Beam dynamics simulations with hollow electron lens

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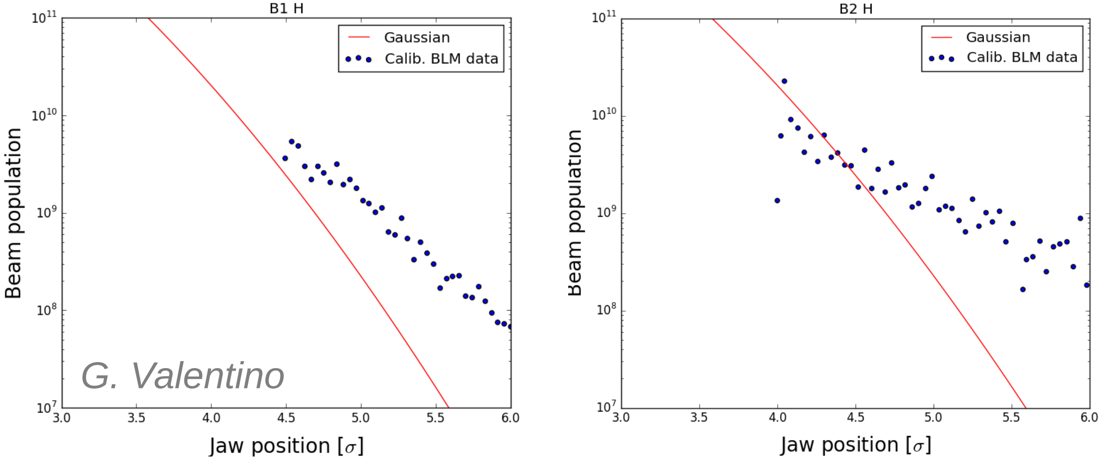
Introduction

- 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!



G. Valentino

Fast failure scenarios:

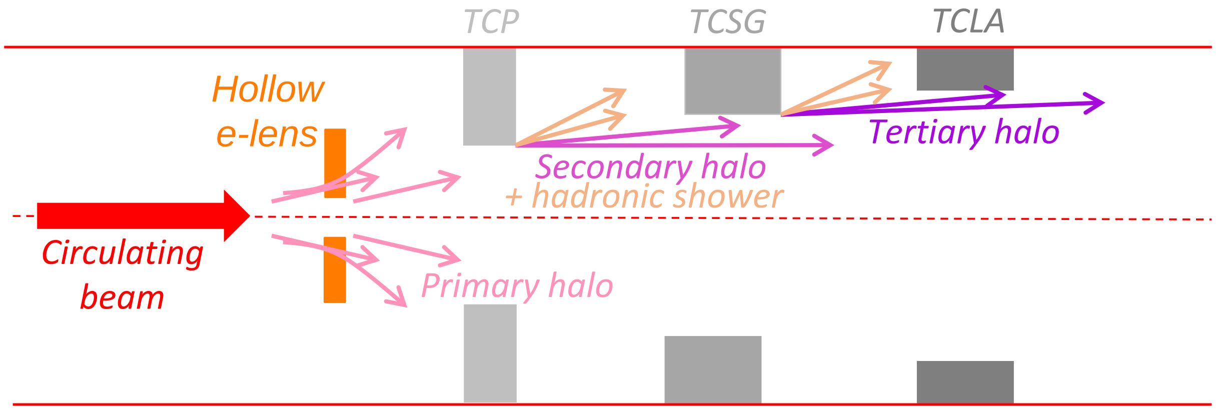
Orbit jitter
Crab cavity phase slip

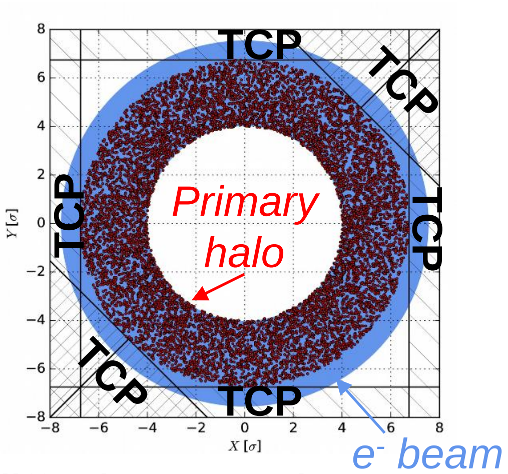
Possible consequences:

Magnet quench
Permanent damage to TCPs

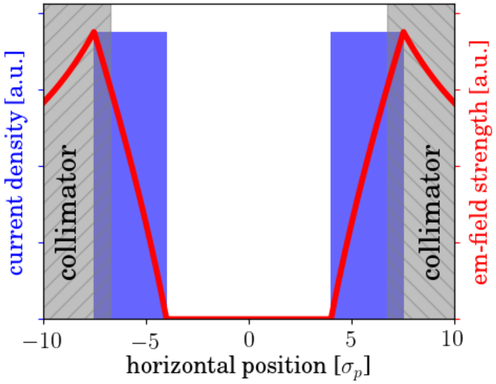
Hollow e-lens assisted collimation

__Working principle:__ **hollow electron beam** as **additional hierarchy layer**

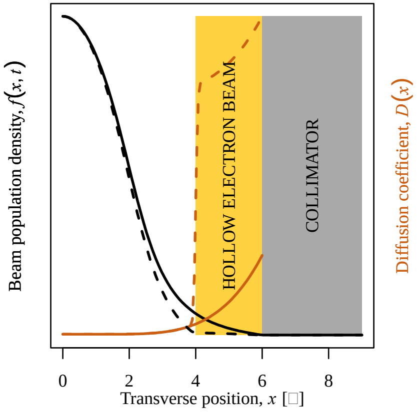




__em-field acting only on halo particles__



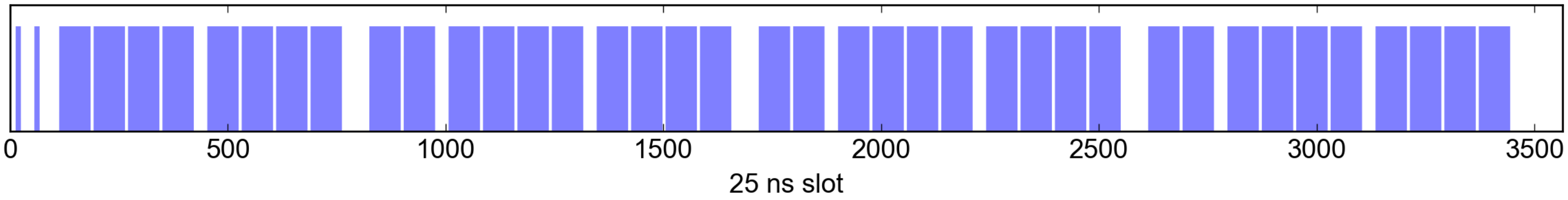
__Increased diffusion speed and depleted halo population__



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

Main requirements on **halo depletion**:

Crab cavity (CC) failure

2 σ 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

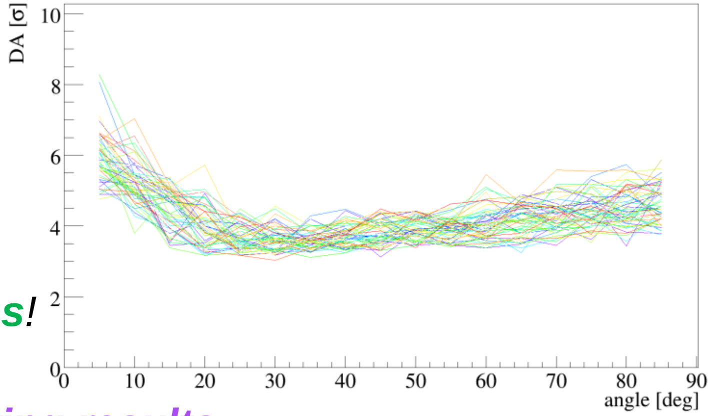
- *Effect of several parameters studied:*
  - ✓ **Inner radius (r1):** 3, 5, 7, 9 σ
  - ✓ **Pulsing pattern:** Continuous (DC), Random ON-OFF (RND), Continuous with random current between 0 A and 5A (RNDI), pulsed every 1, 2, 3, …, 10 turns
  - ✓ **e-beam current:** 1 A, 2 A, 3 A, 4 A, 5 A
  - ✓ **Octupole 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**, **β*= 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**:

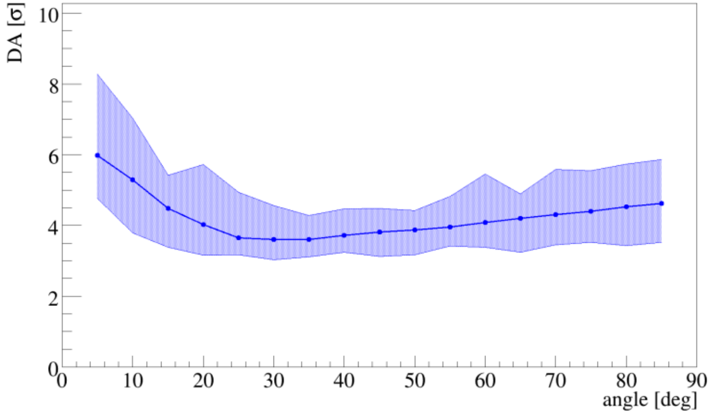
- **multipolar errors** (w/o beam-beam)
- **10^6 turns**
- **60 seeds**, **17 angles**, **10 amplitudes**



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

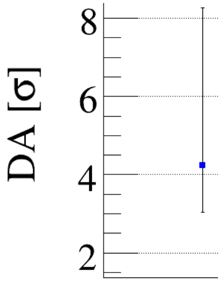
Two ways of showing results

Average DA over all seeds



Envelope: absolute min and max DA
over all seeds

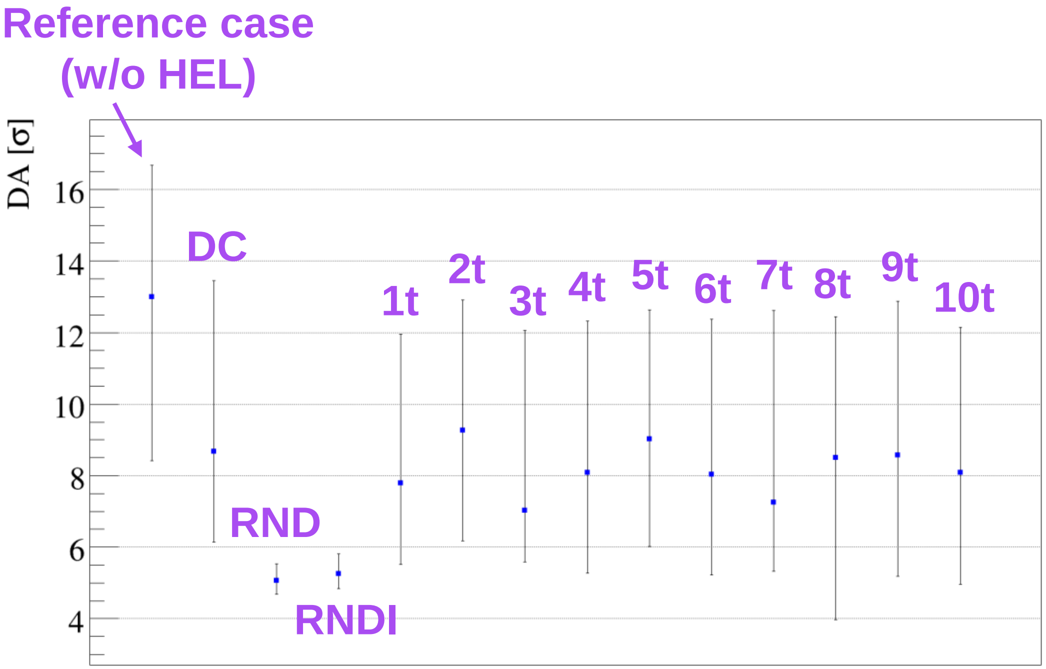
Average DA over all seeds and angles



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 σ, MO = 0 A and Q' = 2 (e-beam current always 5 A, except for random current modulation RNDI)***

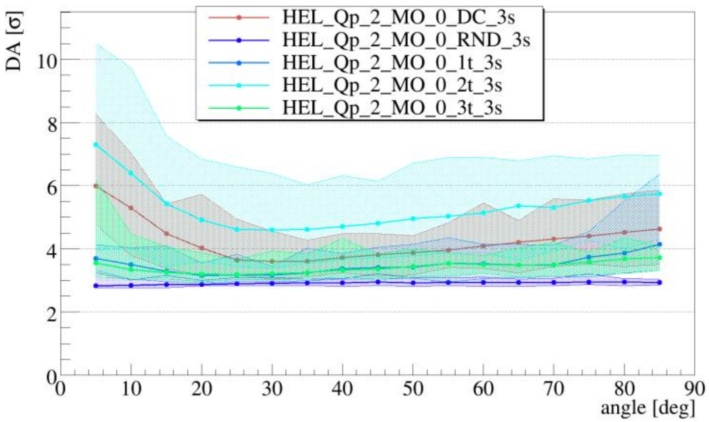


- **Clear effect of e-lens on DA:** the closer the DA to r1, the more efficient the excitation mode

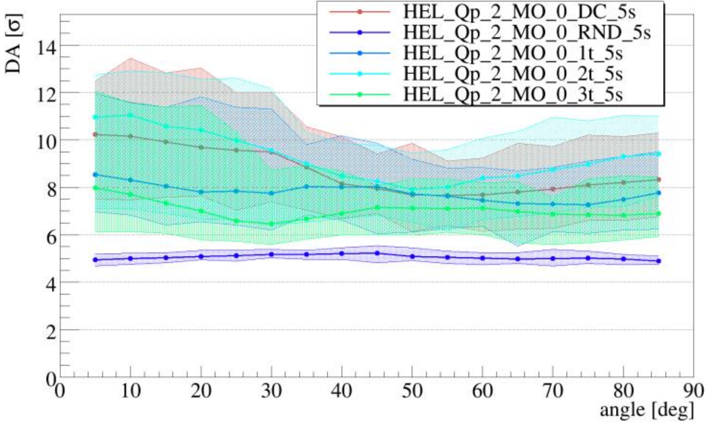
Ranking of efficiency (avr DA) = ***RND, RNDI, 3t, 7t, 1t, 6t, 4t, 10t, 8t, 9t, DC, 5t, 2t***

