Halo removal and effects on beam core of electron lens in HL-LHC

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Acknowledgments: G. Stancari

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

joint WP2-WP5 Meeting, 15th September 2020, CERN

Outline

I. *Introduction*

II. *On-going studies*

III. *Halo removal*

IV. *Effects on beam core*

V. *Towards operational scenario*

VI. *Conclusions*

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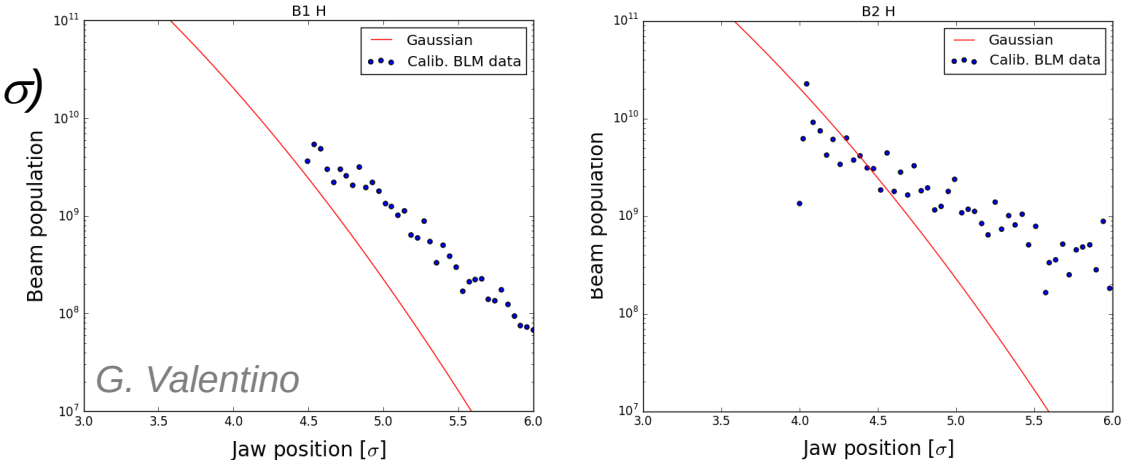
Introduction

- 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 σ) while 0.22% if Gaussian

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



Fast failure scenarios:

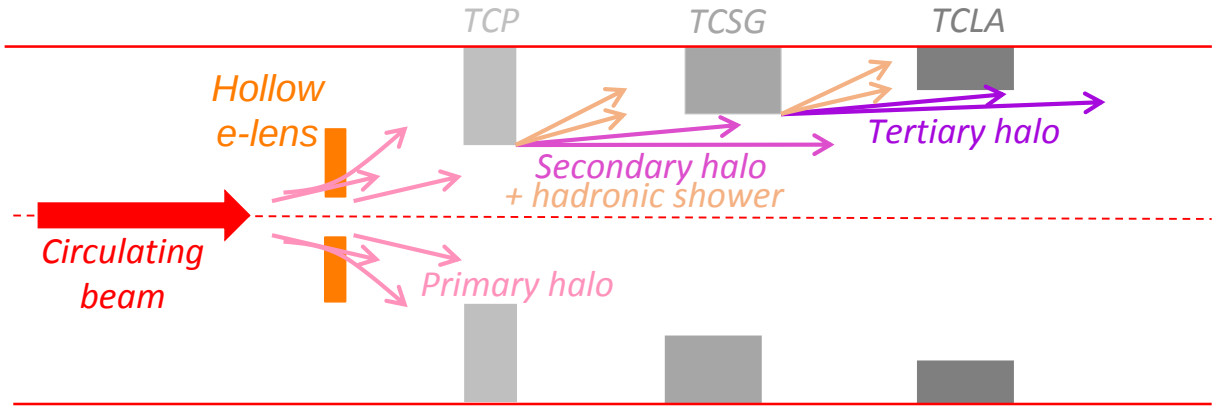
Orbit jitter
Crab cavity phase slip

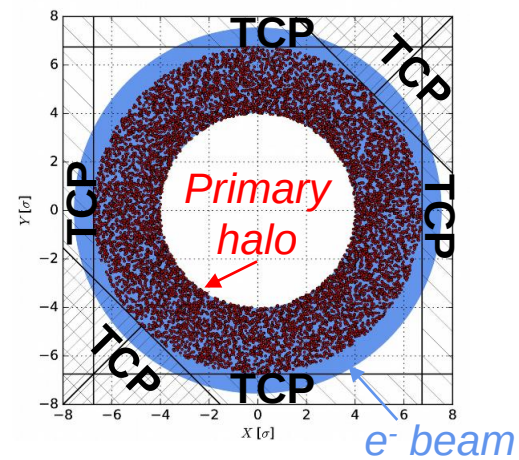
Possible consequences:

Magnet quench
Permanent damage to TCPs

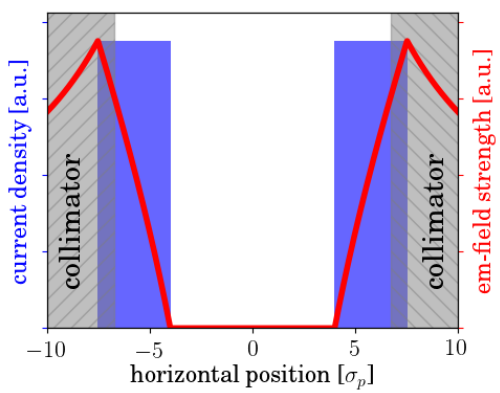
Hollow e-lens assisted collimation

Working principle: **hollow electron beam** as **additional hierarchy layer**

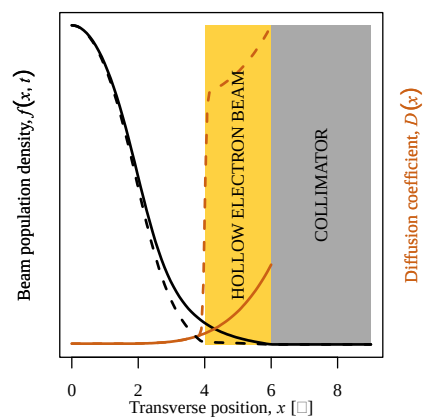




em-field acting only on halo particles



Increased diffusion speed and depleted halo population



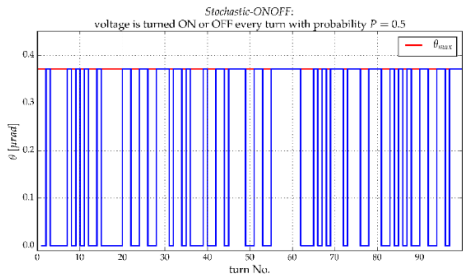
Possible pulsing pattern

- **Continuous (DC)**: always ON and with same e^- beam current

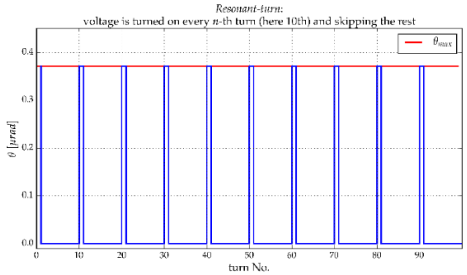
Two main modulation can be envisaged:

Tuning the switching while keeping constant current

- **Stochastic-ONOFF:**



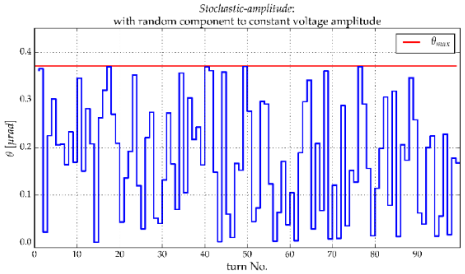
- **Resonant-turn:**



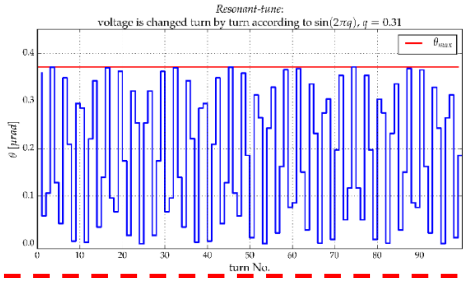
✓ Main focus

Tuning e^- beam current while keeping always ON

- **Stochastic-amplitude:**



- **Resonant-tune:**

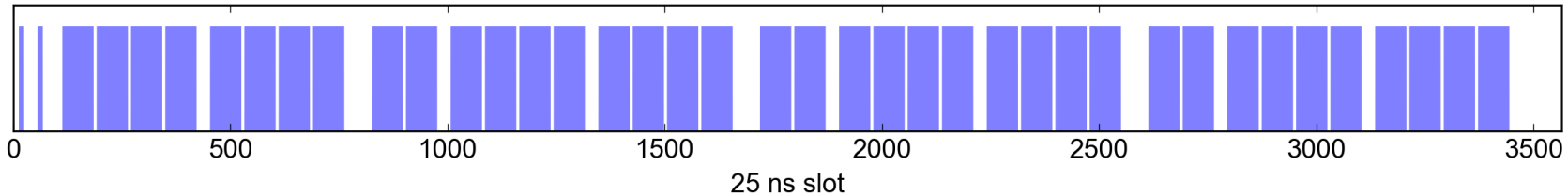


✗ Challenging HW!

Requested functionality

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 μs to 86 μs** (48 bunches to entire beam w/o AG)
  - ✓ full range of current **0 – 5 A always available**

Main requirements on **halo depletion**:

Crab cavity (CC) failure

2 σ depleted halo before TCP

Always ON when CC ON

Orbit jitter

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

Compromise between removal rate and effects on core

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Strategy of 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**

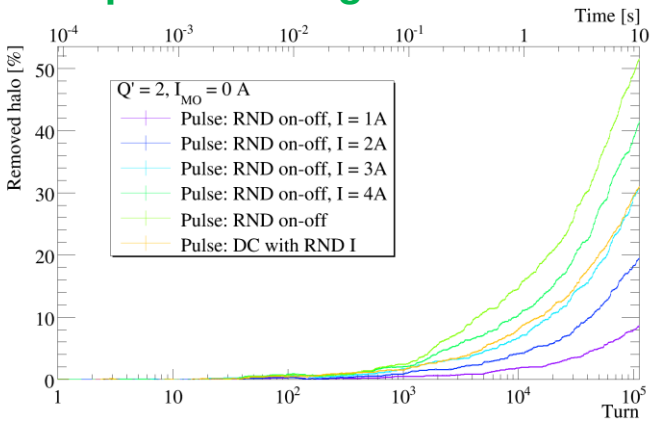
   → Fast simulations to **explore the parameter space** and guide the choice of a subset

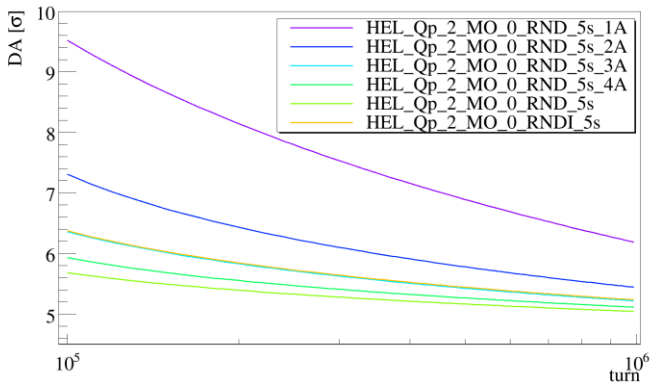
2. **Complete tracking** simulations tacking into account **collimation**

