Status of SixTrack Implementation for Hollow Electron Lenses

A. Mereghetti

Acknowledgements: R. Bruce, M. Giovannozzi, D. Mirarchi, S. Redaelli

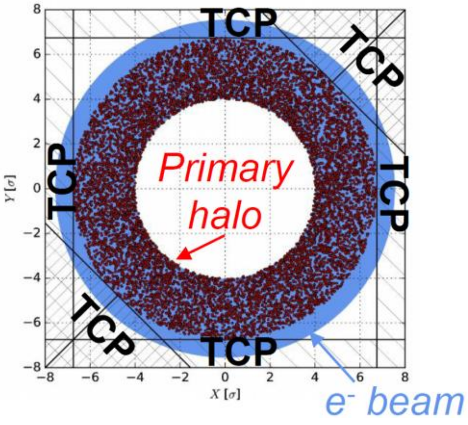
Material substantially the same as that presented at [ColUSM #122, Informal review of the HL-LHC electron lens design]

E-Beam – #2 Remote WG Meeting

1st April 2020

Introduction

- Hollow Electron Lenses (HELs) are presently part of the baseline upgrade foreseen by the High Luminosity Large Hadron Collider (HL-LHC) project;
- Their scope is to clean beam tails (e.g. >3.5σ) to avoid magnet quenches or permanent damage to collimators in case of orbit jitters or crab cavity phase slips;
  - Scaling scraping measurements of beam population at the LHC to HL–LHC beam intensities shows that ~35 MJ are expected in the beam tails at flat top (B. Salvachua Ferrando, International Review of the HL–LHC Collimation System);
- Working principle:
  - The electron beam is hollow, covering the amplitude range between the desired cut and the TCP cut;
  - Diffusion speed of tails is enhanced on purpose to dispose them;
  - The beam core should be un-affected;
- Big simulation campaign, to define operational scenarios and optimal parameters of e-Lens;
  - Using ideal e-Lens;
  - Pulsing mode: most promising, for fast removal of tails;
  - DC mode: promising for continuous and less aggressive tail cleaning;
  - D. Mirarchi, 9th HL-LHC Annual Meeting;



Ideal Electron Lens: SixTrack Implementation

- Electron beam: indefinitely long, with cylindrical symmetry, no changes along the lens;
- No longitudinal component of field lines taken into account, no update of energy of beam particles;
  - Kick applied only to transverse momenta, based only on transverse position;
- No fringe fields;
- Thin lens only!
- Can simulate hollow and full lens
  - Foxification (i.e. 6D closed orbit calculation via Taylor maps) of full e-lens completed!
- Can simulate three radial profiles: constant, Gaussian, from ASCII file (e.g. from measurements);
- Compatible with all species tracked by SixTrack;
- Lenses are DYNK-able (i.e. kick can be varied with time);
- Dynamic memory allocation, i.e. no hard-coded limit in number of lenses;
- Flexible user interface;
  - E.g. beam of lens composed by particles other than electrons and geometrical parameters of lens expressed in normalised units;

As done in other tracking codes, like LifeTrack or Merlin

Implied implementing a general module for polynomial interpolation in SixTrack
→ Interpolation of any desired degree!

Recent enhancements with respect to previous implementation by M. Fitterer *et al.*

Assumption fine for beams of few GeV (Z);
→ Outlook: considering to extend the implementation, starting from an approximated Hamiltonian;

Ideal Electron Lens: SixTrack Implementation (II)

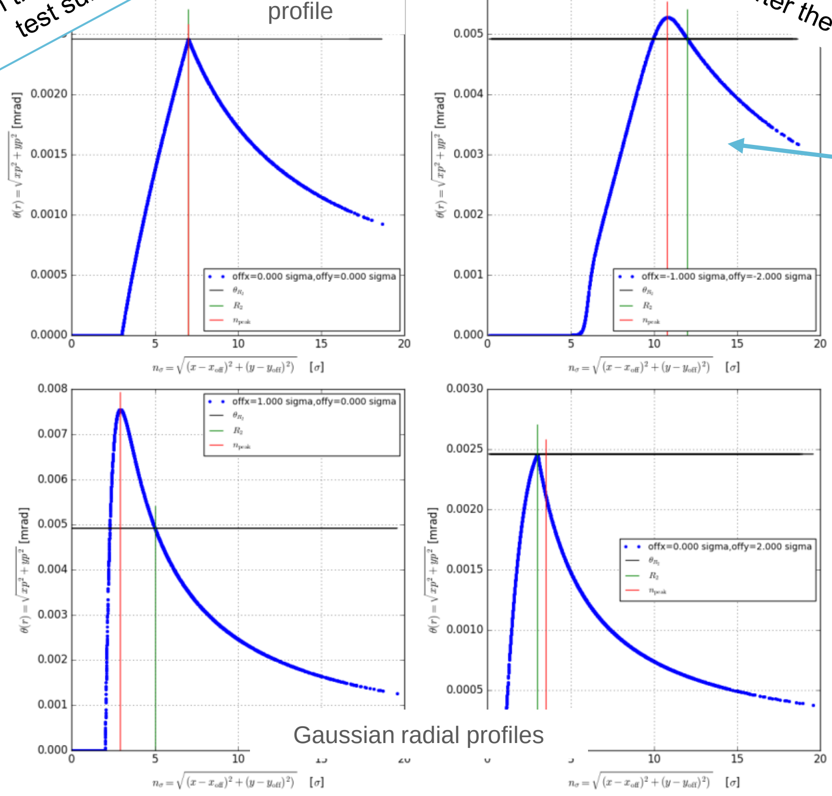
Examples taken from the SixTrack test suite