Summary r1 scan

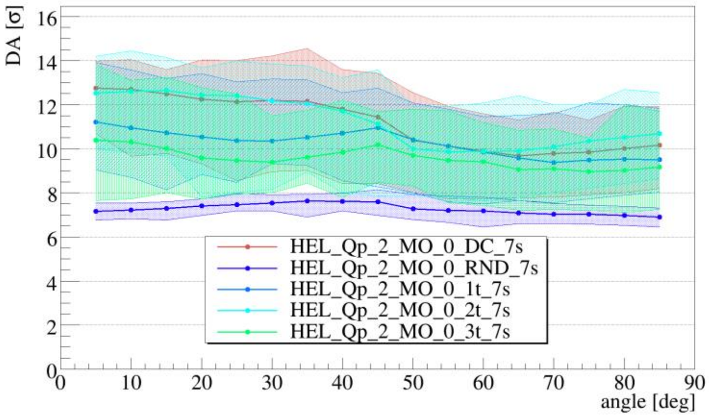
r1 = 3 σ



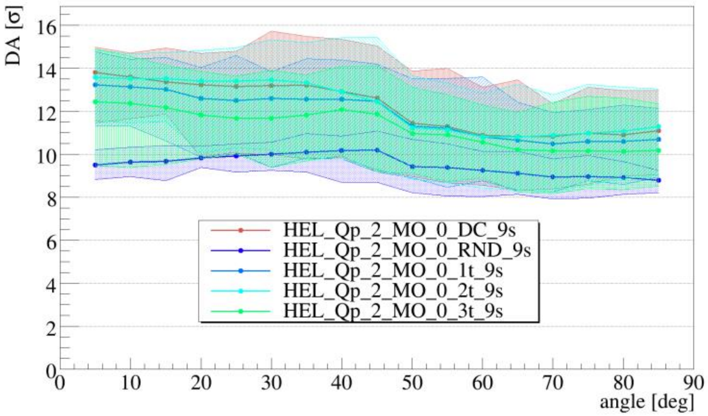
r1 = 5 σ



r1 = 7 σ



r1 = 9 σ

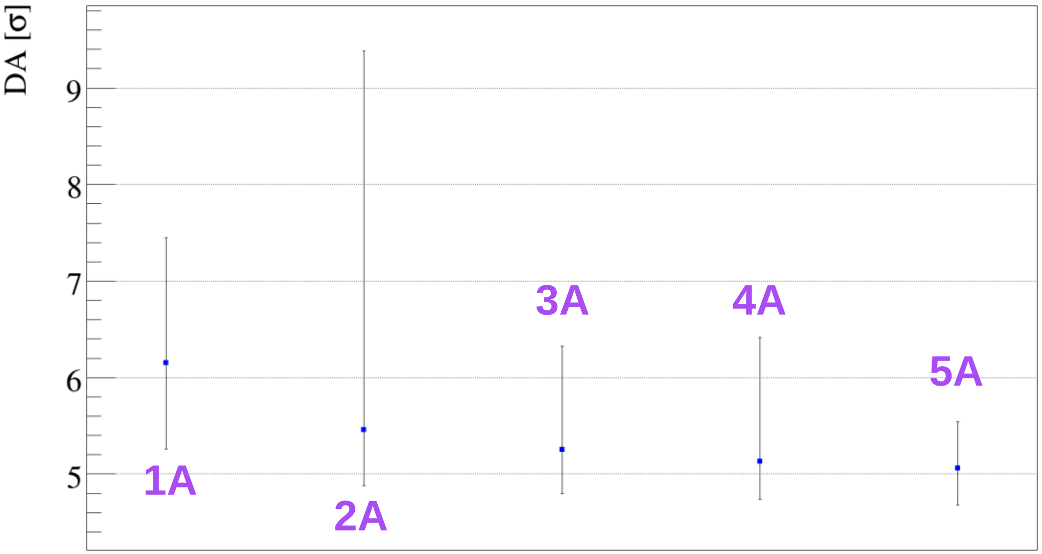


The **larger r1**, the worse the **magnetic field quality** and smaller the **e-beam density** ⇒