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

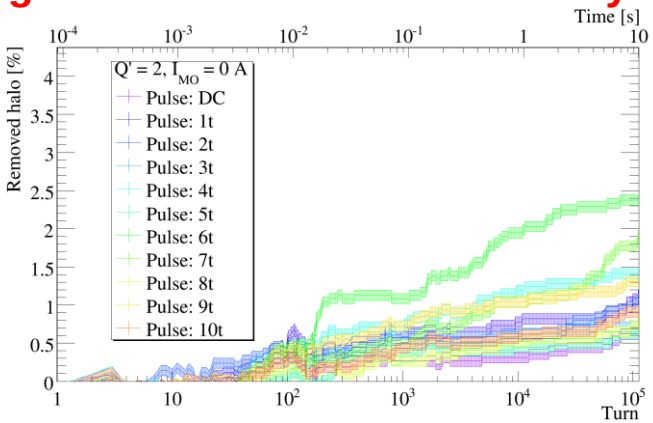
Recap of previous studies

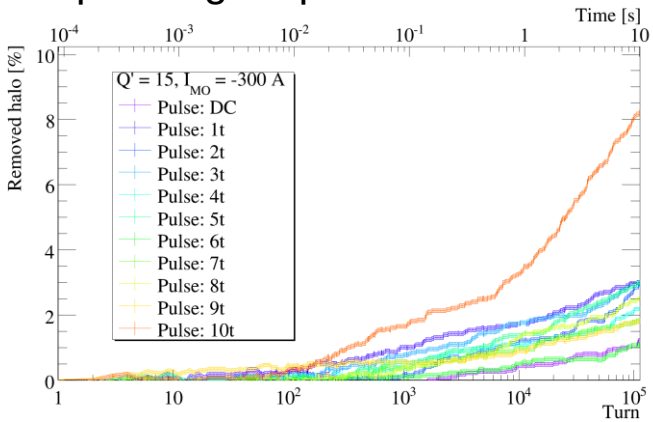
- **Good qualitative agreement** between **halo removal performance** and **DA**





- **Significant effect of non linearity** on loss rate depending on pulse used





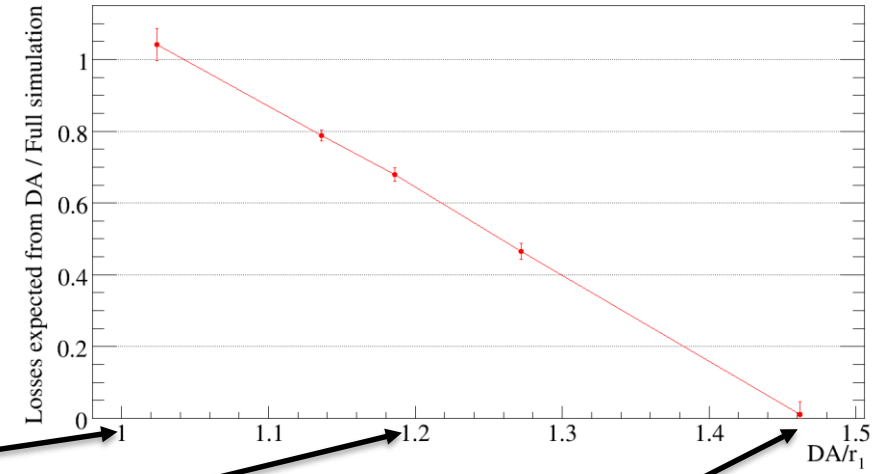
- ***Main qualitative observations from FMAs:***
  - ✓ Clear distortion of Q phase space
  - ✓ **e-lens enhances** effects due to **non linearity**

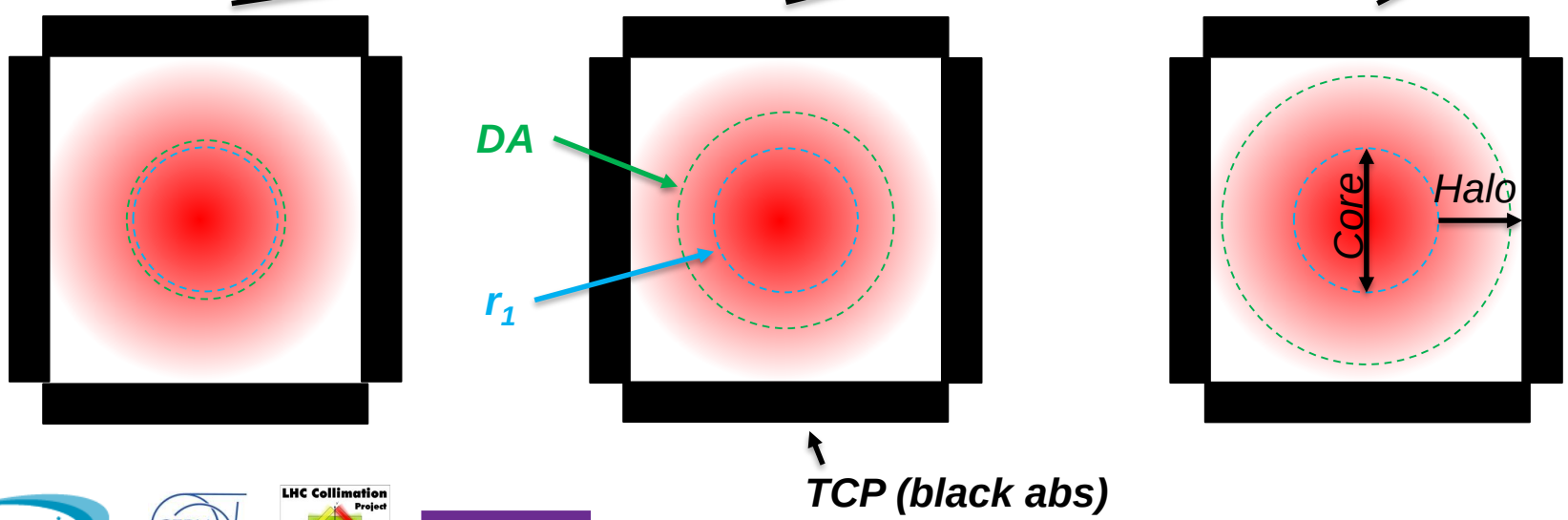
DA vs losses

Estimation of **removed halo** from DA simulations **underestimate if DA > inner radius** (r_1)

Complete **halo depletion simulations needed** for quantitative evaluation

To be combined with **emittance blow-up simulations**



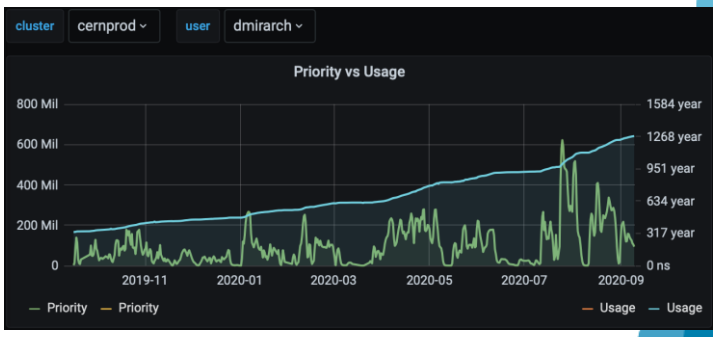


Present studies

- *Disclaimer:* present studies to be considered as **"academic"**
  - Optics v1.3, β^* = 15 cm, no beam-beam, Q' = 15, MO = -300A
  - Only H&V TCP at 6.7 σ treated as black absorber
  - Ideal e-lens used, with inner radius $r_1 = 5\ \sigma$ (for halo depletion studies)
  - e-lens replaced with dipolar kick in the V plane (for core blow-up studies)
- **Minimal requirements** to define specifications and operational scenarios:
  - ✓ Optics v1.5 (at least v1.4) at each matched point of the HL-LHC cycle

Large computing power needed! Exploiting SixTrack potentiality!

Turns	10^5	10^6	10^7
Time/job (2p tracked)	~1h	~few h	~few days
Study:	FMA	DA / Halo / Core	Core
jobs/case:	~600	10200 / 7500 / 5000	5000
Simulated cases:	~40	~200 / ~700 / ~100	~20



*Impossible without combining **HTC and BOINC!***
***>1000 years of CPU** used on HTC!*

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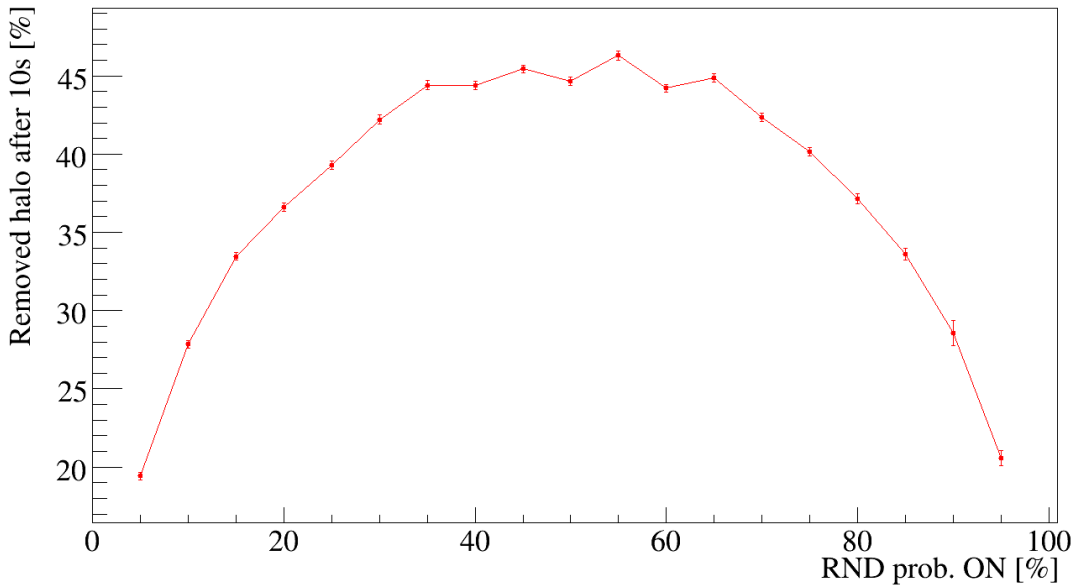
Halo removed with “stochastic-ONOFF” (RND)

Performance with **different probabilities to be ON** probed (keeping e^- beam current 5 A):