Hollow e-lenses

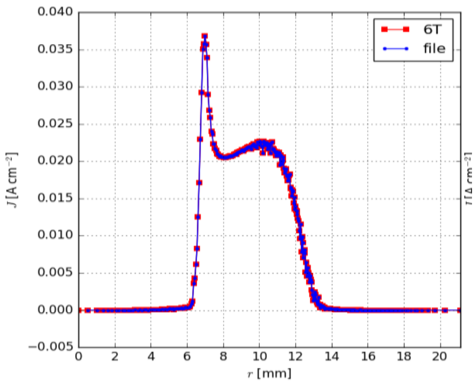
Constant radial profile

Radial profile from .txt file

Difference in "radial" angle (i.e. sqrt(x'²+y'²)) between before and after the electron lens



Gaussian radial profiles



Original radial profile

Preliminary draft 09:42 31 March 2020

31 March 2020
alessio.mereghetti@cern.ch

Physics of the Implementation of Electron Lenses in SixTrack v5.xx.yy

Alessio Mereghetti
CERN, CH-1211 Geneva, Switzerland

Keywords: Electron lens, SixTrack, symplectic tracking map

Report about implemented physics in preparation!
(including proof of symplecticity)

Towards a More Realistic Description of the Electron Lens

- The description of the ideal electron lens can be deployed to identify key working parameters;
- When evaluating impact of electron lens on beam tails and core, it is important also to take into account other effects, e.g.:
  - Effect of electric field in the region of the main bends of the electron lens (injection/extraction of electron beam);
  - Evolution of transverse distribution of electron beam along the lens (e.g. due to space-charge in electron beam);
- In order to take into account these effects, it is necessary to simulate the actual magnetic configuration of the lens and the electron beam dynamics;
  - Approach can be only numerical!
- Method outlined by G. Stancari in FERMILAB-FN-0972-APC, based on Chebyshev polynomials:
  1. Use numerical simulations to define distribution of electrons and compute the electric potential and field thus generated as 3D maps;
  2. Longitudinally integrate the maps, to get the integrated values – from 3D maps to 2D maps;
  3. Fit the 2D maps by means of Chebyshev polynomials – from 2D maps to fit coefficients;
  4. Deploy the fit coefficients in tracking code, to estimate effects of integrated fields on proton beam;
- The method is effective to simulate heavily (transversely) non-linear electric fields in a CPU-efficient way;
  - Method already implemented in LifeTrack;

We need a simulation set-up that allows to take into account asymmetries in the electron beam

First implementation in SixTrack!

Method

- Method outlined by G. Stancari in FERMILAB-FN-0972-APC, based on Chebyshev polynomials:
  1. Use numerical simulations to define distribution of electrons and compute the electric potential and field thus generated as 3D maps;
  2. Longitudinally integrate the maps, to get the integrated values – from 3D maps to 2D maps;
  3. Fit the 2D maps by means of Chebyshev polynomials – from 2D maps to fit coefficients;
  4. Deploy the fit coefficients in SixTrack, to estimate effects of integrated fields on proton beam;

This formalism is symplectic by construction (see FERMILAB-FN-0972-APC)

Electric Potential

Longitudinal integration

$$V(x,y) = \int_{z_1}^{z_2} \phi(x,y,z)\,dz$$

Definition based on Chebyshev polynomials

$$\begin{aligned} V(x,y) &= C_{00} + C_{10}\cdot T_1\left(\frac{x}{a}\right) + C_{01}\cdot T_1\left(\frac{y}{a}\right) + \\ &\quad C_{20}\cdot T_2\left(\frac{x}{a}\right) + C_{11}\cdot T_1\left(\frac{x}{a}\right)\cdot T_1\left(\frac{y}{a}\right) + C_{02}\cdot T_2\left(\frac{y}{a}\right) + \dots \\ &= \sum_{n=0}^{N}\sum_{j=0}^{n} C_{j,(n-j)}\cdot T_j\left(\frac{x}{a}\right)\cdot T_{n-j}\left(\frac{y}{a}\right) \end{aligned}$$

Definition of Chebyshev polynomials

$$\begin{aligned} T_0(u) &= 1 \\ T_1(u) &= u \\ T_n(u) &= 2u\cdot T_{n-1}(u) - T_{n-2}(u) \end{aligned}$$

Electric Field

$$\begin{aligned} k_x(x,y) &\equiv \int_{z_1}^{z_2} E_x(x,y,z)\,dz, \\ k_y(x,y) &\equiv \int_{z_1}^{z_2} E_y(x,y,z)\,dz, \end{aligned}$$

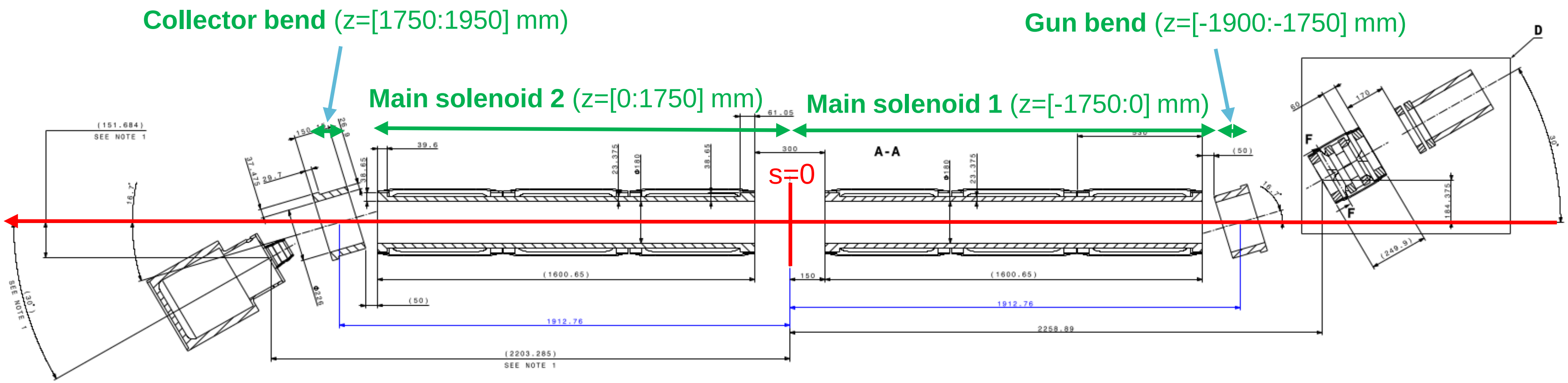
$$\begin{aligned} k_x(x,y) &= -\frac{\partial V}{\partial x} = -\frac{1}{a}\sum_{n=0}^{N}\sum_{j=0}^{n} C_{j,(n-j)}\cdot T'_j\left(\frac{x}{a}\right)\cdot T_{n-j}\left(\frac{y}{a}\right) \\ k_y(x,y) &= -\frac{\partial V}{\partial y} = -\frac{1}{a}\sum_{n=0}^{N}\sum_{j=0}^{n} C_{j,(n-j)}\cdot T_j\left(\frac{x}{a}\right)\cdot T'_{n-j}\left(\frac{y}{a}\right) \end{aligned}$$