⇒ **Reduced difference** of efficiency for between **pulsing patterns**

Summary e-beam current scan

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

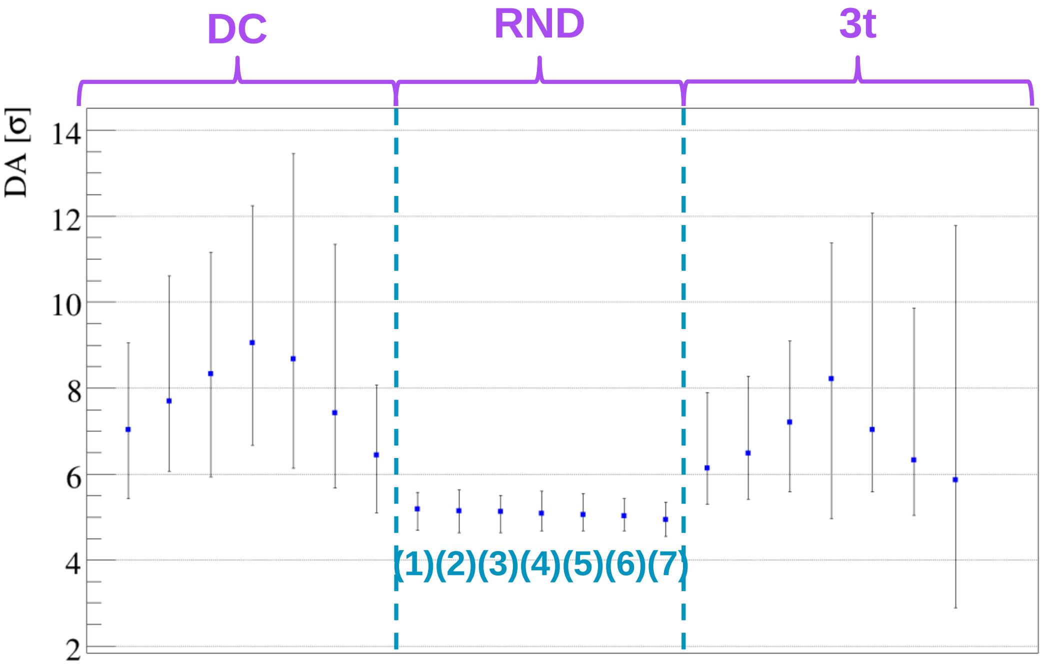


- **Very similar** average DA with **I > 3A**

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

Summary MO current scan

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

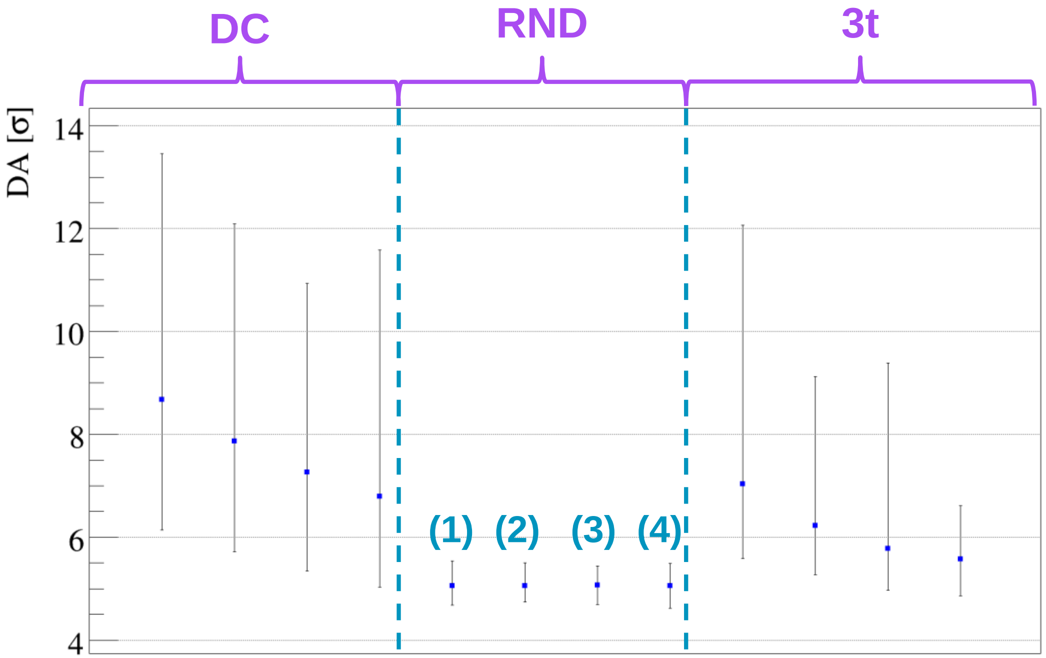


(1) MO = -600 A , (2) MO = -450 A , (3) MO = -300 A , (4) MO = -150 A , (5) MO = 0 A , (6) MO = 150 A , (7) MO = 300 A

- **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 σ and MO = 0 A***



(1) Q' = 2 , (2) Q' = 5 , (3) Q' = 10 , (4) Q' = 15

- **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**

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

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

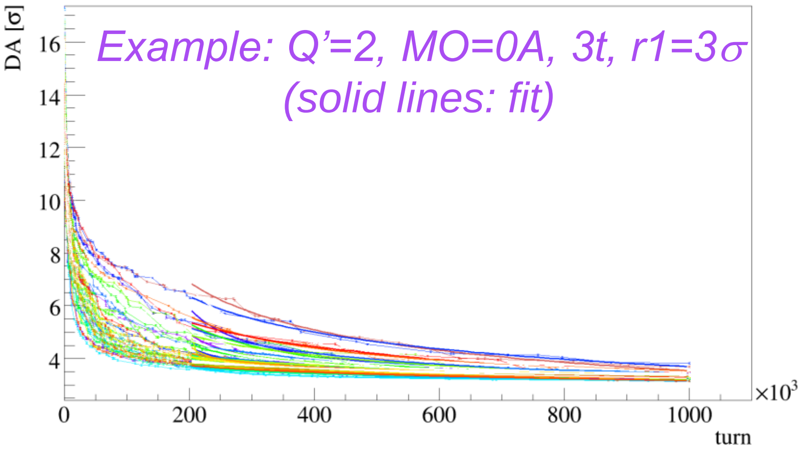
$$DA(N) = b\left[\ln\mu N + \frac{\kappa}{2}\ln\left(\frac{2}{\kappa}\ln\mu N\right)\right]^{-\kappa}$$

- **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)

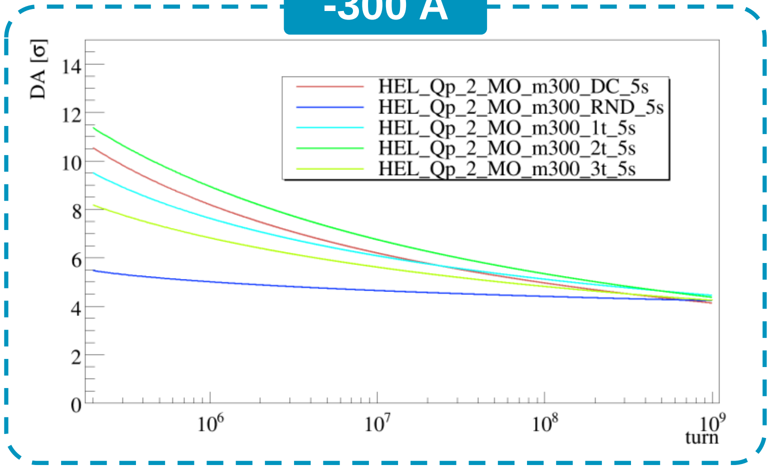
Checked **difference between two models: below 4%** along the 10^9 turns

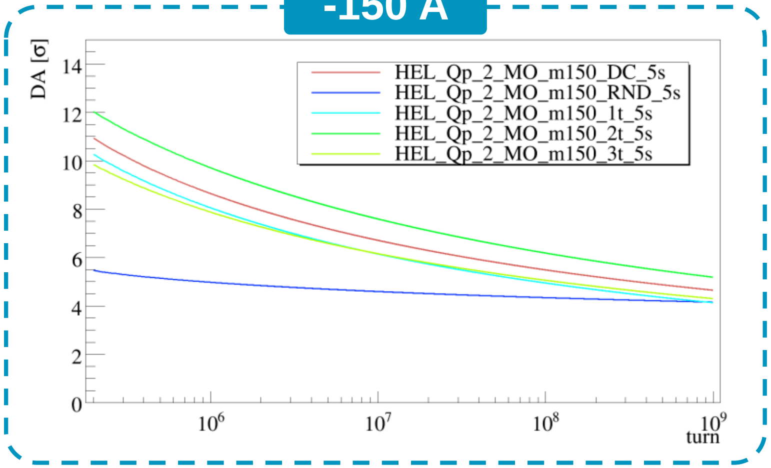


Example: Q'=2, MO=0A, 3t, r1=3σ
(solid lines: fit)

Dynamic Aperture Vs Turns and MO current

Example for ***different excitations modes with r1 = 5 σ and Q' = 2***

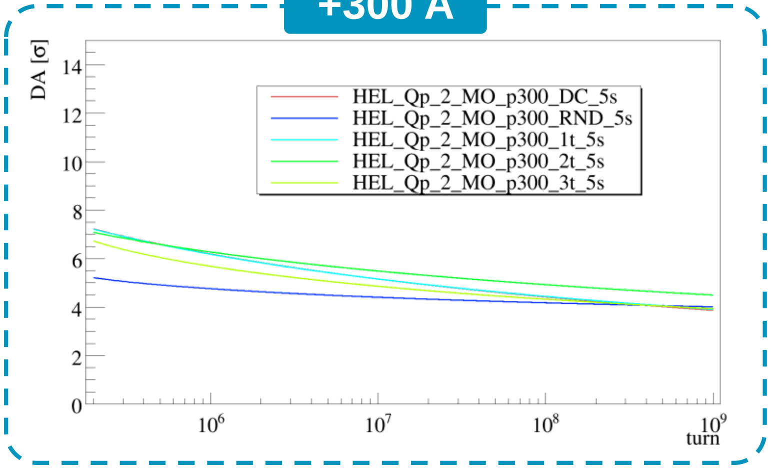

-300 A


-150 A

The larger the MO current

The smaller the initial DA and decay rate

(Similar behaviour as a function of Q'**)**

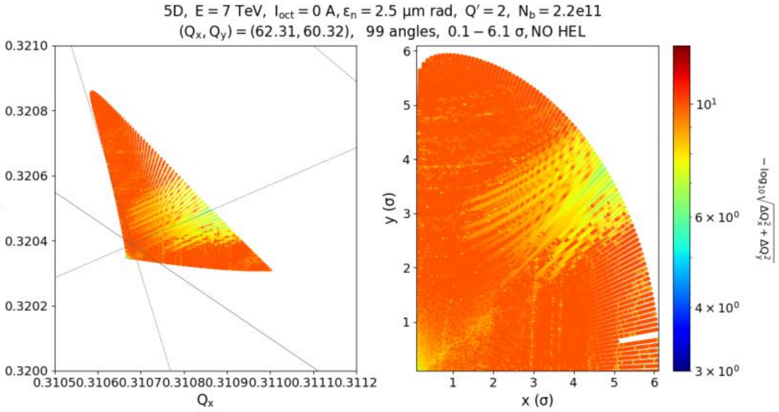

+300 A

Frequency Map Analysis

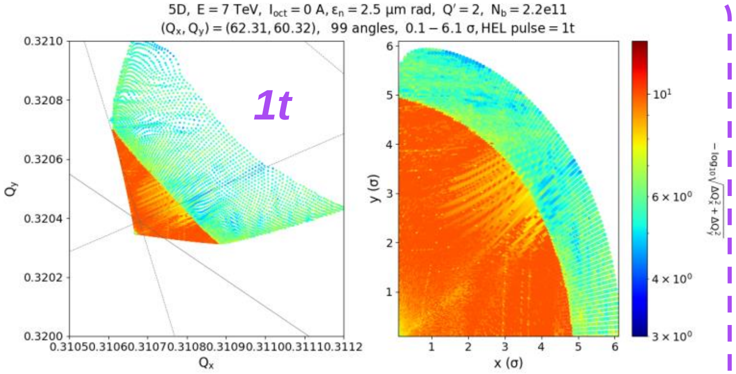
Main aim: understand driving terms to enhance halo diffusion speed

