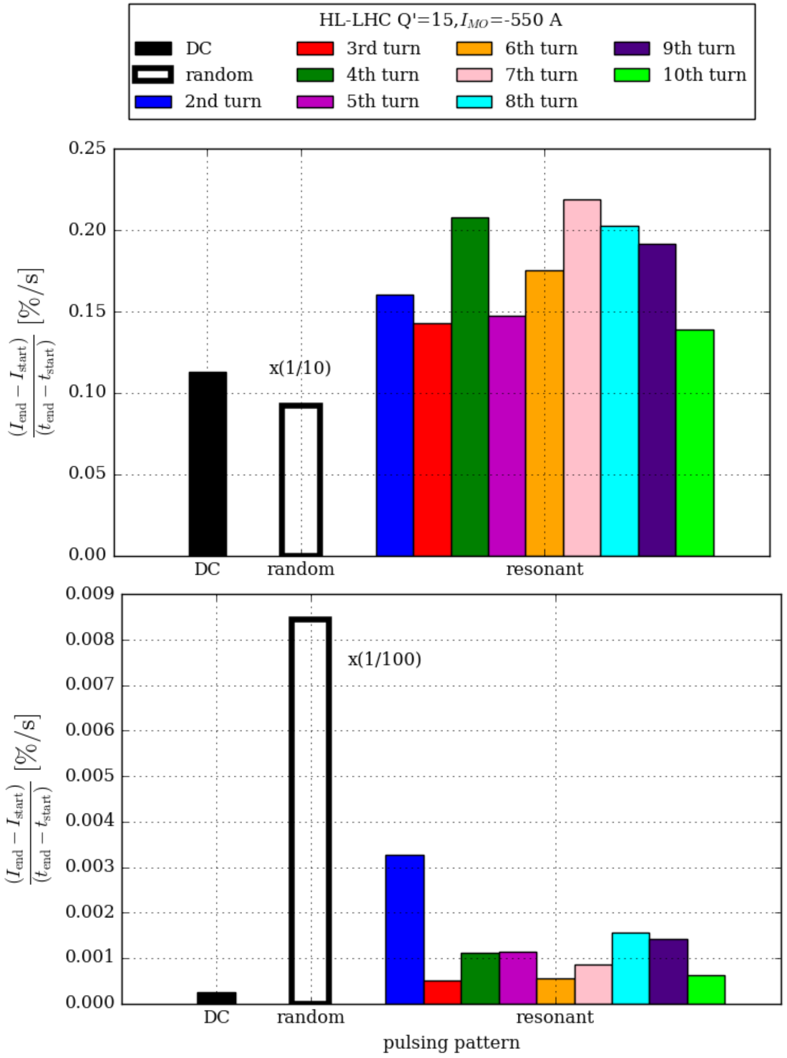




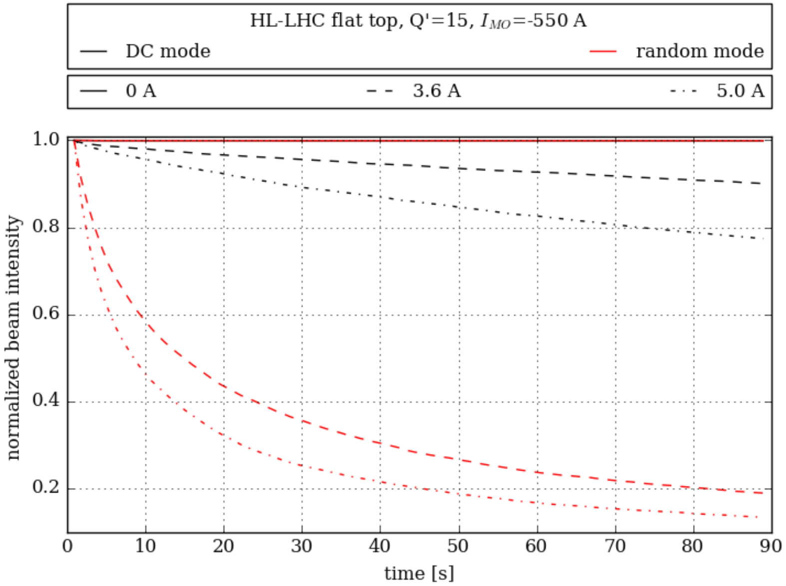
- already losses without HEL (small DA)
- highest halo removal rate for β*=70 cm (smallest DA)
- halo removal rates for 3.6 A around x2 higher than at flat top, explicitly between 0.20 %s (= 11.70 %/min = 702 %/h) and 0.30 %/s (= 17.76 %/min = 1060 %/h)