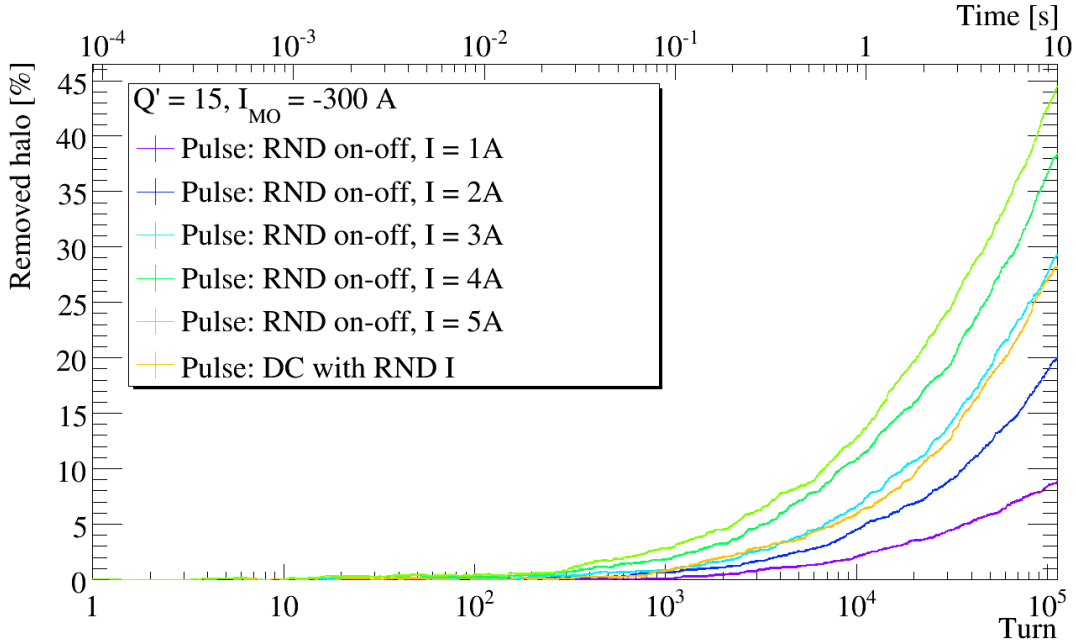


- **Stable performance** between **35% - 65%** of e^- beam ON
- Still **significant** removal with probability **< 35%** and **> 65%**

*Useful knob to **reduce** possible **effects on core** and **power deposition on collector**, while keeping **efficient halo removal***

Current scan with RND pulse

Performance with **different e⁻ beam current** probed (keeping 50% prob. e⁻ beam ON):



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

  → Current can be reduced while keeping efficient halo removal

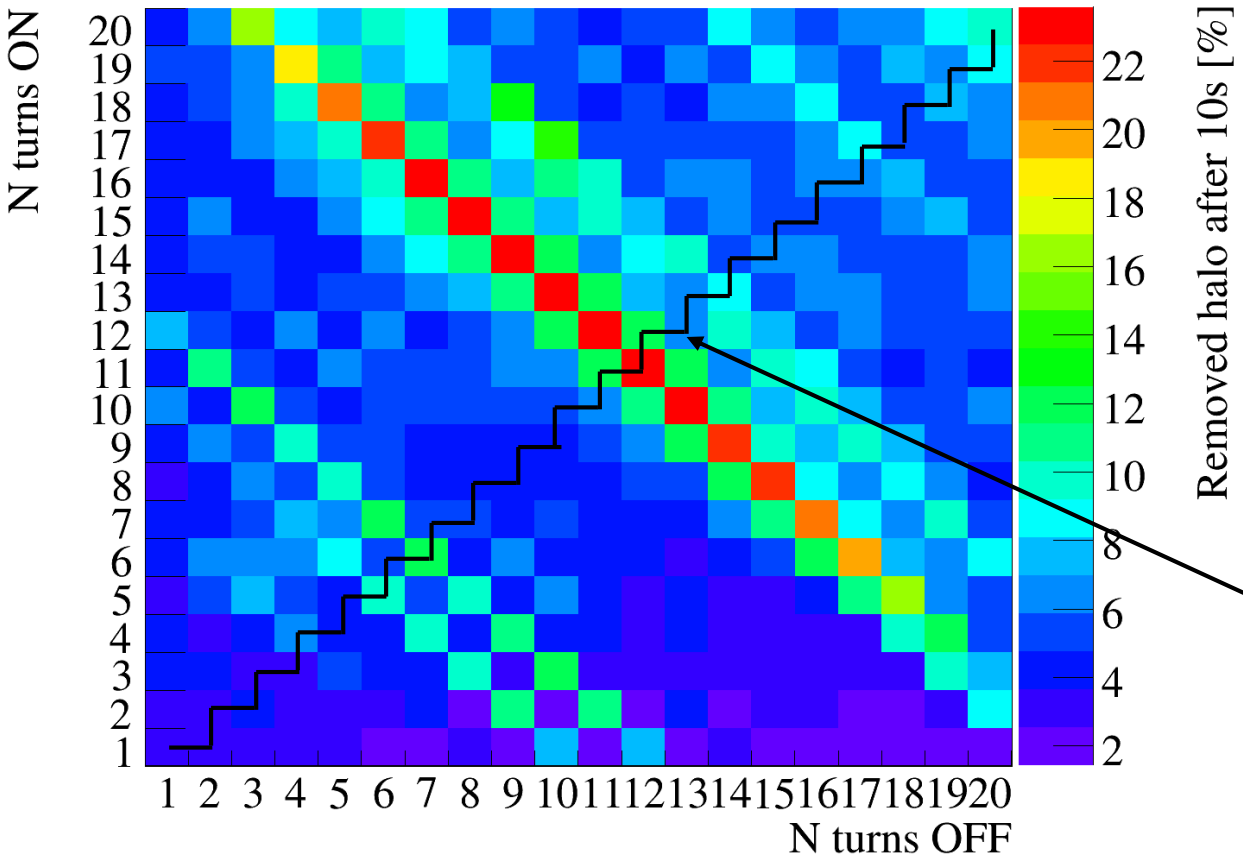
- **"stochastic-amplitude"** pulse **equivalent to RND 50% with ~3 A**

  → Is it worth keep investigating HW options that would make it possible?

Halo removed with "resonant-turn" (pulsed)

Usually explored patterns with **N_{ON} = 1 turn** and **N_{OFF} = # turns**

Studies extended to investigate dependence on both parameters



Clear "resonances" depending on pulse period

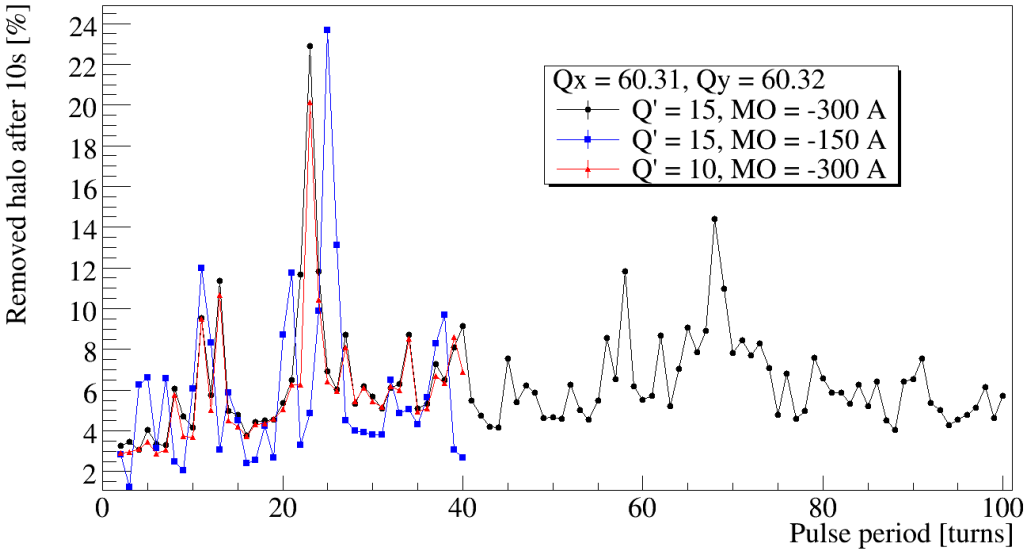
Highest losses observed for $T = N_{ON} + N_{OFF}$ = 23 turns

Investigated larger $T = N_{ON} + N_{OFF}$ moving on this diagonal

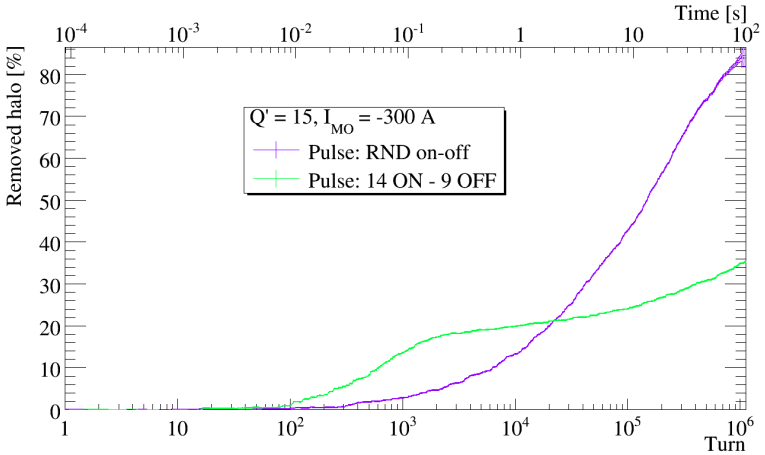
Halo removed vs $T = N_{ON} + N_{OFF}$

- **No effect** changing **Q'**
- I_{MO} modify the **"resonance"** lines

I_{MO} acts on **detuning with amplitude**



*Tried to find a recursive pattern to **build a simple model** to find **optimal T analytically***



Harder than expected:
Strong dependence also on time!
No clear signature observed in FMAs and FFTs

Analytical **model on-hold**
and complete simulations performed

Any idea is very welcome!
(on-going work with Univ. Bologna)

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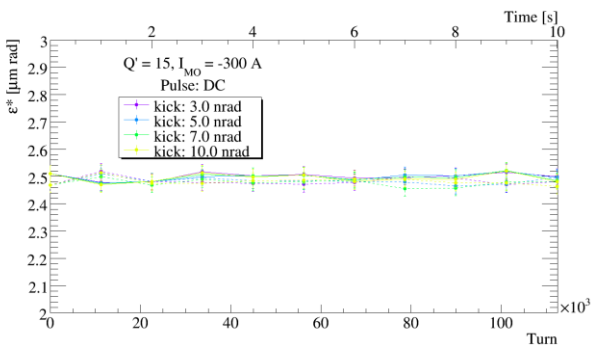
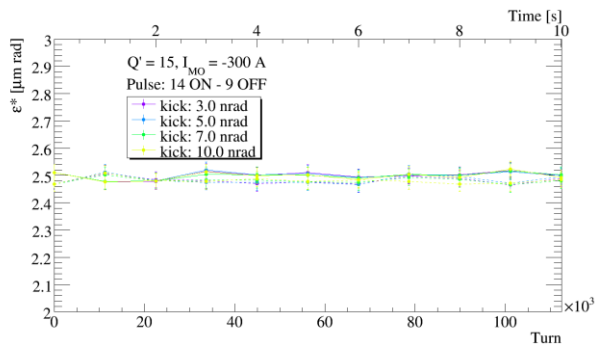
Core blow-up

- Ideal e-lens replaced with **vertical dipolar kick** dynamically tuned according to pulsing pattern
- Estimates **residual kick** using present magnetic design (A. Mereghetti at e-beam WG):
  - ✓ **V plane: 5.22(3.78) nrad** for a symmetric(entire) map
  - ✓ H plane: 0.085(0.082) nrad for a symmetric(entire) map
- **Tolerated** emittance **blow-up** in HL-LHC = **0.05 μm/h ≅ 1.39 × 10^{-5} μm/s**