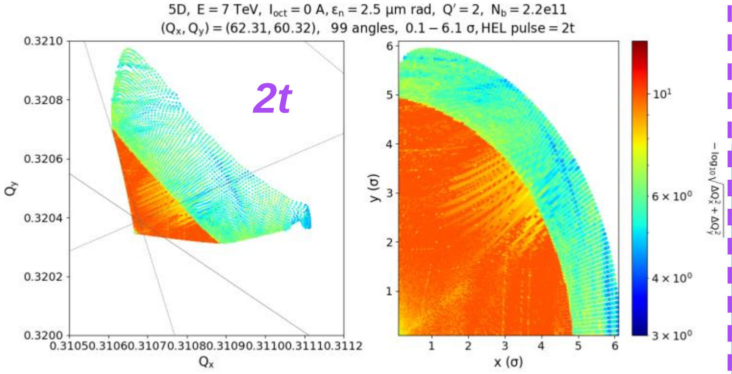
- *10000 turns simulated:*
  - **Initial Q** calculated over the **first 3000 turns**
  - **Final Q** calculated over the **last 3000 turns**

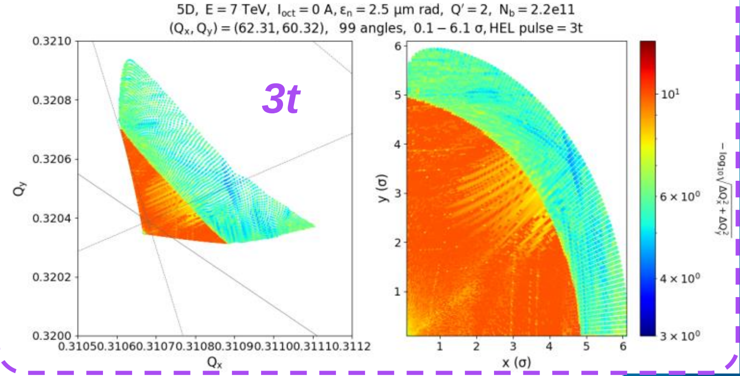
Example of FMA w/o e-lens
I_{MO} = 0 A, Q' = 2



Ideal case to study e-lens effect
(r1 = 5 σ)

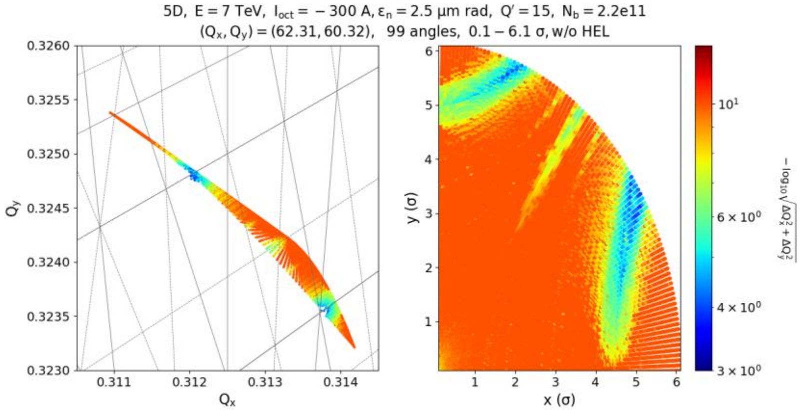


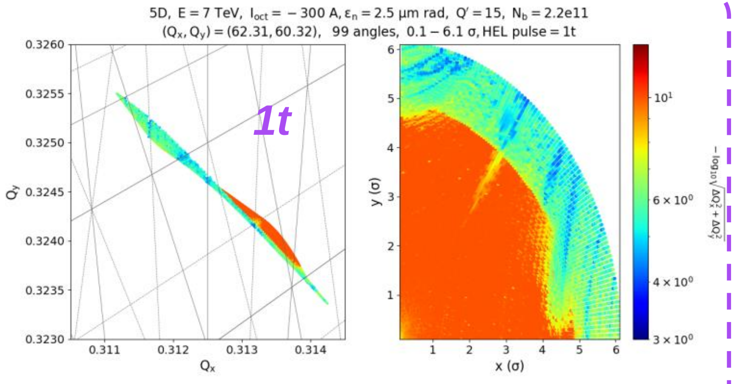


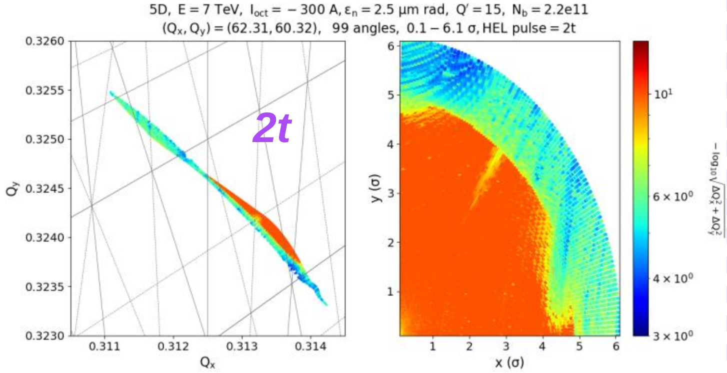


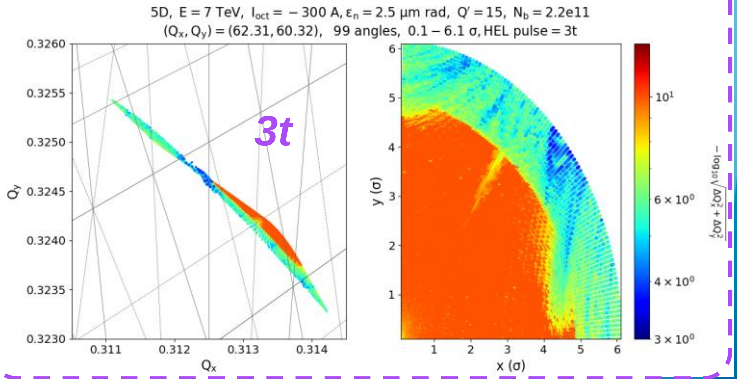
Coupling with non linearity

Example of FMA w/o e-lens
I_{MO} = -300 A, Q' = 15









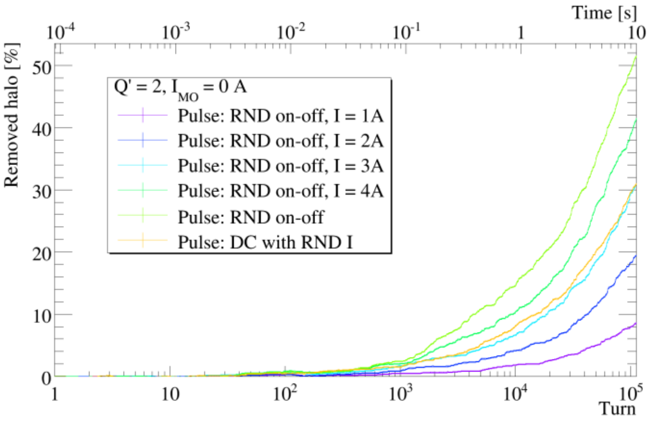
Main qualitative observations:

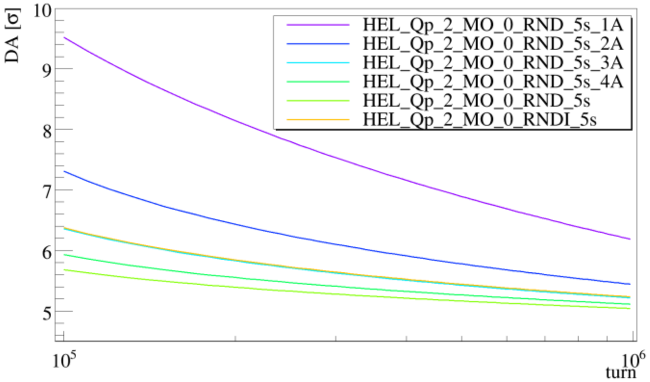
- Clear distortion of Q phase space
- **e-lens enhances** effects due to **non linearity**

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

Simulated particle losses vs DA

- **Good agreement** between **efficiency from DA or Losses if DA < aperture TCPs (6.7 σ)**



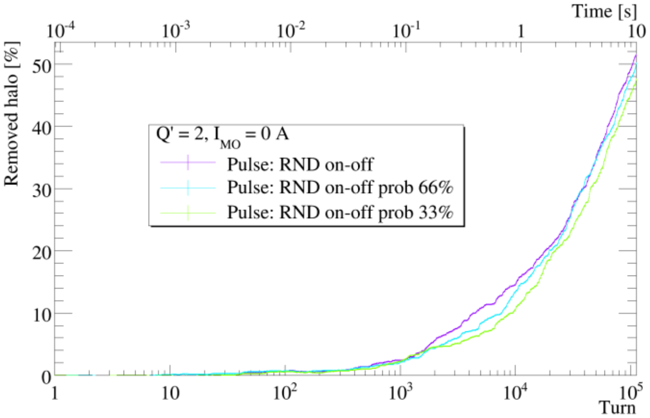


✓ **Significant margins on e-beam current** with RND mode

Knob to play with in the case of emittance blow-up due to residual fields

Studied the effect of
different probabilities of random switch on-off

Lower probabilities under study to possibly
relax requirements on hardware

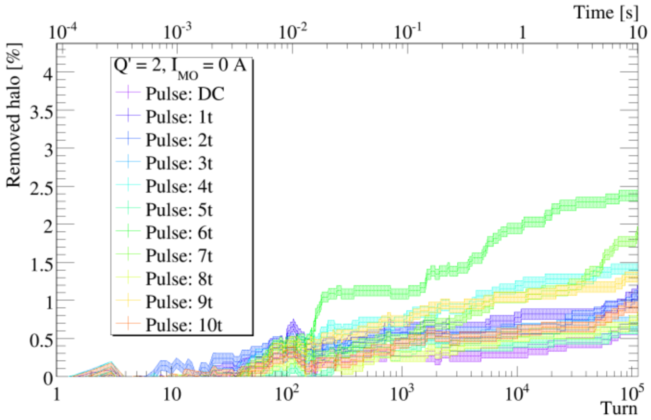


Simulated particle losses vs Non Linearity

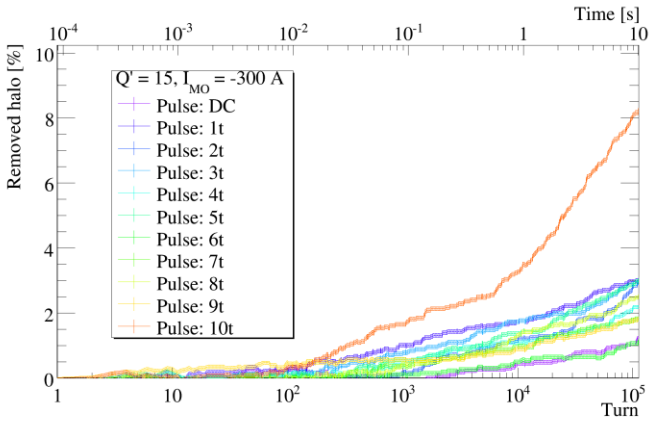
- **Significant effect** on loss rate of the type of pulse used

About factor 10 increase of losses with 10t turn pulse

I_{MO} = 0 A, Q' = 2



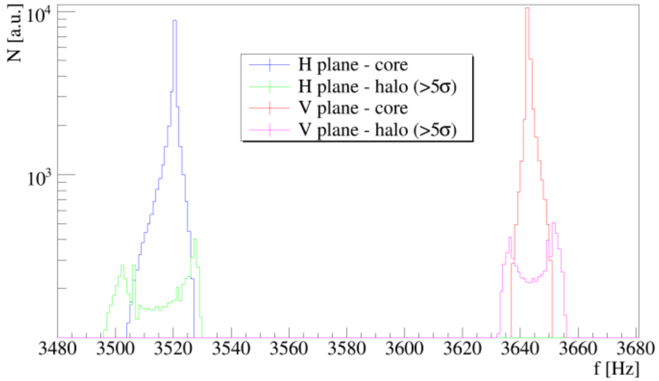
I_{MO} = -300 A, Q' = 15



FFT studies show that

frequency spectrum dominant parameter

On-going: "Ad-hoc spectrum" tuned to act only on halo



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**)
  - ❖ **Poor** depletion using **DC**: continue studying alternative methods (not perturbing core)
  - ❖ **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:**
  - ➢ **Complete DA, FMA and Halo depletion** simulations for all combinations
  - ➢ Introduction of **residual field (bends)** to study effects on the **beam core** (**field maps from BINP just arrived**, but with some issues to discuss)

Thank you for your attention!

Outline

Backup

Machine settings

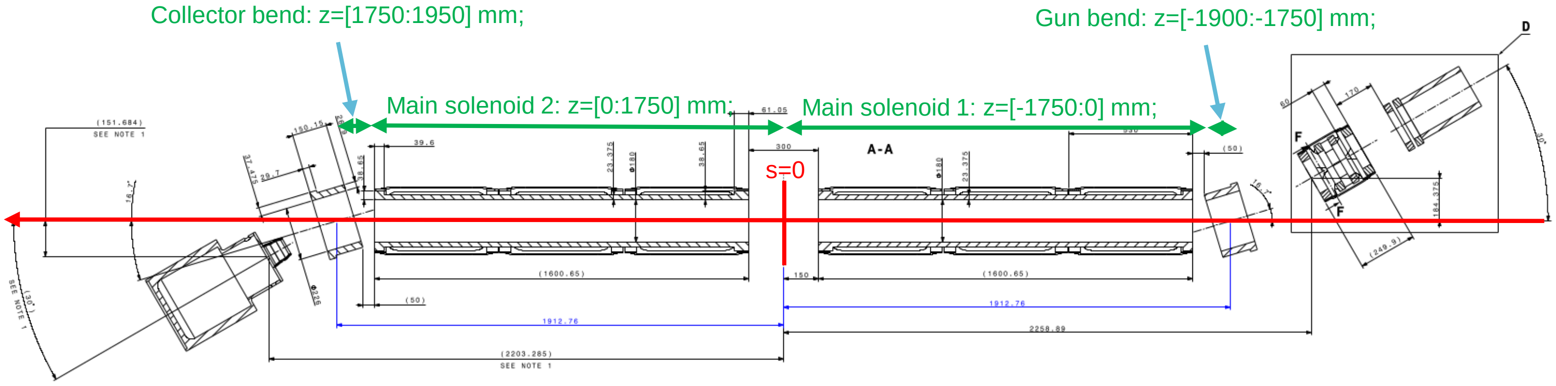
- Optics = HL-LHC v1.3
- BP = collision (but still separated beams)
- Beam-beam = NO
- Field errors = MBRB, MBRC, MBRS, MBX, MBW, MQW, MQTL, MQMC, MQX, MQY, MQM, MQML, MQ, MQXF
- Turns = 1e6
- Angles = 17
- Aperture steps = 10 (from 2σ to 22σ with 2σ step)
- Seeds = 60