HL-LHC HEL halo simulations

flat-top with pulsing:



- random mode: pulsing becomes dominant loss mechanism for (for random even the same for δp/p =0 and (z,δp/p))
- random mode much more effective than resonant mode, in particular for δp/p =0
- random, 3.6 A: around 0.92 %/s (= 55.26 %/min = 3320 %/h)
- resonant, 3.6 A: 0.14 %s (= 8.58 %/min = 514 %/h) to 0.22 %/s (= 13.14 %/min = 789 %/h)



Conclusion and Outlook

Halo:

- HEL increases the halo removal rates in all cases considerably

- stronger non-linearities imply in general higher halo removal rates
- pulsing considerably increases the diffusion, random mode much more efficient than resonant mode

- small removal rates for separated beams compared to colliding beams

  ➡ do we need to pulse at flat top in order to clean the halo within minutes?
- for colliding beams 11.70 %/min - 17.76 %/min are reached, sufficient for continuous halo depletion ➡ no pulsing

- losses can differ by a order of magnitude for on and off-momentum particles

  ➡ more studies needed: changes with real IR3/IR7 betatron and momentum cleaning, dependence on dispersion@HEL, …

Conclusion and Outlook

Core:

- in DC mode configuration no effect in terms of increased losses or emittance growth on the beam core is expected (even with U-shape)

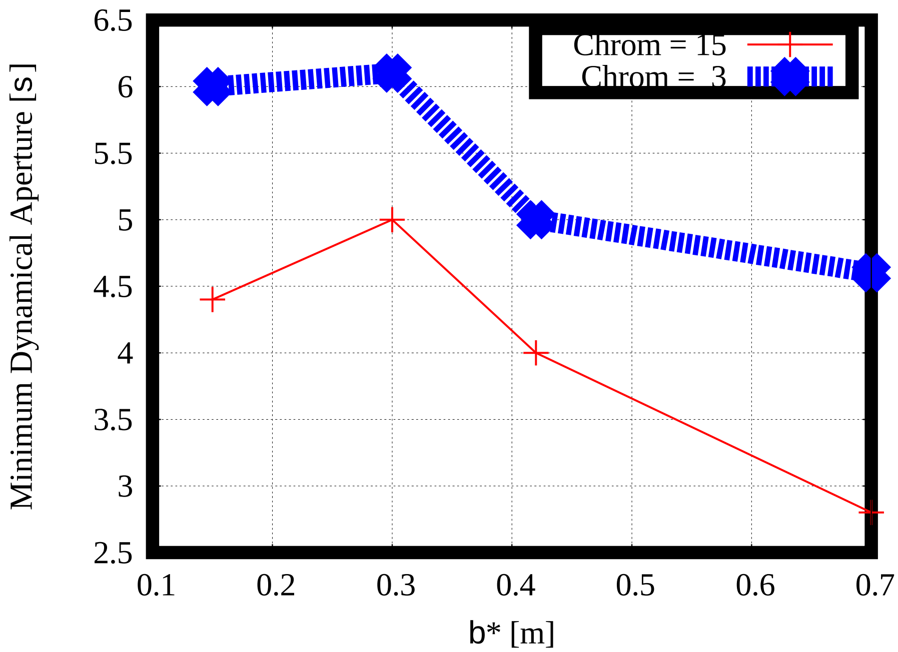
- pulsed e-lens operation:
  - random mode much more efficient than resonant mode
  - with the resonant mode one could find an excitation pattern which doesn’t affect the core, but depletes the halo (remember: only certain resonances are driven)
  - in case of profile imperfections in the e-beam, pulsing induces noise on the p-beam