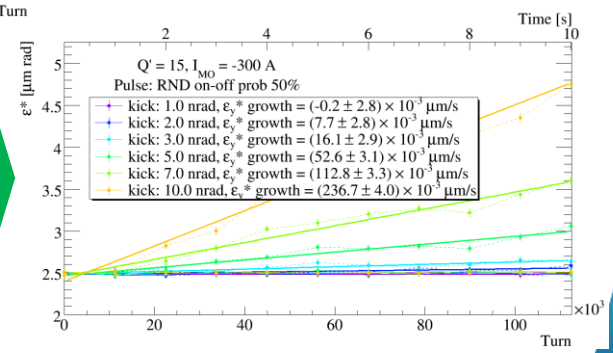
Main focus *given to most promising patterns for operational purposes:*



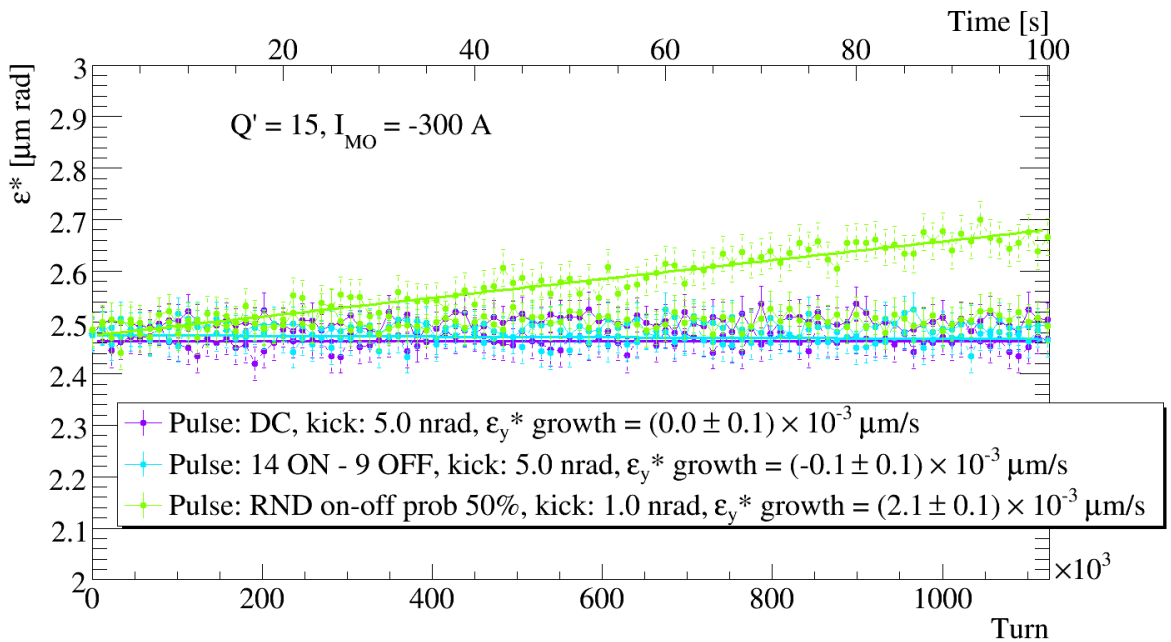


No emittance growth visible with **DC** and **N_{ON} = 14 – N_{OFF} = 9** with up to **10 nrad kick!**

Significant blow-up observed with **RND** mode
Not usable with present design (~0.5 μm increase in10s!)
Longer simulation needed to provide OP specifications



Increasing sensitivity



- Still **no emittance growth** visible with **5 nrad** kick for **DC** and **N_{ON} = 14 – N_{OFF} = 9**!

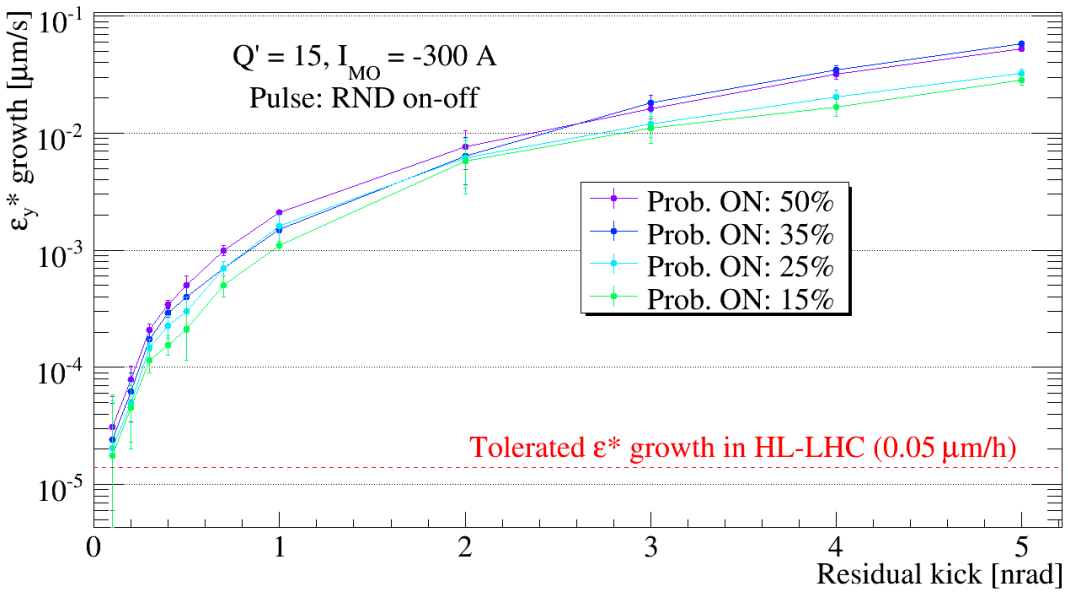
  → Simulations performed up to 10^7 turns (~16min) for a sensitivity of ~ 2×10^{-5}μm/s

- **Visible blow-up** with **1 nrad** kick for **RND** mode!

  → Is there any "threshold"?

Tolerable residual kick with RND mode

Probed the effect of **different probabilities to be ON**



- **Still on the edge** tolerated continuous blow-up with residual **kick of 0.1 nrad**!
- Two **possible knobs** to mitigate emittance growth

Reduce **e⁻ beam current** (assuming linear scaling of the residual kick)

About a factor 2 less blow-up going from 50% to 15% **probability to be ON**

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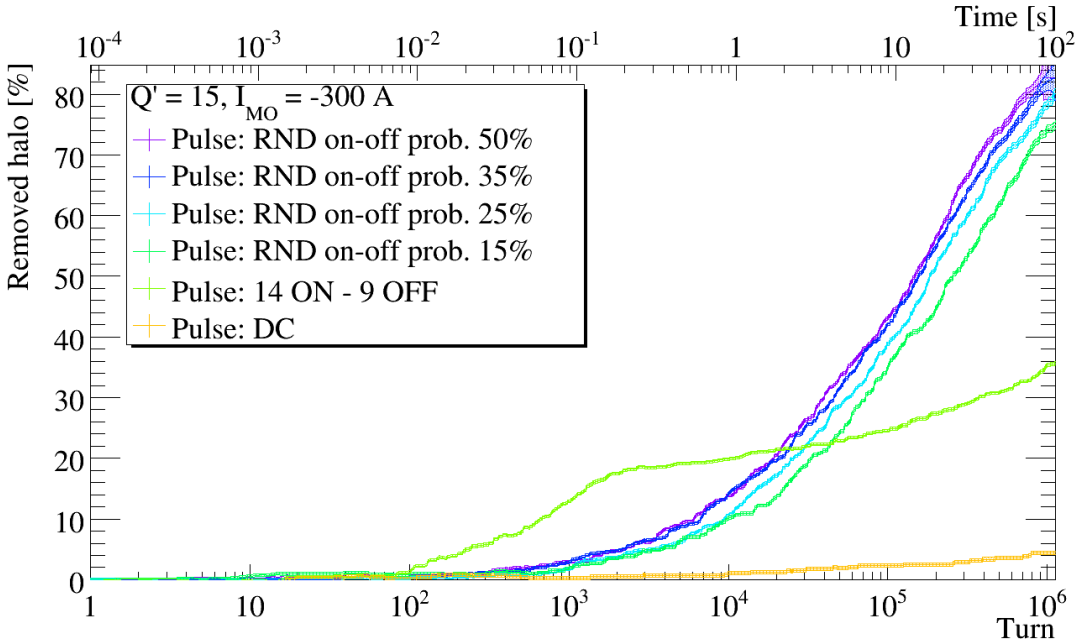
Combining core and halo performance



- **Significant** fraction of **halo removed** with **15%** probability (see also slide 13)
- Pulse **N_{ON} = 14 – N_{OFF} = 9 much more efficient than DC without inducing blow-up!**

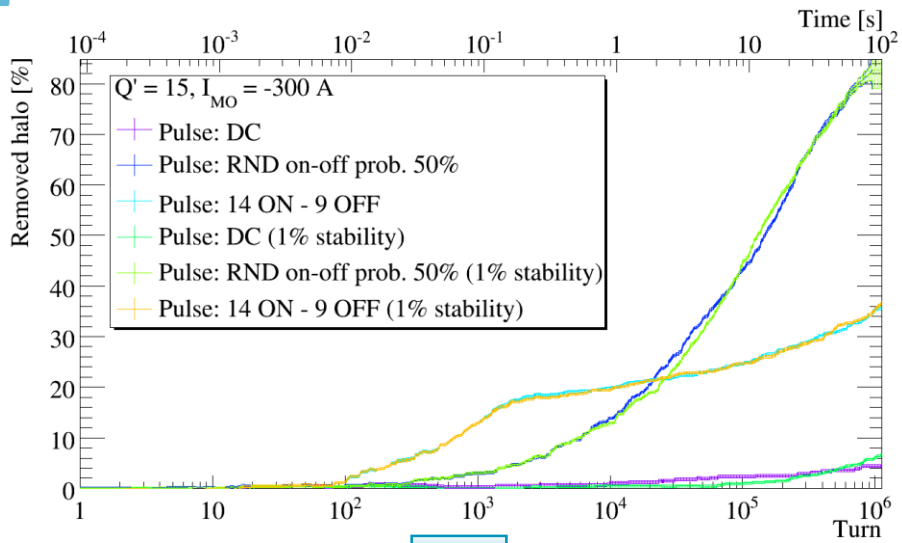
Possible strategy:

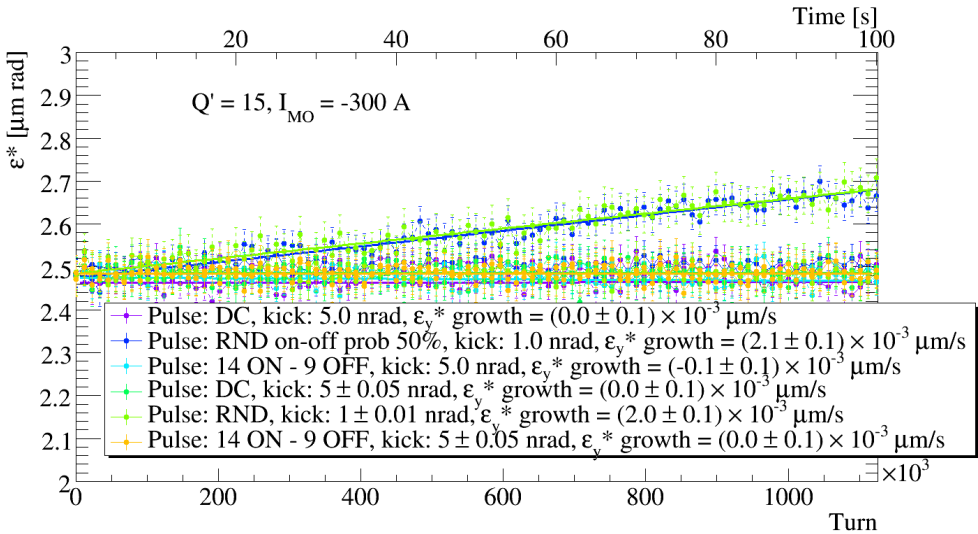
1. **Short** use of **RND** mode **until adjust** (few s) **tuning** e^- beam **current** and **probability**
2. **Continuous** depletion using **N_{ON} = 14 – N_{OFF} = 9 while colliding**

Considering pulse-to-pulse stability

Random component with **Gauss** distribution cut at a 3 σ and **σ = 1 %** of considered:

- e^- beam current
- Dipolar kick





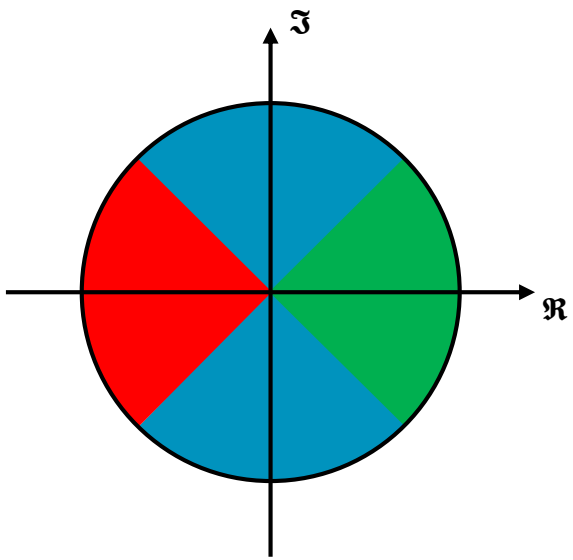
Minor effect on **halo depletion** with **DC** pulse (adding random e^- beam current component)

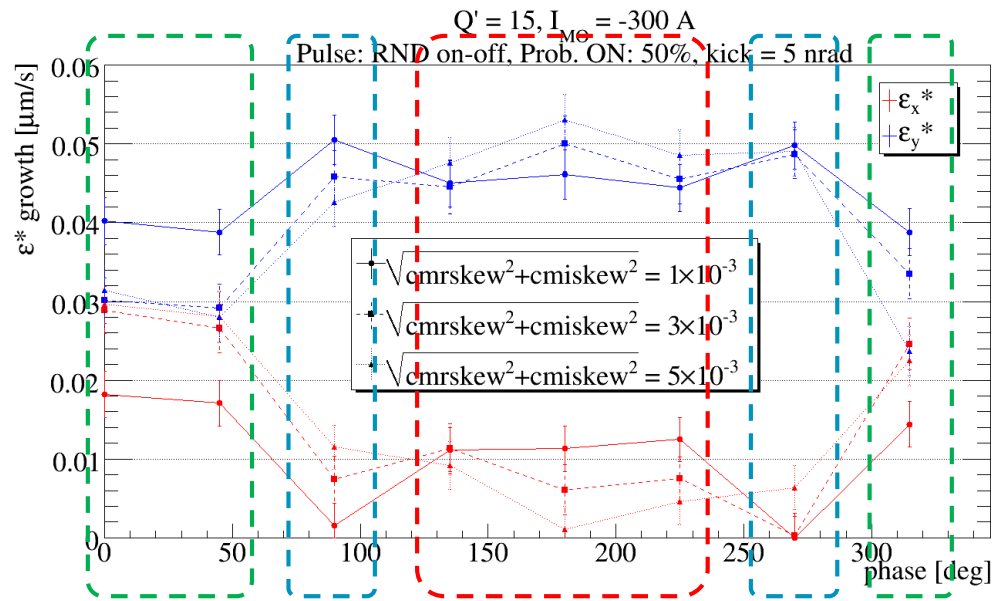
No effect expected on **emittance growth**

1%** pulse-to-pulse stability **should be within reach**: **to be confirmed** at the **test stand

Introducing linear coupling

Dipolar kick acting only on V plane: invariant provided by $\varepsilon_x^*+\varepsilon_y^*$





- **The larger the amplitude, the larger the sharing between planes**
- **The larger the amplitude, the smaller the sharing between planes**
- **The larger the amplitude, the larger the sharing between planes, but most of the growth still in the excitation plane**

Useful knob to distribute eventual blow-up between planes:
phase roughly 315º - 45º would prevent $\mathcal{L}$ unbalance in IP1-5 due to Xing form factor

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Conclusions

Halo removal:

- **RND** pulse confirmed to be the **most efficient**

  → **Significant margins** on e^- beam **current** and **probability** to be ON
- RND **modulation of e^- beam current do not justify efforts** to investigate HW options
- Very **poor** performance of **DC** mode
- Pulse **N_{ON} = 14 – N_{OFF} = 9 much more efficient than DC and other resonant**

Effects on core:

- **RND** pulse lead to **unacceptable** emittance **growth** with present magnetic design
- **No** emittance **growth** visible with **DC** and **N_{ON} = 14 – N_{OFF} = 9** with up to **10 nrad kick!**

Pulse-to-pulse stability: Negligible effects expected with 1% stability

Linear coupling: Useful knob to distribute eventual blow-up between planes

Conceptual operational strategy based on present studies:

1. Find **best compromise** between **magnetic design**, **e^- beam current** and **probability** to be ON to use **RND** mode **until adjust** for **few s** when needed
2. **Constant** depletion using **N_{ON} = 14 – N_{OFF} = 9** with **colliding** beams

Next steps

Much clearer path of studies needed to draw OP specs! But plenty of work to be done!

- Repeat present studies in **realistic machine configurations** (no drastic changes expected):
  - ✓ **Mask for Flat Top** optics needed
  - ✓ **Mask** needed for different matched point of **β^* levelling**, including **beam-beam**
  - ✓ Still **asymmetric β at e-lens** in **HLv1.3**…at least **HLv1.4 needed**
  - ✓ Use **three primary** collimators (skew TCP not considered yet)
  - ✓ Use **4.7 σ as inner radius** (present studies done with 5.0 σ)
  - ✓ **Mask during ramp** to study solutions for **11T flux jump**?

- **Additional checks done/open points:**
  - ➢ Tested pulse with **frequency content tuned on halo spectrum**
    - → Quite fast effect that vanishes once halo starts drifting
      - → Frequency content able to drift the until collimators needed
        - → It becomes essentially the RND pulse
  - ➢ **Why $T = N_{ON} + N_{OFF} = 23$ turns** is so more efficient than others?
    - No clear differences observed in FMAs
    - No clear correlation with FFT: other T have a peak falling into the halo spectrum but are less efficient

Thank you for your attention!

Outline

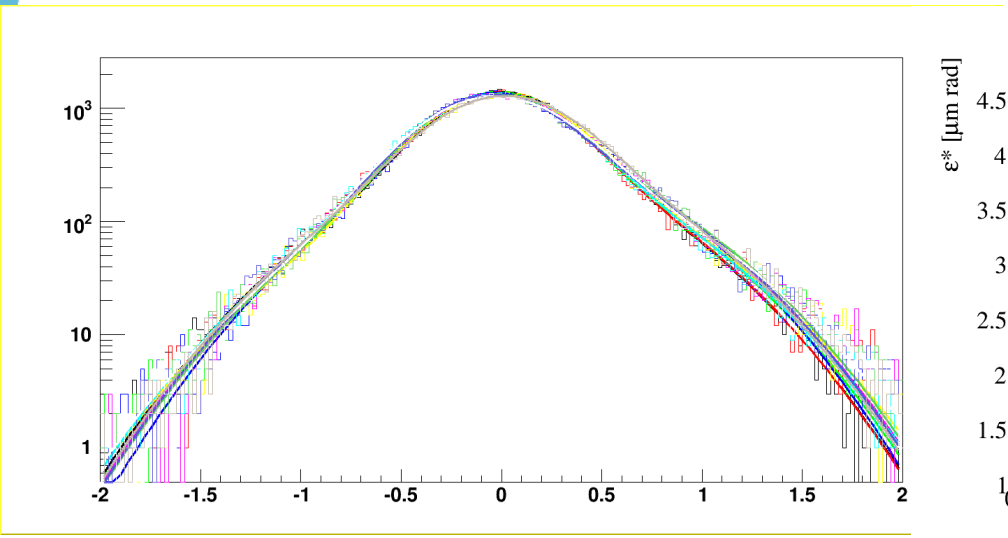
Backup

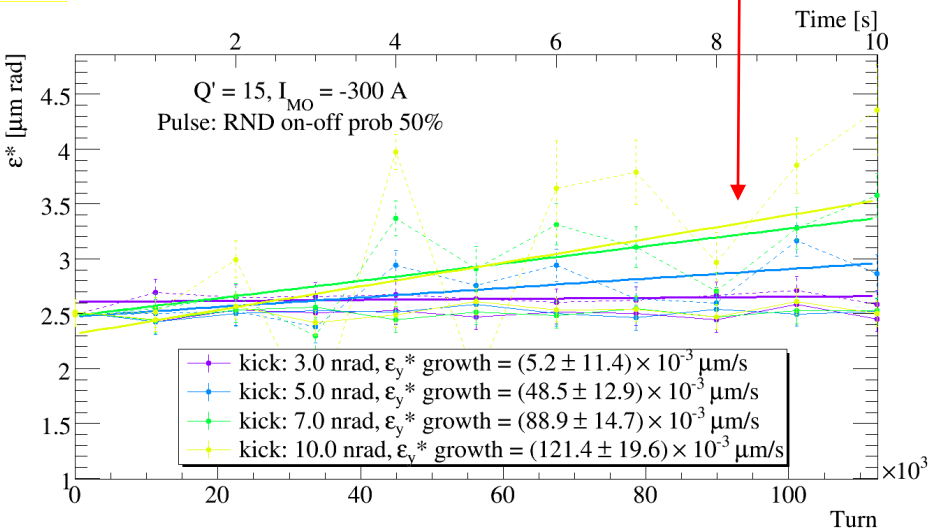
Double gauss to study effects on core? (I)

- Best distribution to be used for tracking?