$$(1-u^2)\cdot T'_n(u) = n\cdot[T_{n-1}(u) - u\cdot T_n(u)]$$

Applying the Method to the HL-LHC HEL

1. To get 3D maps of electric field and electric potential – D.Nikiforov, with CST;
2. To integrate them longitudinally and fit them with Chebyshev polynomials – A.Mereghetti, numpy;
3. To plug Chebyshev polynomials into SixTrack and see the effect in tracking simulations;

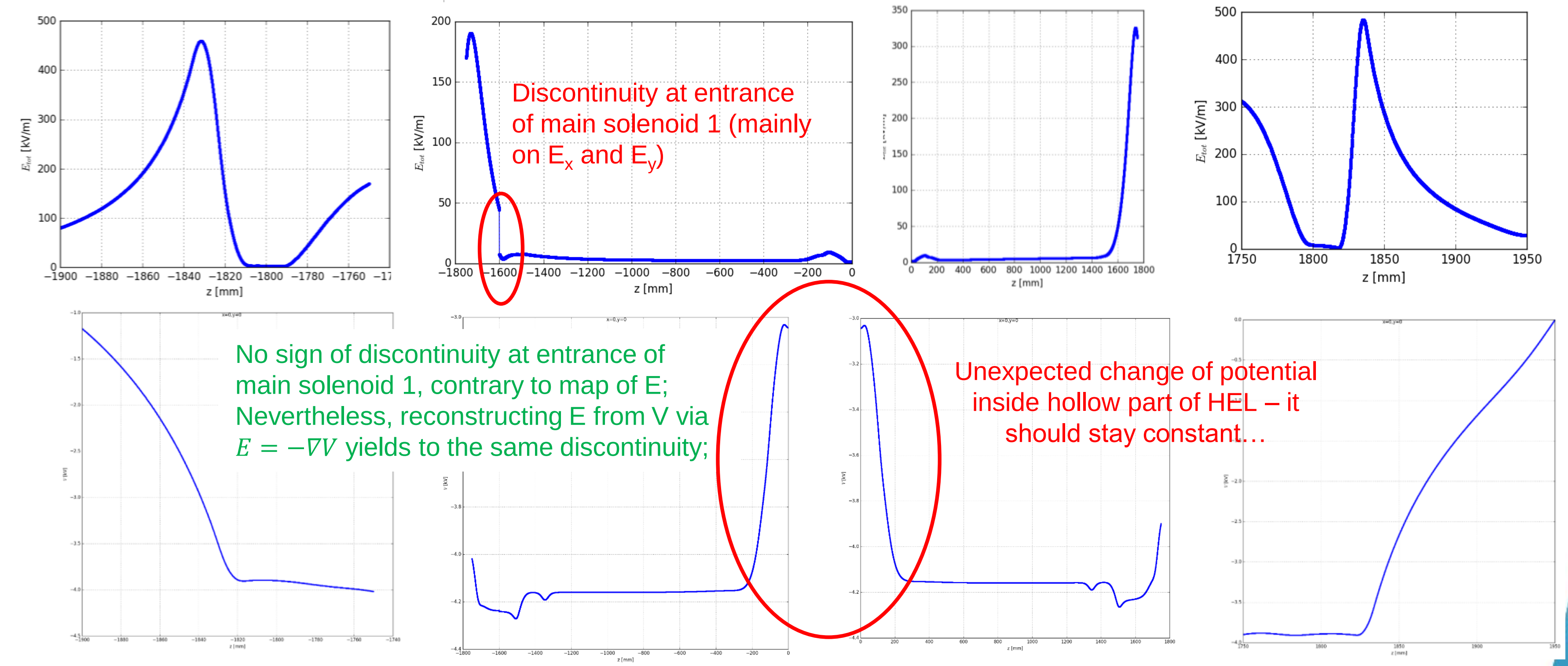
- Maps generated by D.Nikiforov:
  - x=[-5:5:0.1] mm, y=[-5:5:0.1] mm, z=[-1900:1950:0.1] mm;
  - Electron current: 5A, beam potential in main solenoid: 11.2kV (electron beam compression);
  - ASCII files very large: ~35 GB for E field, ~10 GB for V → split in 4 pieces:



Longitudinal Profile (1D) at x=0, y=0

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

Electric Potential



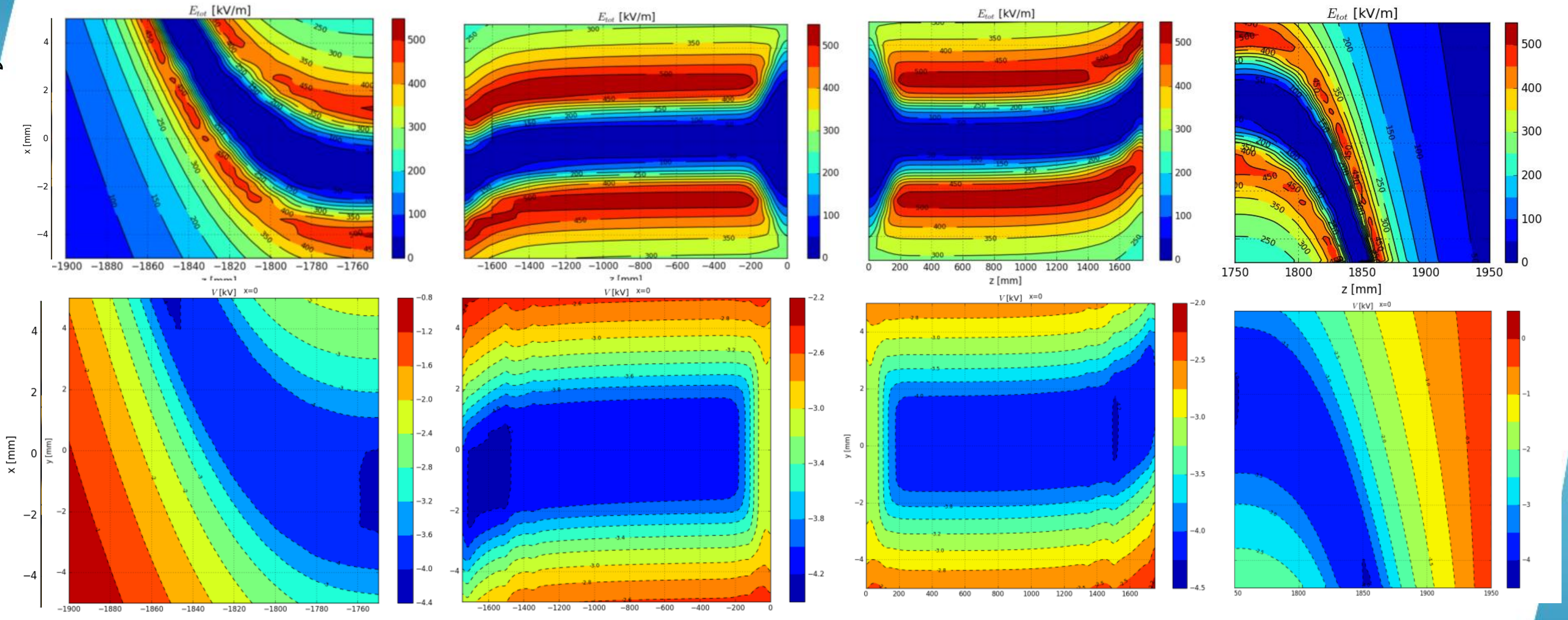
Unclear origin of discontinuity in electric field at entrance of main solenoid 1;
→ cannot proceed with these maps for production of results;
In contact with D. Nikiforov to check origin of issue (mostly caused by matching boundary conditions);

Longitudinal Profile (2D) at x=0

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

V

Gun bend | Main solenoid 1 | Main solenoid 2 | Collector bend

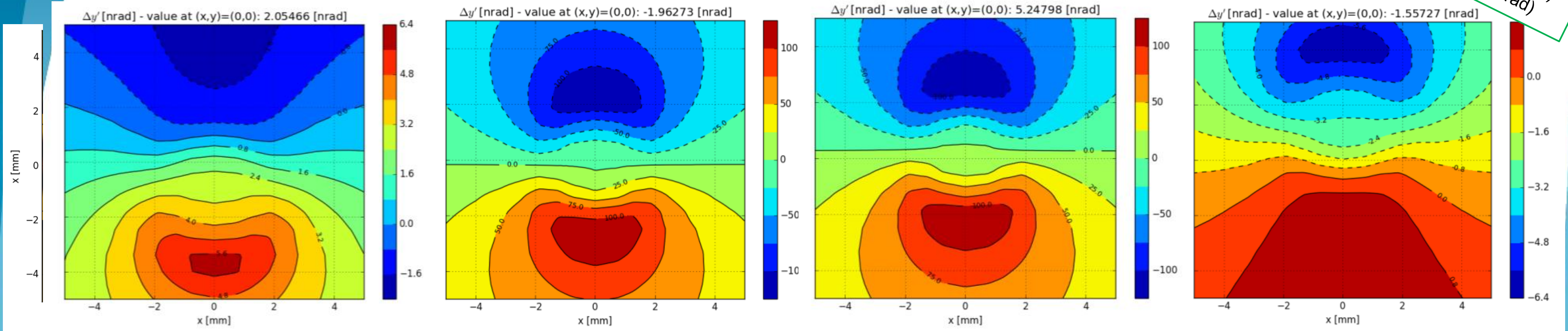


Shift at entrance and exit of main solenoid clearly visible (also presented by A.Rossi, E-beams, #1 remote WG meeting);
→ Proposal of mitigation presented by D.Nikiforov (ColUSM #122);

Integrated Kicks

All maps: (integrated) vertical kick (nrad)