    ➡ solid definition of tolerances on profile imperfections needed

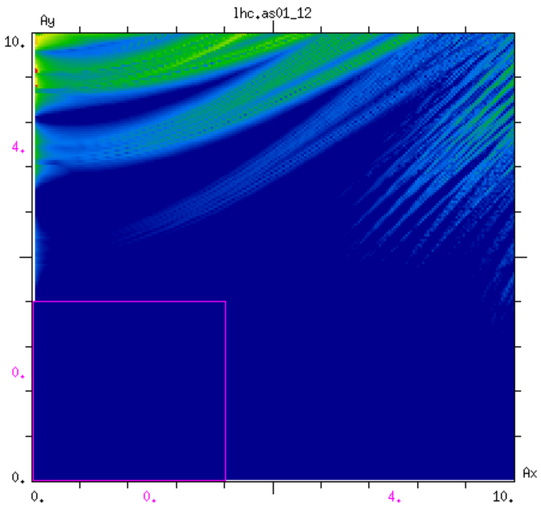
Backup Slides

DA for beta*-leveling HL-LHC

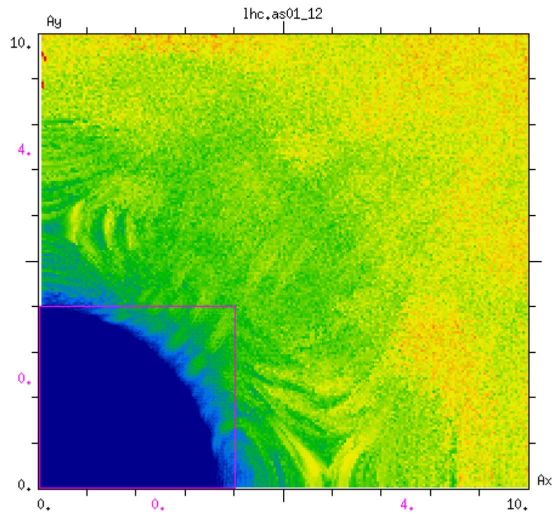
- minimum DA caluclated with LifeTrac
- no errors, octupole current of -550 A (MOF)
- spectrometer configuration in IR2/8 yielding smallest DA
- half crossing angle IR1/5: 295 urad
- beam-beam: full crabbing + long range



FMA analysis

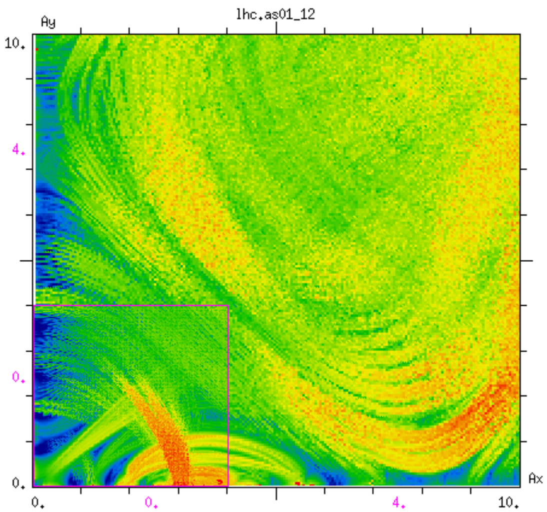


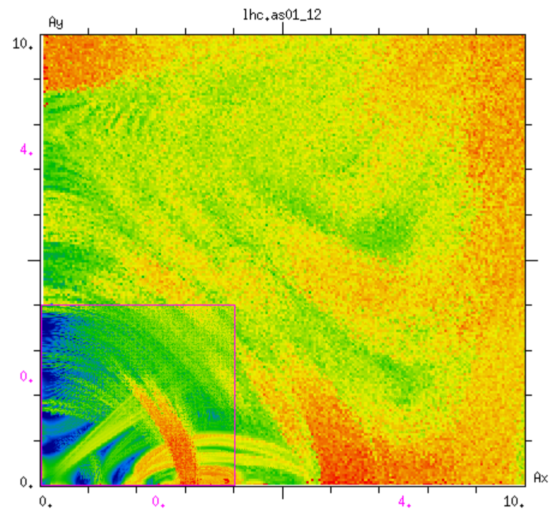
no HEL



3.6 A

flat top, Q'=15, IMO=-550 A
- small non-linearities
- "uniform" enhancement of diffusion





15 cm β*, Q'=3, IMO=-550 A
- strong non-linearities
- HEL enhances resonances

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Simulation Parameters LHC

for details: V. Previtali, G. Stancari, A. Valishev , S. Redaelli, FERMILAB-TM-2560-APC, FERMILAB-TM-2584-APC

- uniform transverse distribution between 4 and 6 σ, Gaussian in $(z,\delta p/p)$ or $\delta p/p=0$
- nominal LHC V6.503 collision optics ($\beta^*_{IP1/5}$=50 cm), no errors, no octupoles, Q'=2
- single collimator (black absorber) @ 6 σ
- equal $\beta_x = \beta_y$ =180 m @ e-lens, installed in IR4 @ -40 m from IP
- beam parameters: $N_p=1.15\times10^{11}$, $\varepsilon_N=3.75$ µm, $\sigma_E=1.1\times10^{-4}$, $\sigma_z=7.5$ cm
- 10^4 particles, 5×10^6 turns = 450 s real machine time
- with and without beam-beam
- in case of beam-beam: collisions in IP1/5/8, 94 long-range interactions, 25 ns bunch spacing