Solid "dots": H plane
Dashed "dots": V plane

Double gaussian distribution used for halo removal studies:





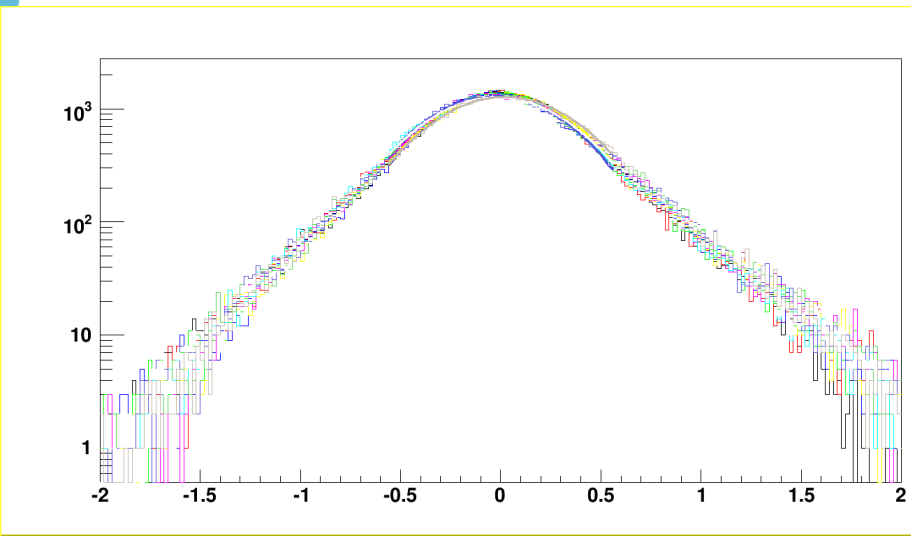
but

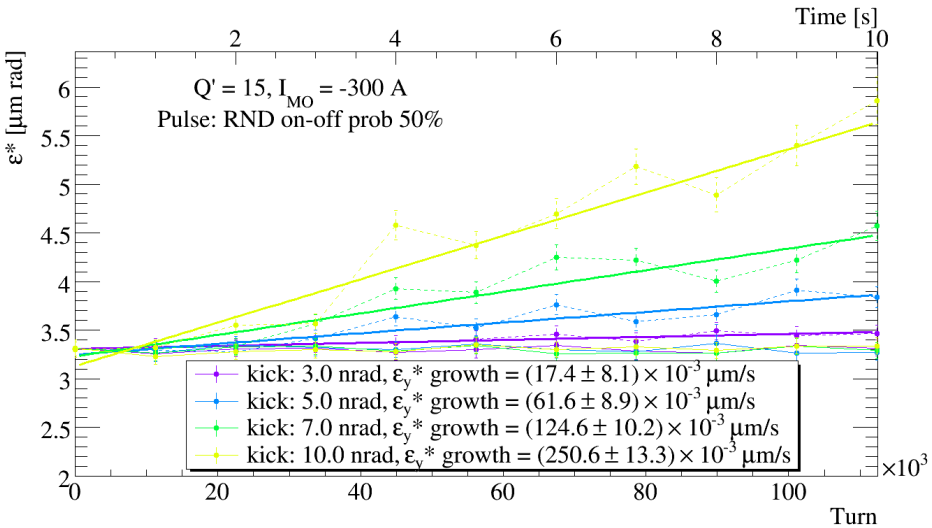
Unstable parameters for the core gauss
(particularly when increasing the kick)
(maybe more stat needed?)

Double gauss to study effects on core? (II)

Solid "dots": H plane
Dashed "dots": V plane

- Thus, lets try to fit only the core of the double gauss (i.e. within 2σ)





better

Much more stable fit of ε* core
(but still quite large errors on blow-up)

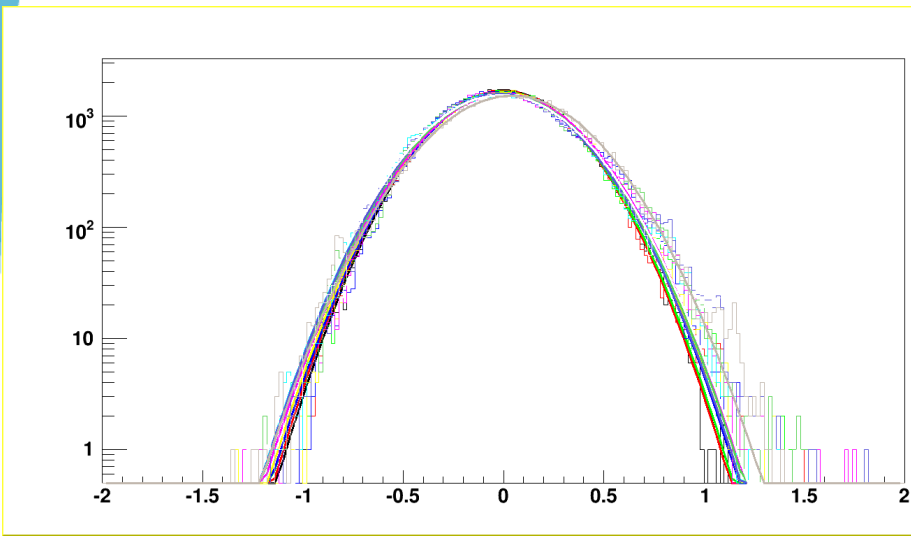
but

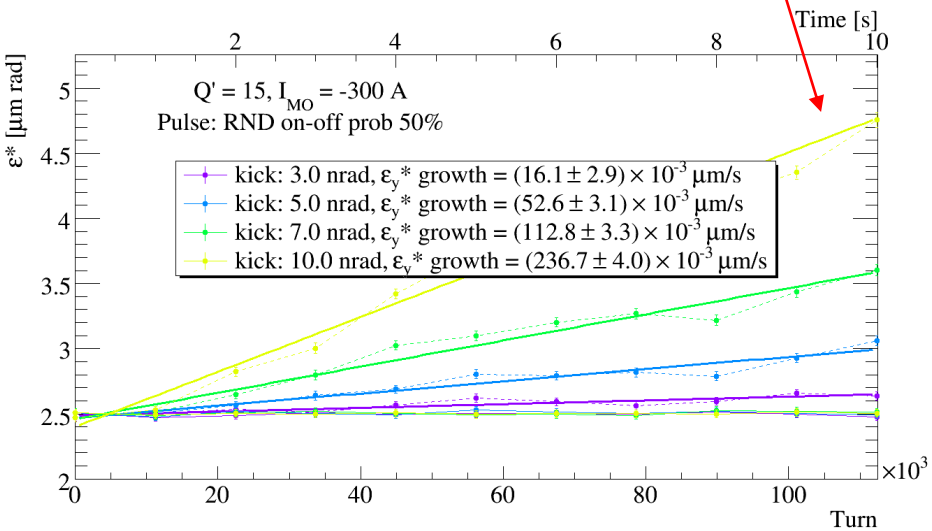
Absolute ε* value faked by single gauss fit on double gauss distribution

Single gauss to study effects on core?

- Thus, lets try a single gauss distribution

Solid "dots": H plane
Dashed "dots": V plane





Global fit quality "not bad"

- ✓ ε* growth consistent with evaluation on core of double gauss distribution
- ✓ Correct absolute ε* value

Single gauss distribution used!

Can we mitigate blow-up using the ADT?

Device	s	μx	μy	Δμx [deg]	Δμy [deg]
ELENS.5L4.B1	3292.28	7.46627842812048	6.7572551707864		
ADTKH.D5L4.B1	3301.32	7.47389311496707	6.76399600520599	2.7	2.4
ADTKH.C5L4.B1	3302.92	7.47531391358864	6.76518024621676	3.3	2.9
ADTKH.B5L4.B1	3305.52	7.47767071736065	6.76709767147852	4.1	3.5
ADTKH.A5L4.B1	3307.12	7.47915106222935	6.76827315522284	4.6	4.0
ADTKV.A5R4.B1	3358.25	7.53952598671491	6.80347280001075	26.4	16.6
ADTKV.B5R4.B1	3359.85	7.54181606339435	6.80448667060766	27.2	17.0
ADTKV.C5R4.B1	3362.45	7.54558080331911	6.80612165579858	28.5	17.6
ADTKV.D5R4.B1	3364.05	7.54792310256214	6.80712002953557	29.4	18.0

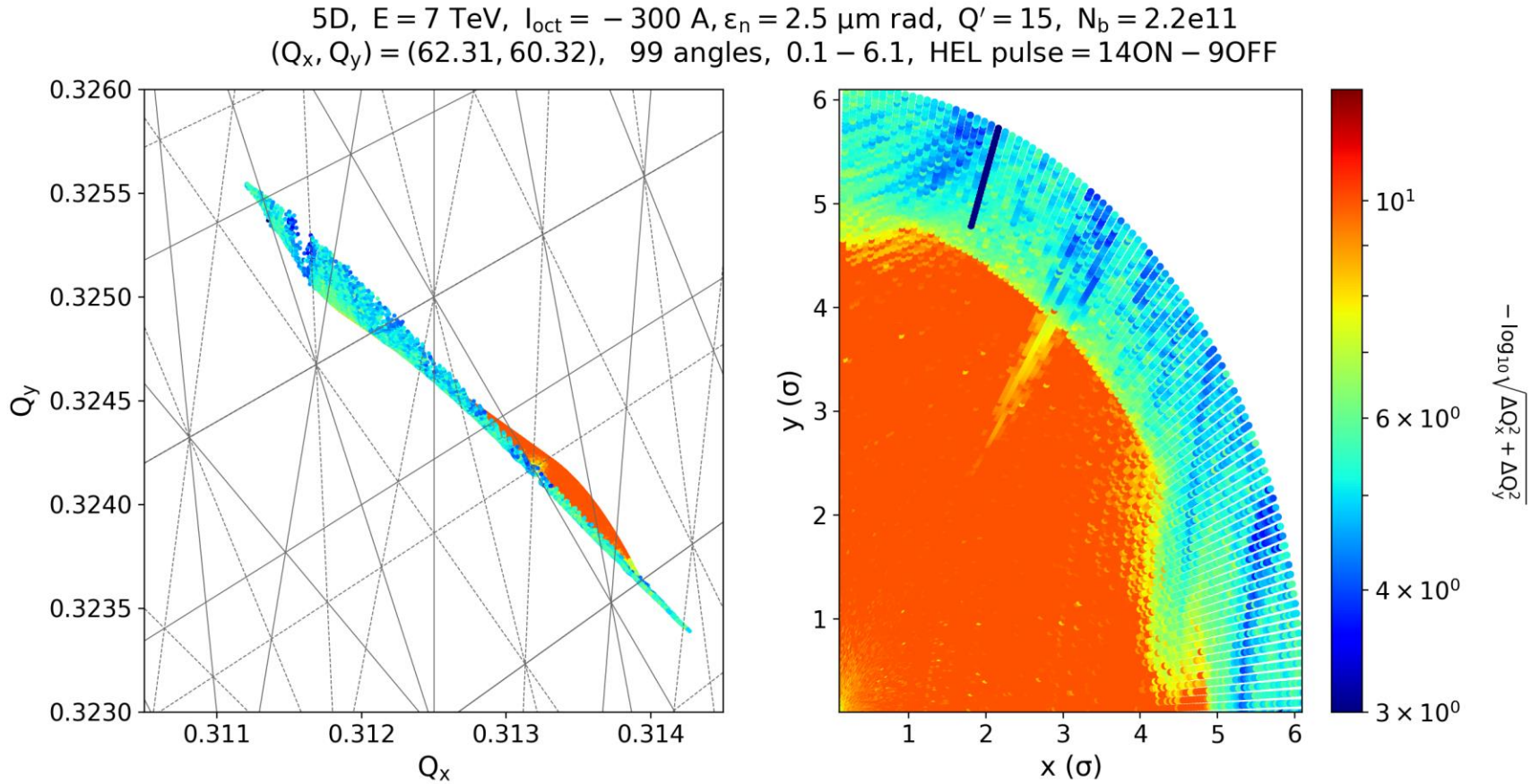
Measured emittance blow-up in LHC

https://indico.cern.ch/event/751857/contributions/3259404/attachments/1782364/3276979/paper_emitGrowth_Evian2019_stef.pdf

Table 3: Measured and extra emittance growth in collisions.