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 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:



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

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

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

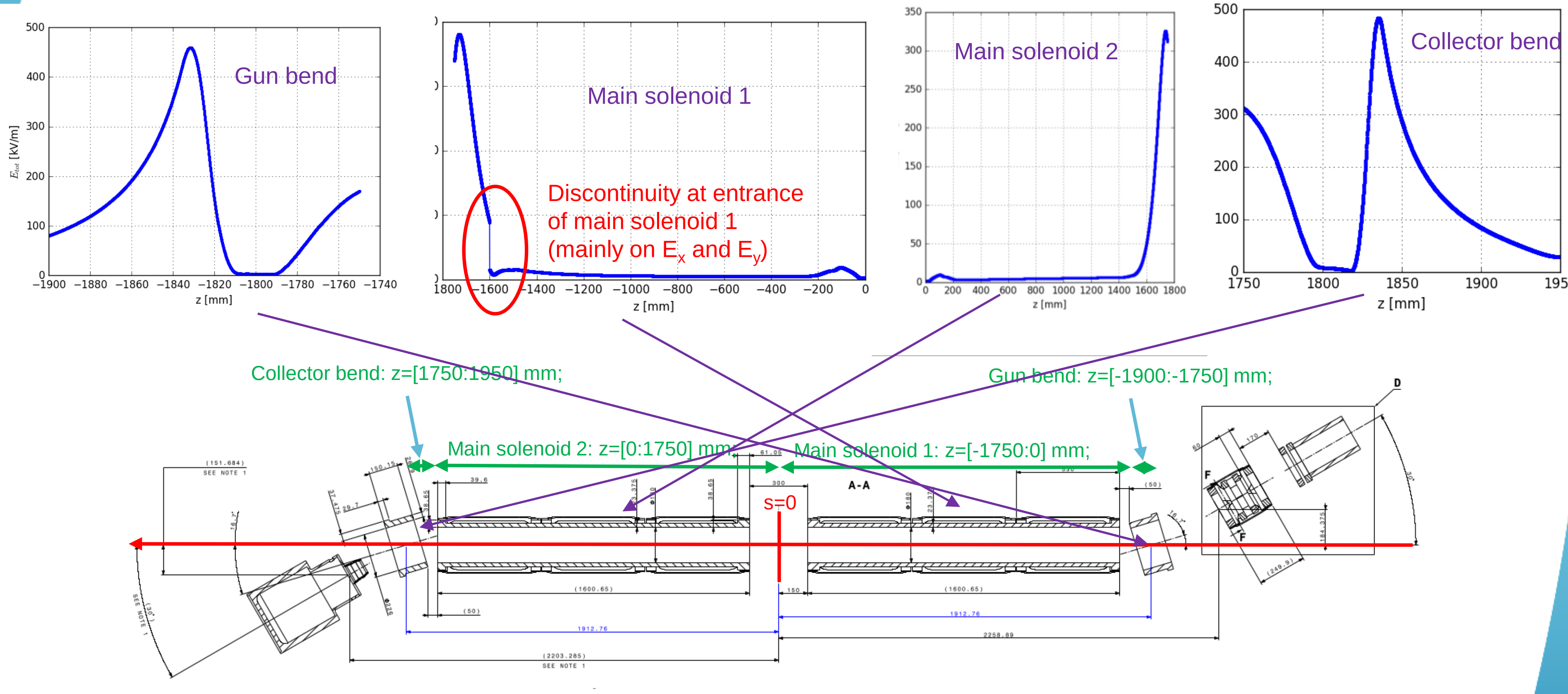
Main solenoid 1: z=[-1750:0] mm;

s=0

A. Mereghetti

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

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



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

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

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

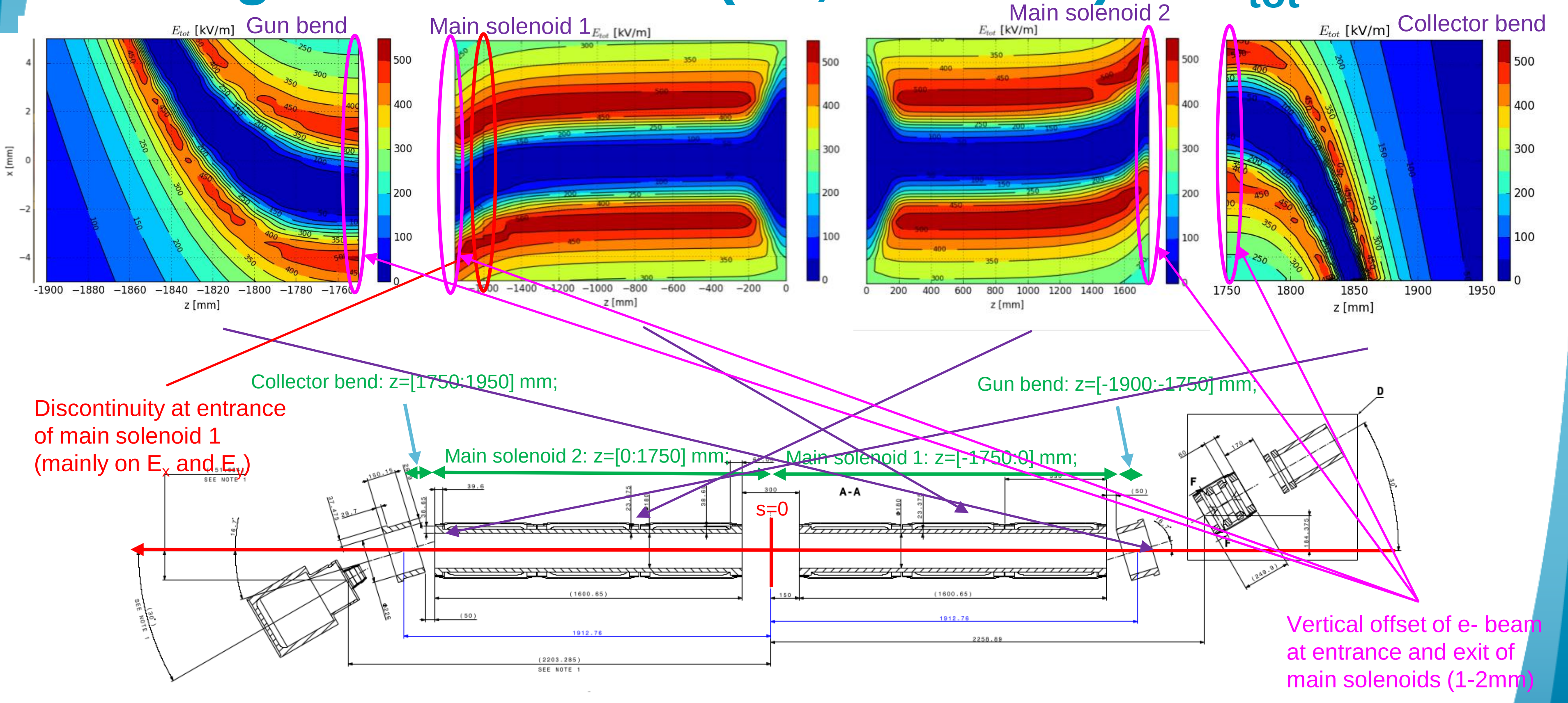
Main solenoid 2: z=[0:1750] mm;

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

A. Mereghetti

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

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



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;