Gun bend | Main solenoid 1 | Main solenoid 2 | Collector bend



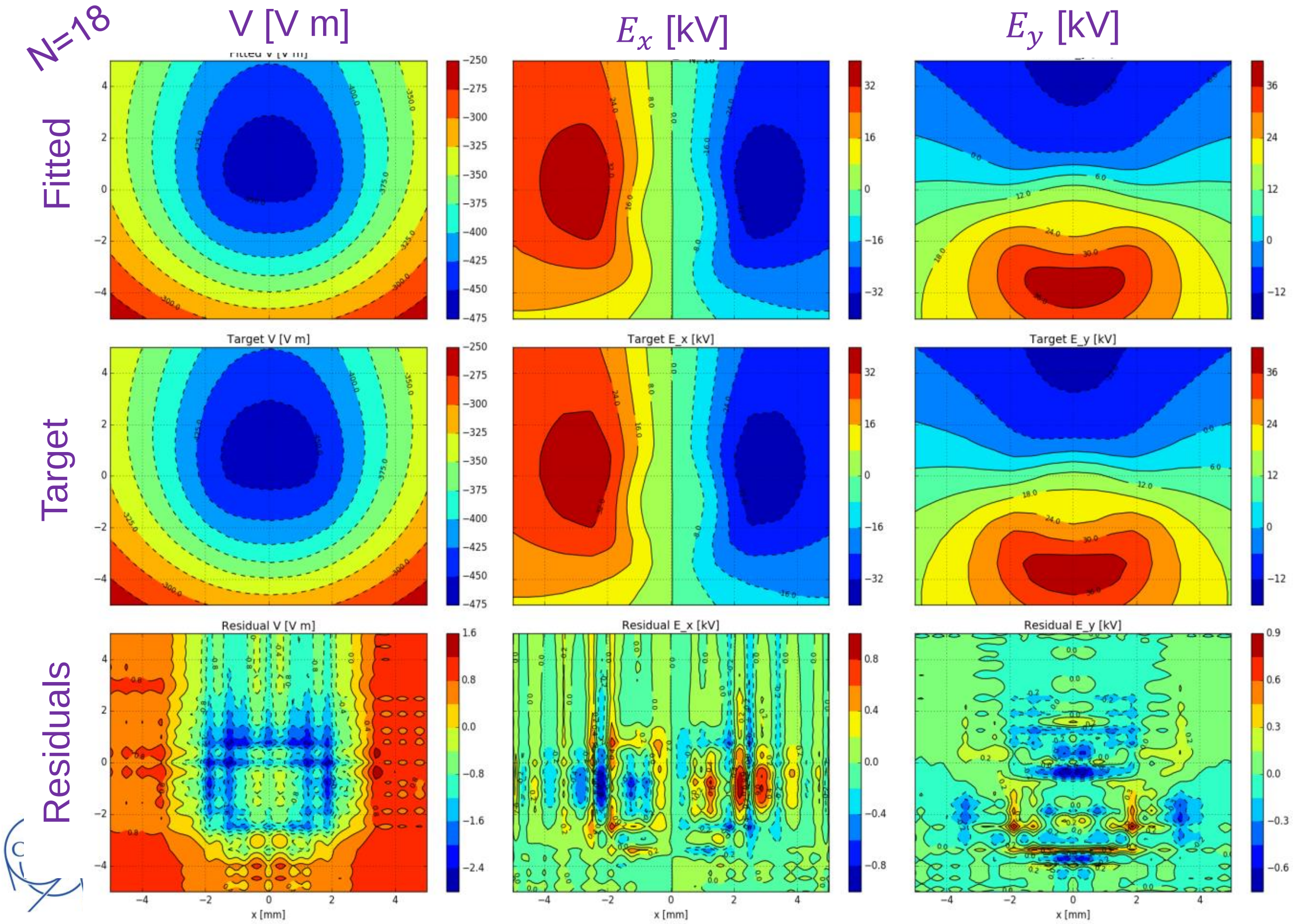
x=y=0, 7TeV	Δx' [nrad]	Δy' [nrad]	ΔE [keV]
Gun Bend	0.052	2.05	2.85
Main 1 solenoid	0.4	-1.96	-0.98
Main 2 solenoid	-0.4	5.25	0.85
Collector Bend	0.03	-1.56	-3.9

(V) Values at gun/collector bends are comparable to those computed by G. Stancari in FERMILAB-FN-0972-APC

NB: Ref sys of e-beam → proton beam has a local ref sys rotate by 180° around the y-axis

LHC Collimation Project
CERN

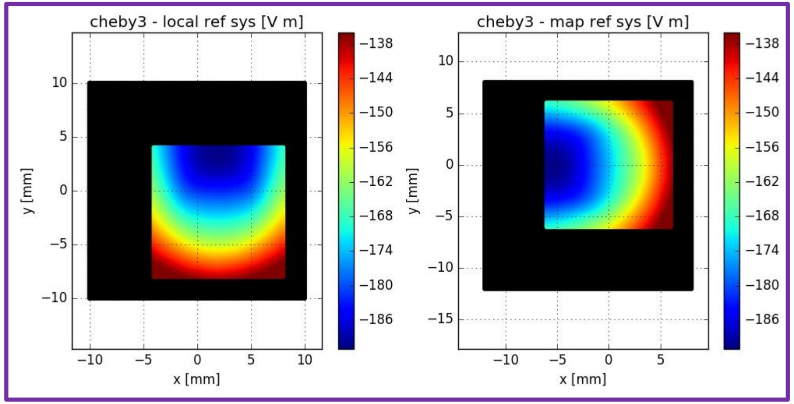
Fitting the Maps – Example: Gun Bend

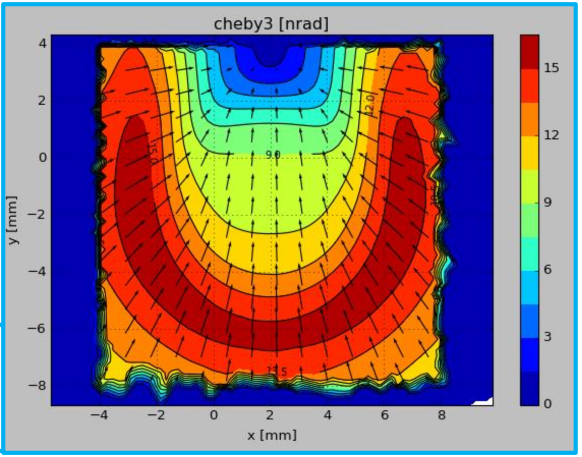


Chebyshev Lens: SixTrack Implementation

- Chebyshev polynomials implemented;
  - Module separate from that of ideal electron lens, so that it can be used for other purposes – e.g. e-cloud?
  - Electric field only, for the time being;
  - Outlook: considering magnetic fields as well, and their superposition;
- Compatible with all species tracked by SixTrack;
- Echo of integrated potential map as from read Chebyshev coefficients;
- Possibility to rotate and offset original maps;
- Dynamic allocation of memory, i.e. no hard-coded limit in number of elements or dimension of map;
- Lenses are DYNK-able (i.e. kick can be varied with time);
- Foxification (i.e. 6D closed orbit calculation via Taylor maps) almost done;