Emittance growth [μm/h]	B1H	B1V	B2H	B2V
Measured	0.04	0.04	0.06	0.05
on top of model	0.02	0.07	0.03	0.09

FMA, N_{ON} = 14 – N_{OFF} = 9



Resonance line drawn up to 23rd order

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
- Collimators = only H&V TCPs treated as black absorbers
- Turns = 1e6
- Angles = 17
- Aperture steps = 10 (from 2σ to 22σ with 2σ step)
- Seeds = 60

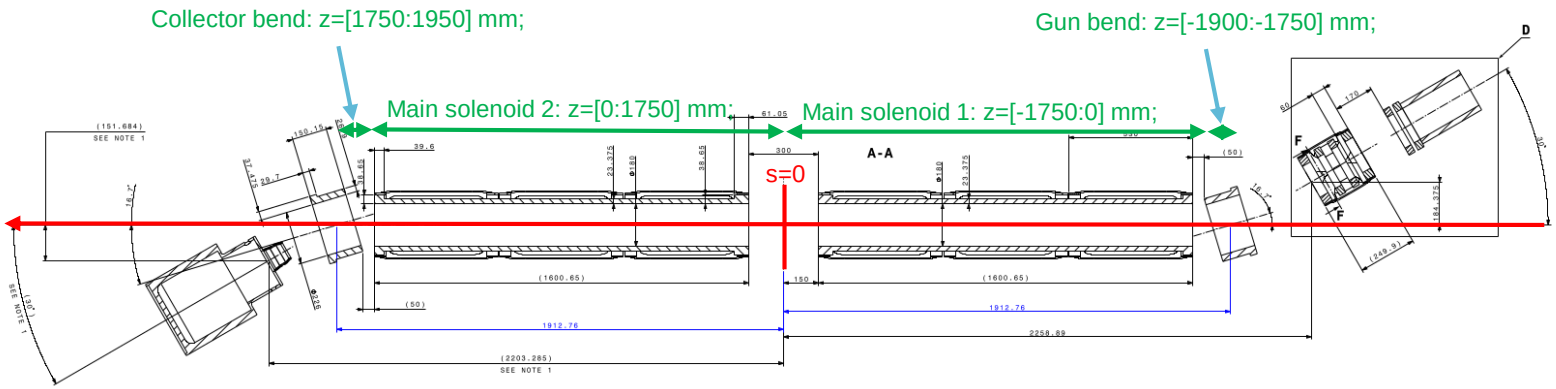
} Specific for DA studies

e-lens settings

- Length = 3 m
- e-beam current = 5 A
- e- kinetic energy = 10 keV
- e- distribution = UNIFORM
- r1 = 5 σ
- r2 = given by magnetic compression using real e-gun dimension (r1=4.025mm, r2=8.05mm)
- Bending solenoids = NO

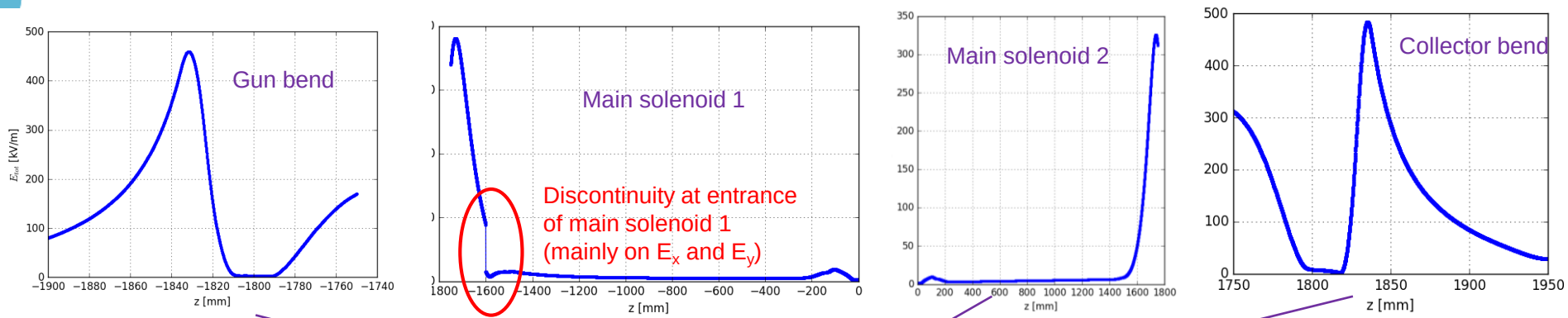
3D Map of Electrical Field

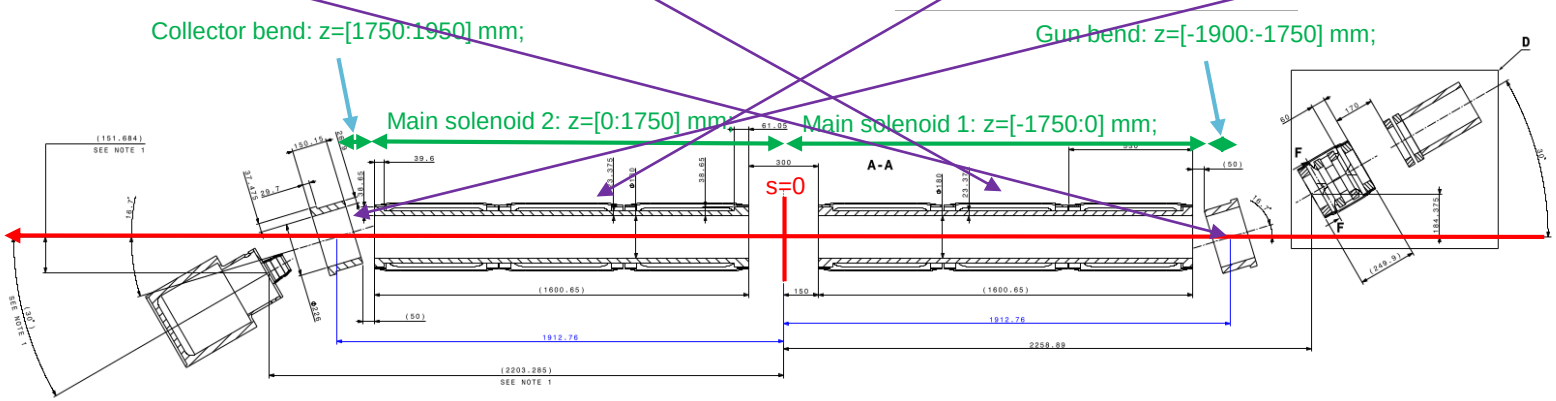
- 3D map of Ex, Ey and Ez is necessary to evaluate:
  - Integrated strength along the longitudinal axis of e-Lens → first idea of effects on core of proton beam;
  - Maps of longitudinally-integrated kicks as effect of asymmetries in electron beam profile (e.g. regions of injection/extraction of electrons), or non-ideal electron beam distributions (e.g. towards the end of e-Lens);
- Map received by D. Nikiforov, 2019-10-11;
- Very detailed mesh: x=[-5:5:0.1] mm, y=[-5:5:0.1] mm, z=[-1900:1950:0.1] mm;
- .txt file at 30 GB → split into 4 pieces:



Longitudinal Profile (1D) of E_{tot} at x=0, y=0

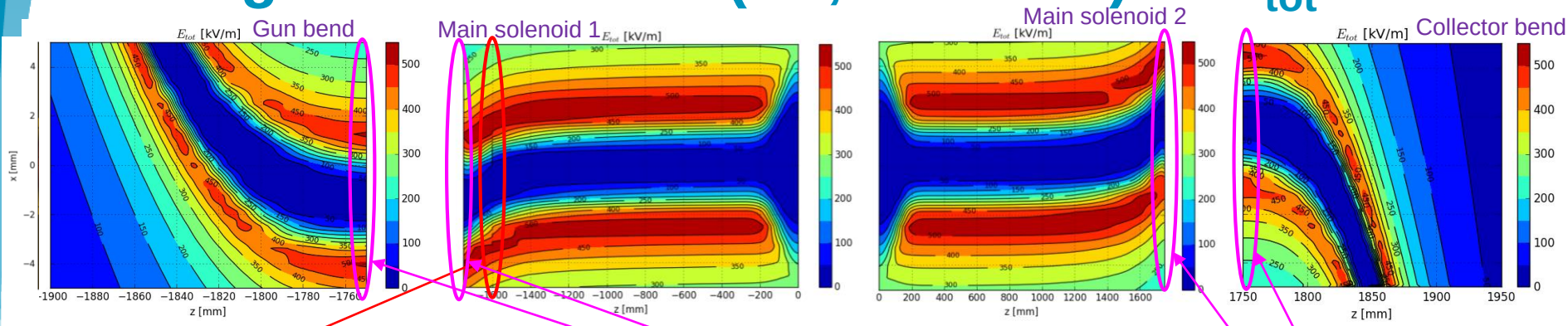
$$E_{tot}^2 = E_x^2 + E_y^2 + E_z^2$$





$$E_{tot}^2 = E_x^2 + E_y^2 + E_z^2$$

Longitudinal Profile (2D, Ver view) of E_{tot} at x=0



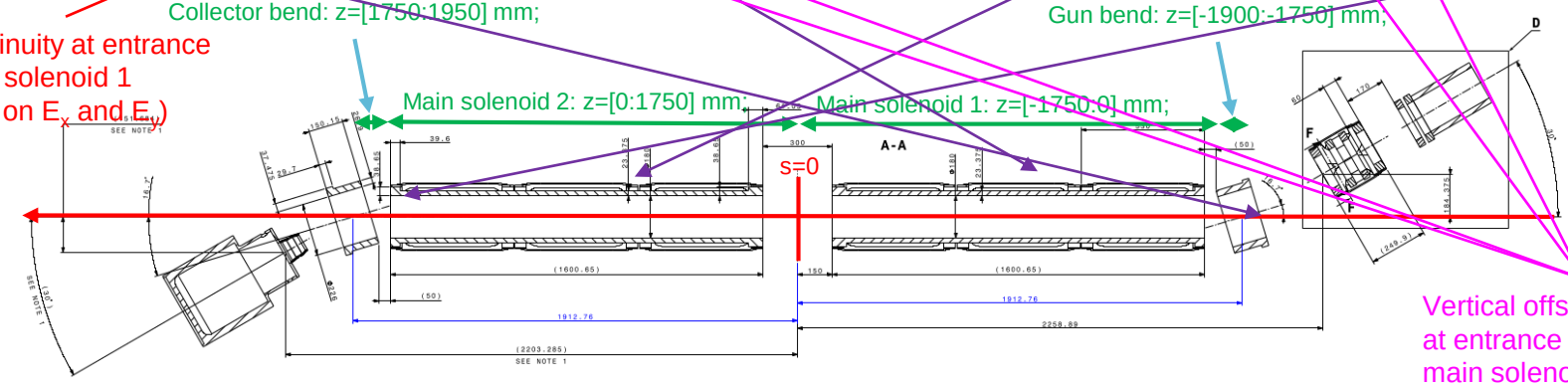
Discontinuity at entrance of main solenoid 1 (mainly on E_x and E_z)