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

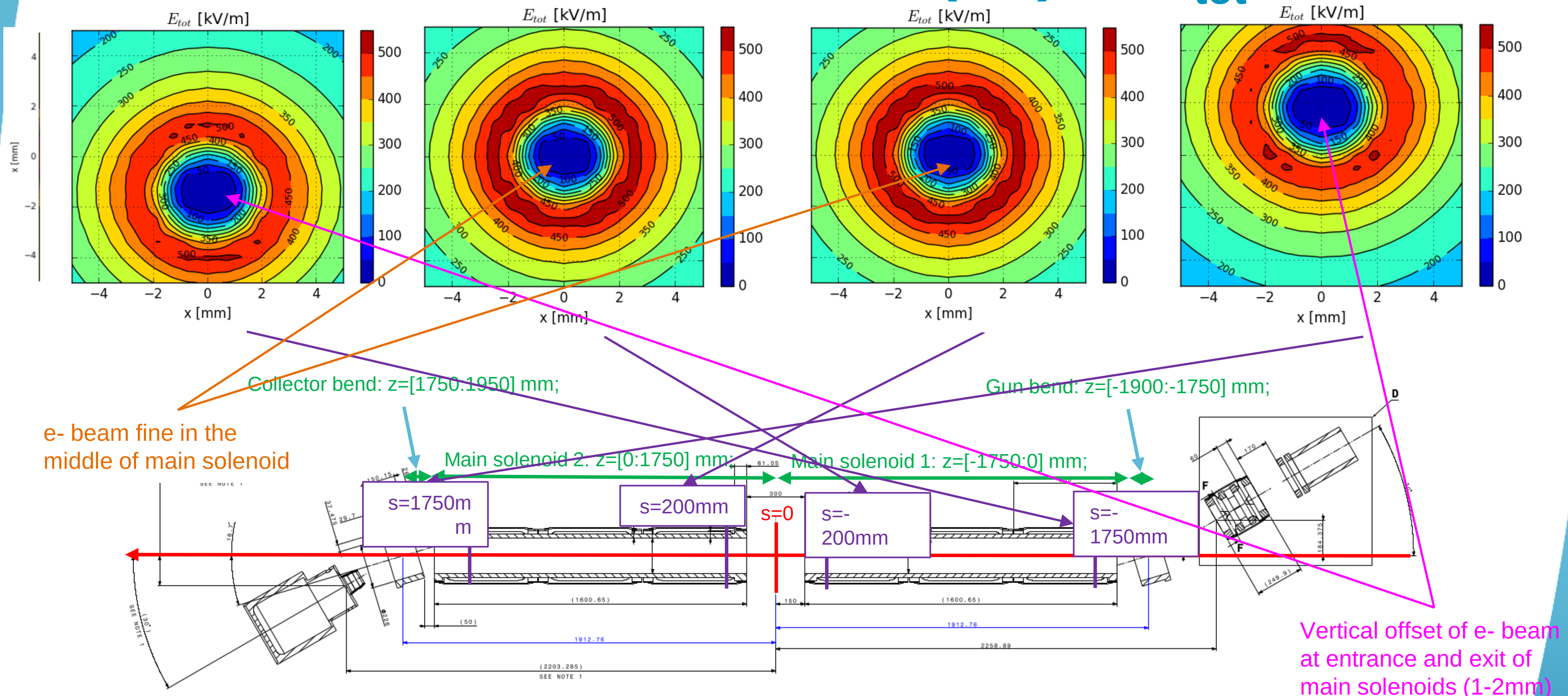
s=0

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

A. Mereghetti

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

Transverse Profile (2D) of E_{tot}



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

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

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

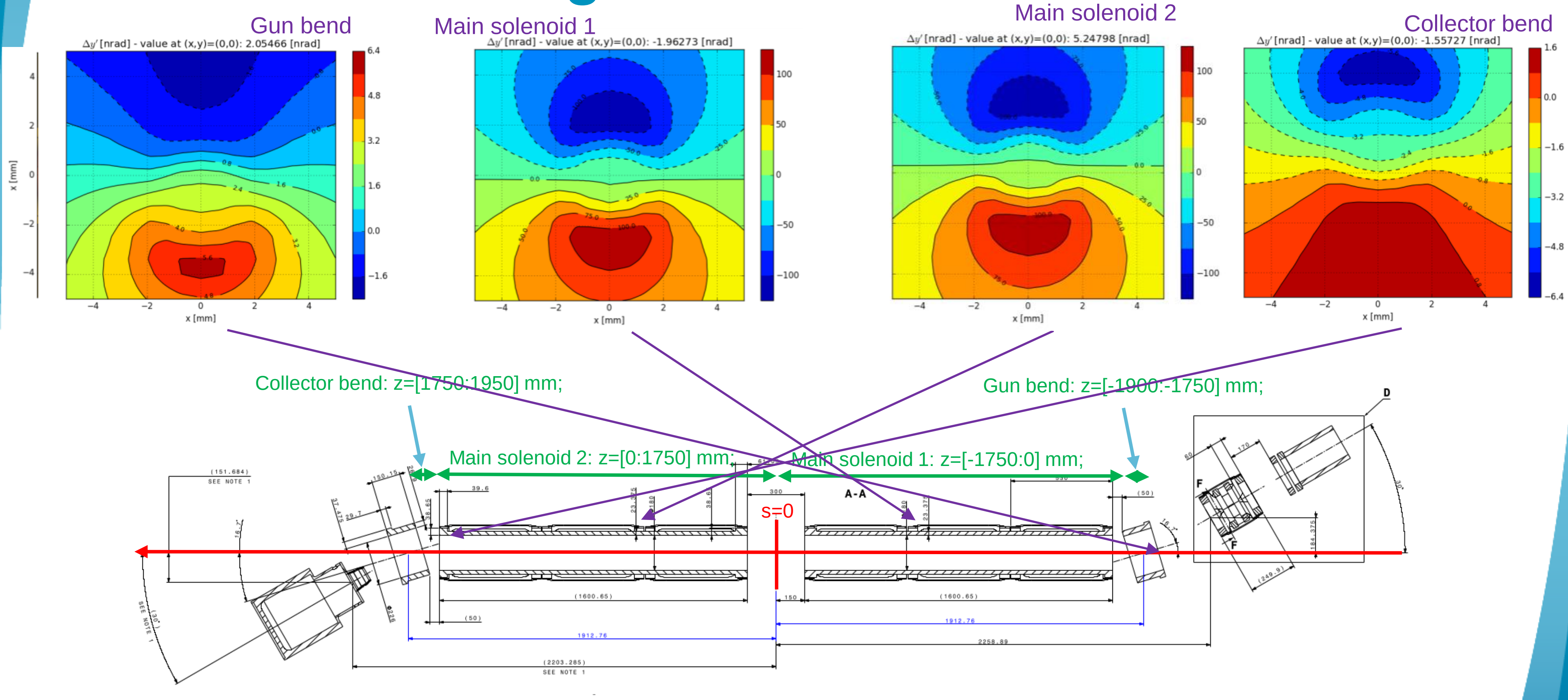
Main solenoid 1: z=[-1750:0] mm;

e- beam fine in the middle of main solenoid

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

A. Mereghetti

Integrated Vertical Kicks



Gun bend

$\Delta y'$ [nrad] - value at (x,y)=(0,0): 2.05466 [nrad]

Main solenoid 1

$\Delta y'$ [nrad] - value at (x,y)=(0,0): -1.96273 [nrad]

Main solenoid 2

$\Delta y'$ [nrad] - value at (x,y)=(0,0): 5.24798 [nrad]

Collector bend

$\Delta y'$ [nrad] - value at (x,y)=(0,0): -1.55727 [nrad]

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;

s=0

A. Mereghetti

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…

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