Echo of potential map





Kick applied to 450 GeV protons (test with 60 protons, 400 turns)

HiLumi HL-LHC PROJECT
CERN
LHC Collimation Project CERN

Conclusions / Remarks

- Solid implementation in SixTrack of a module for simulating ideal electron lenses;
  - Module significantly expanded wrt original implementation (e.g. full lens, Gaussian electron beam, beam from measured radial profile, etc…);
- General module for maps with Chebyshev polynomials for simulating pure electric fields;
  - User can define as many maps as necessary for their application (e.g. several longitudinal slices);
- Modules are pretty flexible and general, with no hard-coded assumptions targeting HL-LHC HELs;
  - Even though HL-LHC HELs are the main study case;
- This is the current framework used for SixTrack simulations for the HL-LHC HELs:
  - Optimization of working point of HEL: ideal electron lens;
  - Effects on proton beam core: module for Chebyshev maps;
  - Issues with 3D maps for Chebyshev polynomials being discussed with our Russian collaborators…
- Outlook:
  - Look into describing the kick by ideal electron lens starting from the Hamiltonian;
  - Look into extending Chebyshev formalism to magnetic fields and mixed fields;

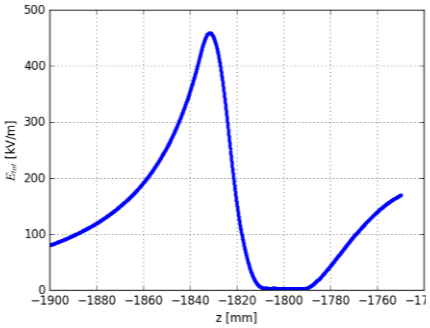
HiLumi HL-LHC PROJECT CERN

Thanks a lot!

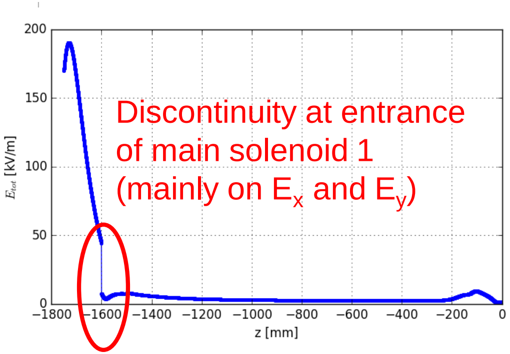
Longitudinal Profile (1D) of E_{tot} at x=0, y=0