Simulation Parameters HL-LHC

for details: M. Fitterer, G. Stancari, A. Valishev, S. Redaelli: FERMILAB-TM-2636-AD

- uniform transverse distribution between 4 and 6 σ, Gaussian in (z,$\delta p/p$)
- HL-LHC V1.0 layout
- single collimator (black absorber) @ 6 σ
- equal $\beta_x = \beta_y$ @ e-lens, installed in IR4 @ -40 m from IP, inner radius adjusted to 4 beam sigma (ε_N=2.5 µm)
- beam parameters flat top: $N_p = 2.2\text{x}10^{11}$, ε_N=2.5 µm, $\sigma_E = 1.1\text{x}10^{-4}$, σ_z=7.5 cm
- beam parameters leveling: $N_p = 1.1\text{-}2.2\text{x}10^{11}$, ε_N=2.5 µm, $\sigma_E = 1.1\text{x}10^{-4}$, σ_z=7.5 cm
- 10^4 particles, 10^6 turns = 90 s real machine time
- with and without beam-beam
- in case of beam-beam: collisions in IP1/2/5/8, 25 ns bunch spacing, full crabbing + long range beam-beam, spectrometer configuration in IP2/8 featuring smallest DA
- latest error tables
- coupling: fine coupling correction stopped at closest1 (matching step omitted)

Halo removal rates HL-LHC at flat top

- uniform transverse distribution between 4 and 6 σ, Gaussian in (z,δp/p)
- HL-LHC V1.0 layout
- single collimator (black absorber) @ 6 σ

HEL current [A]	β*(IP1/2/5/8) [cm]	Q'	oct. current [A]	errors	halo removal rate	
					%/s	%/h
no HEL	6/10/6/3	3	0	no	0.000	0.9
		3	-550		0.001	2.9
		15	-550		0.001	3.2
		15	-550	yes	0.001	2.2
3.6		3	0	no	0.099	355.0
		3	-550		0.058	207.0
		15	-550		0.113	406.0
		15	-550	yes	0.154	555.0
5.0		3	0	no	0.178	642.0
		3	-550		0.140	505.0
		15	-550		0.256	923.0
		15	-550	yes	0.311	1120.0

Halo removal rates HL-LHC during β* leveling

- uniform transverse distribution between 4 and 6 σ, Gaussian in (z,δp/p)
- HL-LHC V1.0 layout
- single collimator (black absorber) @ 6 σ

HEL current [A]	β*(IP1/5) [cm]	bunch intensity [10^{11}]	Q'	oct. current [A]	halo removal rate	
					%/s	%/h
no HEL	7.5/30	2.2	3	-550	0.065	234.0
	15/15	1.1			0.024	87.7
	70/70	1.1			0.105	378.0
3.6	7.5/30	2.2	3	-550	0.271	974.0
	15/15	1.1			0.195	702.0
	70/70	1.1			0.296	1060.0
5.0	7.5/30	2.2	3	-550	0.389	1400.0
	15/15	1.1			0.332	1200.0
	70/70	1.1			0.403	1450.0

Halo removal rates HL-LHC at flat top + pulsing

- uniform transverse distribution between 4 and 6 σ, Gaussian in (z,δp/p)
- HL-LHC V1.0 layout
- single collimator (black absorber) @ 6 σ

HEL current [A]	β*(IP1/2/5/8) [cm]	pulsing pattern	Q'	oct. current [A]	halo removal rate	
					%/s	%/h
3.6	6/10/6/3	none (DC)	15	-550	0.113	406.0
		random			0.921	3320.0
		2nd			0.161	578.0
		3rd			0.143	514.0
		4th			0.208	749.0
		5th			0.147	530.0
		6th			0.176	632.0
		7th			0.219	789.0
		8th			0.203	730.0
		9th			0.192	691.0
		10th			0.139	501.0

Halo removal rates HL-LHC at flat top + pulsing

- uniform transverse distribution between 4 and 6 σ, δp/p =0
- HL-LHC V1.0 layout
- single collimator (black absorber) @ 6 σ

HEL current [A]	β*(IP1/2/5/8) [cm]	pulsing pattern	Q’	oct. current [A]	halo removal rate	
					%/s	%/h
3.6	6/10/6/3	none (DC)	15	-550	0.000	0.9
		random			0.846	3050.0
		2nd			0.001	2.2
		3rd			0.003	11.8
		4th			0.001	1.8
		5th			0.001	4.0
		6th			0.001	4.1
		7th			0.001	2.0
		8th			0.001	3.1
		9th			0.002	5.6
		10th			0.001	5.1