Collector bend: z=[1750:1950] mm;

Gun bend: z=[-1900:-1750] mm;

Main solenoid 2: z=[0:1750] mm;

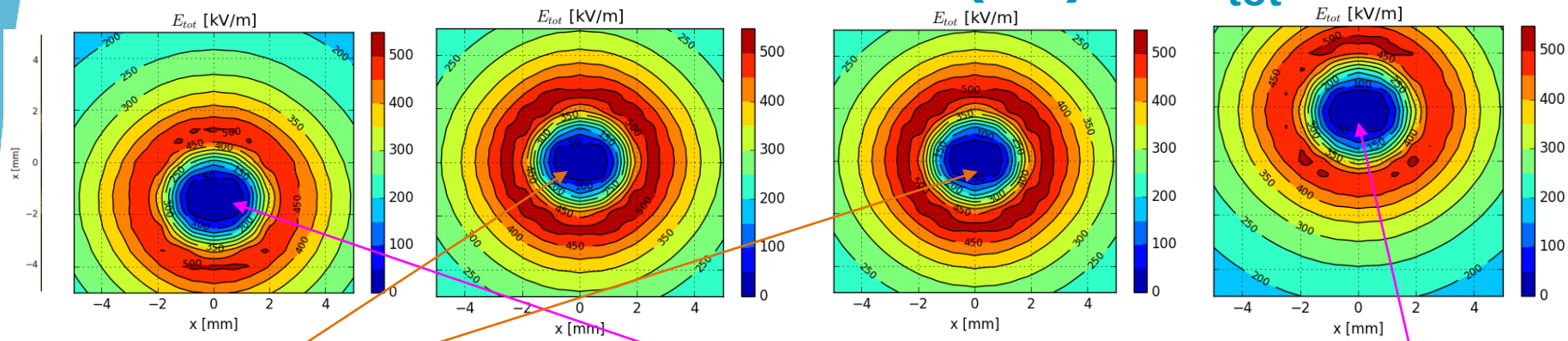
Main solenoid 1: z=[-1750:0] mm;



Vertical offset of e- beam at entrance and exit of main solenoids (1-2mm)

$$E_{tot}^2 = E_x^2 + E_y^2 + E_z^2$$

Transverse Profile (2D) of E_{tot}



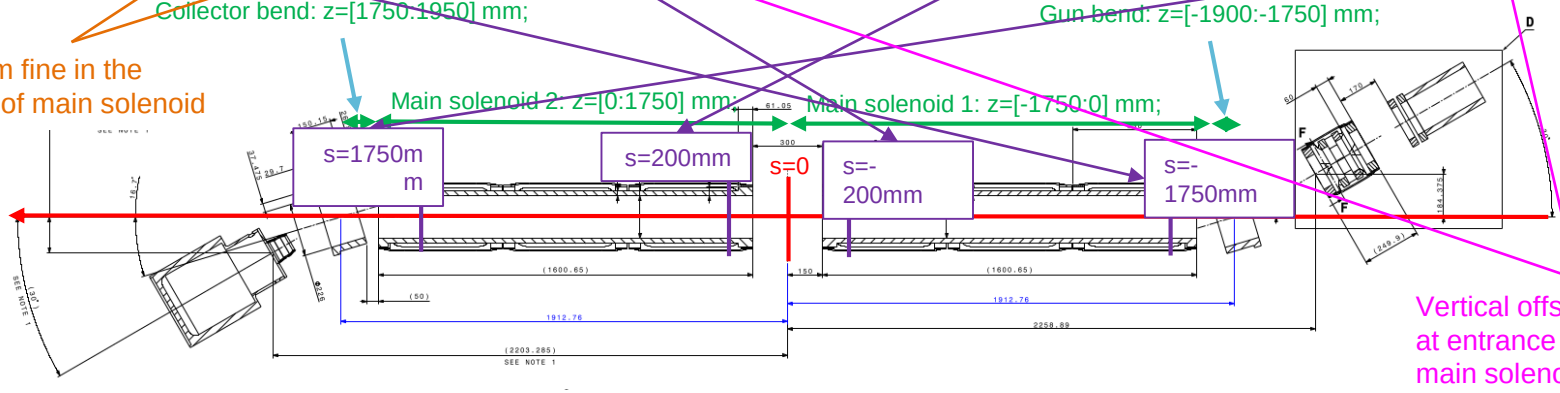
Collector bend: z=[1750:1950] mm;

Gun bend: z=[-1900:-1750] mm;

e- beam fine in the middle of main solenoid

Main solenoid 2: z=[0:1750] mm;

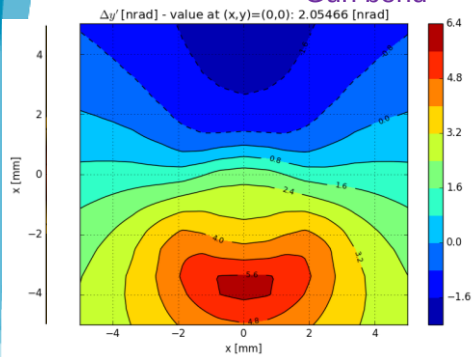
Main solenoid 1: z=[-1750:0] mm;



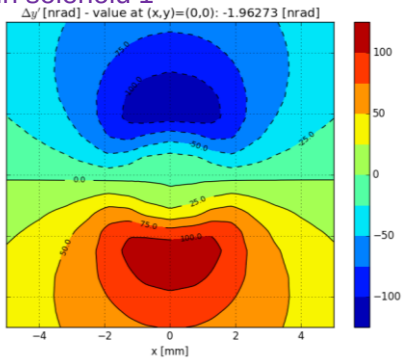
Vertical offset of e- beam at entrance and exit of main solenoids (1-2mm)

Integrated Vertical Kicks

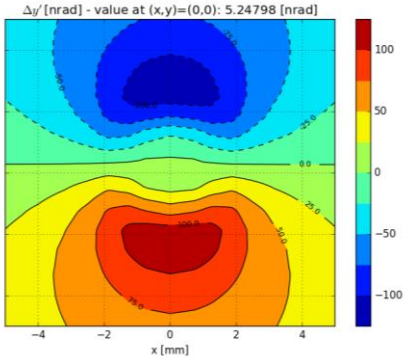
Gun bend



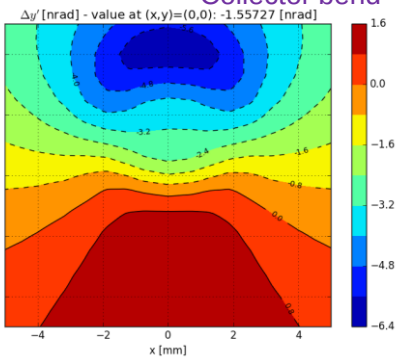
Main solenoid 1



Main solenoid 2



Collector bend

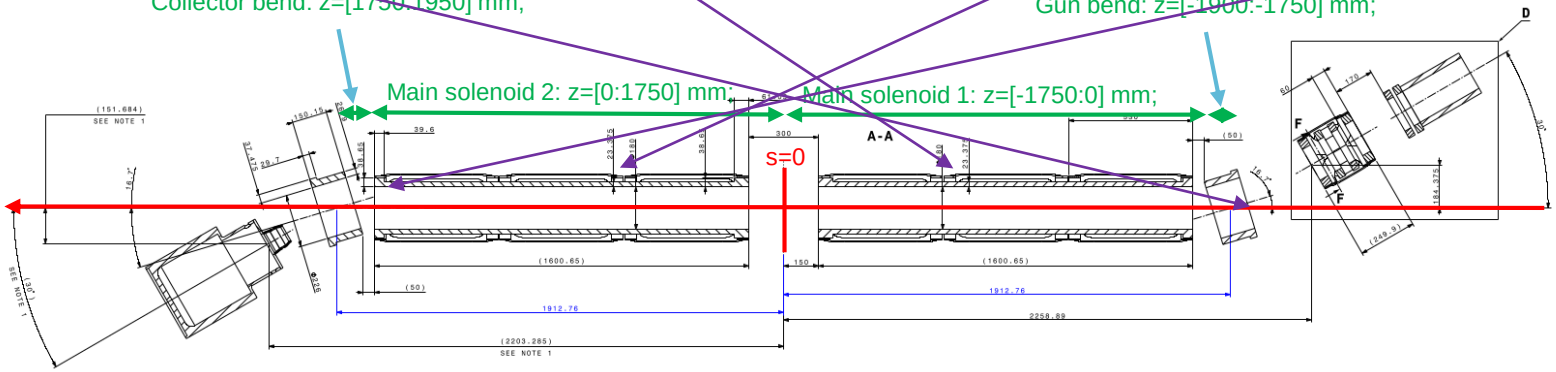


Collector bend: z=[1750:1950] mm;

Gun bend: z=[-1900:-1750] mm;

Main solenoid 2: z=[0:1750] mm;

Main solenoid 1: z=[-1750:0] mm;



Remarks

- 3D map seems fine, apart from discontinuity at ~entrance of first main solenoid (~-1600mm) → D. Nikiforov, can you check this in your generation chain?
  - All plots are available on CERNbox at (you should all have received an e-mail with a direct link): your projects → collimation-team → eLens → ChebyshevMaterial → 3D maps → 2019-10-11
- Large vertical offsets of electron beam at entrance/exit of main solenoid (1-2mm):
  - Can we do anything about it?
  - Is this configuration without correctors? (D.Nikiforov)
- Integrated fields computed → values at gun/collector bends are comparable to those computed by G. Stancari;
- Integrated kicks computed:
  - At (x,y)=(0,0): values are in the order of few nrad (similar to what computed by G. Stancari);
  - Maps of integrated kicks are affected by vertical offsets of e- beam → shall we extend transversally the range covered by the maps?
- How does the picture change when varying (D. Nikiforov):
  - Electron current;
  - Electron energy;
- SixTrack:
  - Kicks at (x,y)=(0,0) could be used to have a first estimate of effects on beam core → Reference system in maps is that of the electron beam! To use data, please keep in mind the rotation by 180° about the y-axis (vertical);
  - Chebyshev fitting still to be done – numpy allows only fitting on a domain in 1D, I have to work out the fitting in a 2D domain…

HEL specs

Parameter	Value or range
Geometry	
Length of the interaction region, L [m]	3
Desired transverse scraping range [σ, $\epsilon = 2.5\mu$m]	3.5–7.1
Inner/outer electron beam radii at 7 TeV [mm]	1.1–2.2
Inner/outer cryostat diameter [mm]	132 / $\approx$ 500
Inner vacuum chamber diameter [mm]	60
Magnetic fields at 7TeV and magnet parameters	
Main solenoid field, B_m [T]	5.0
Gun solenoid field, B_g [T]	0.35-4.0
Beanding solenoid field [T]	3.5
Compression factor , $\sqrt{B_m/B_g}$	3.8
Maximum current in main solenoid [A]	330–350
Electron gun	
Inner/outer cathode diameters [mm]	8.05–16.1
Peak yield at 10 kV, I [A]	5
High-voltage modulator	
Cathode-anode voltage [kV]	15
Rise time (10%–90%) [ns]	200
Repetition rate [kHz]	35