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

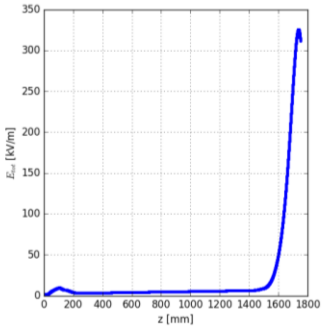
Gun bend



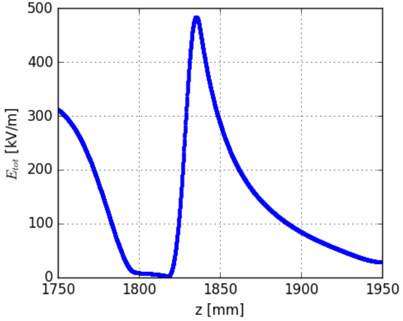
Main solenoid 1



Main solenoid 2

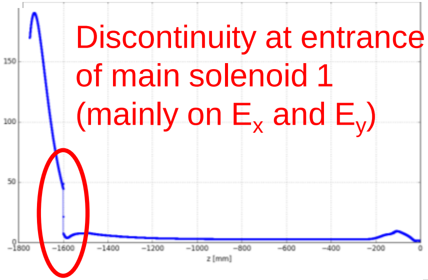


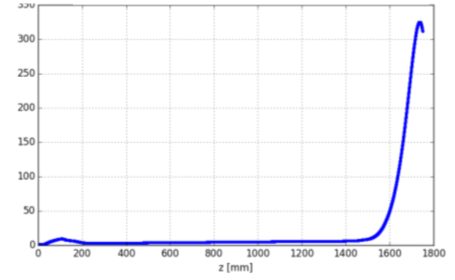
Collector bend

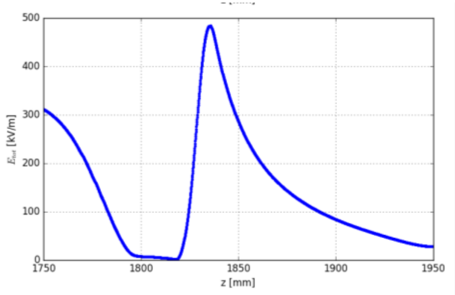


$E_{tot}^2 = E_x^2+E_y^2+E_z^2$

$E = -\nabla V$







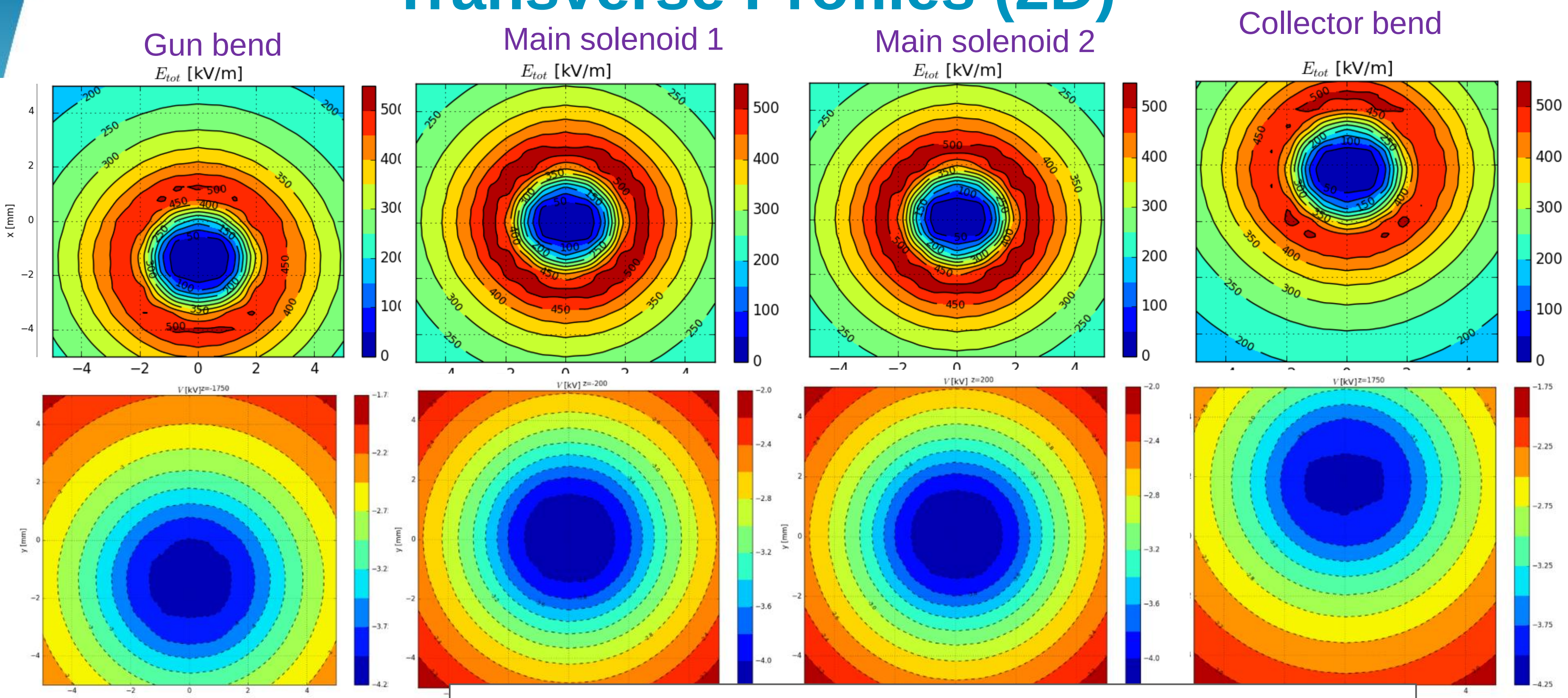
In the effort of by-passing the issue on the electric field, I computed it on my own from $E = -\nabla V$, but got into the same result;
→ Something might be wrong with Opera calculation itself…

HiLumi HL-LHC PROJECT CERN LHC Collimation Project CERN

Transverse Profiles (2D)

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

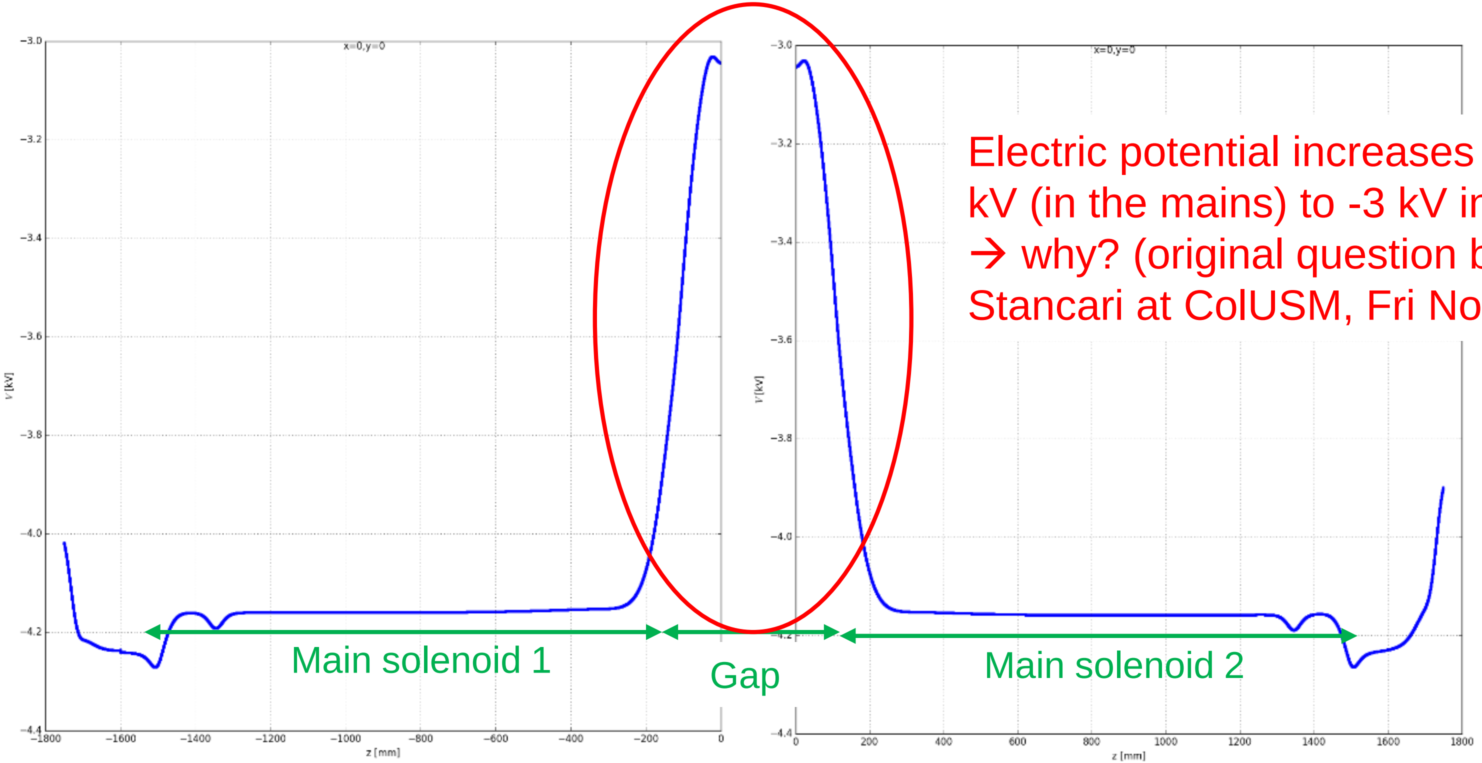
V



Shift at entrance and exit of main solenoid clearly visible (also presented by A.Rossi, E-beams, #1 remote WG meeting);
→ Proposal of mitigation presented by D.Nikiforov (ColUSM #122);

Electric Potential in Gap between Main Solenoids

Electric potential: longitudinal profile at x=0, y=0 (i.e. main solenoids longitudinal axis);



Electric potential increases from -4.2 kV (in the mains) to -3 kV in the gap; → why? (original question by G. Stancari at ColUSM, Fri Nov 22nd)

Electric Potential in Ideal HEL

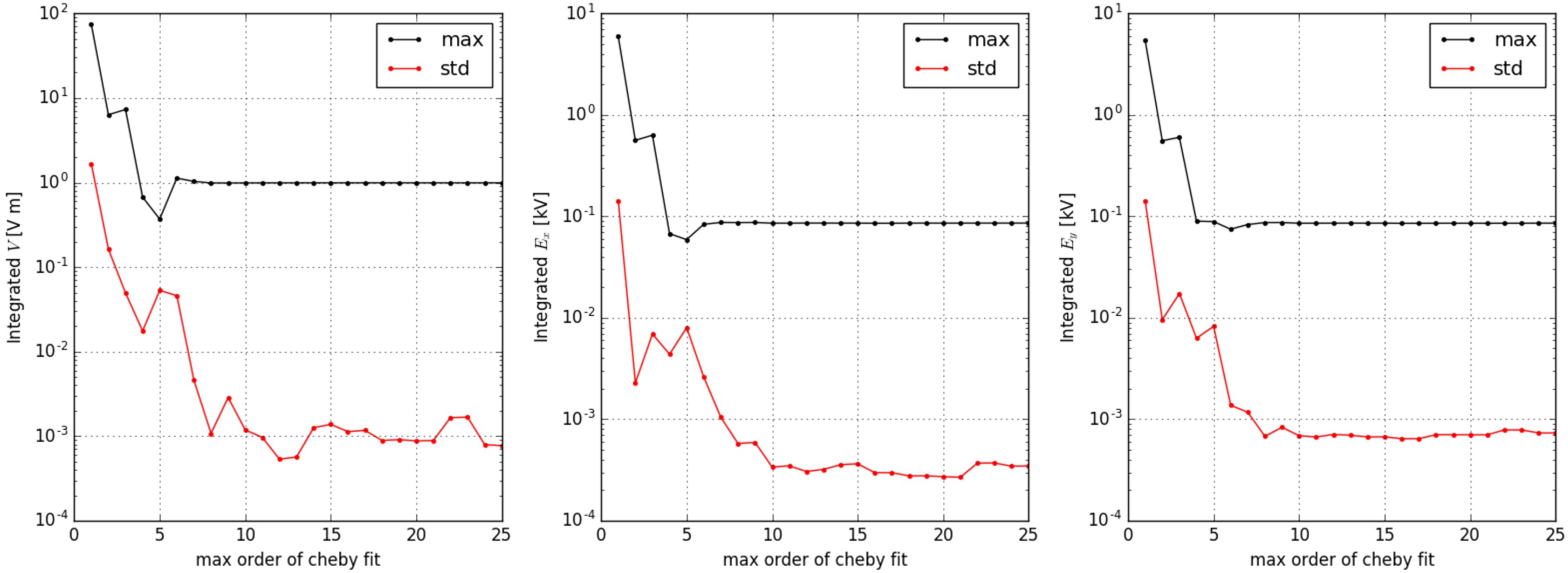
- In an ideal HEL (i.e. e-beam perfectly cylindrical and co-axial with solenoid, infinite solenoid and e-beam, no e-beam injection/extraction, no beam pipes), the electric potential in the hollow part of the HEL is constant and given by the analytical formula (if $V(R_2) = 0$):

$$V_{(r<R_1)} \div \frac{1}{(F^2-1)} \log\left(\frac{1}{F}\right)$$

where R_1 and R_2 are the inner and outer radius of e-beam, respectively, and $F = {}^{R_2}/_{R_1}$;

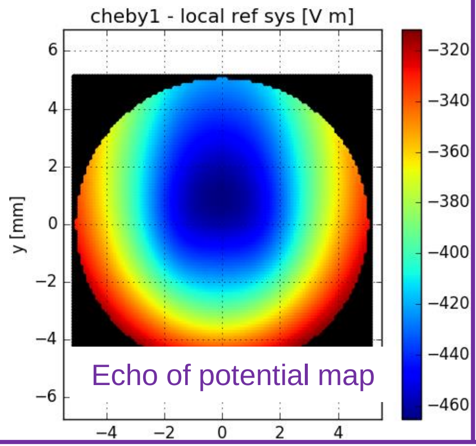
- Why do we see the change in electric potential in the gap between the two main solenoids? Possible answers:
  1. F changes inside the gap;
  2. Asymmetry in e-beam distribution in the gap;

Fitting the Maps – Example: Gun Bend (II)

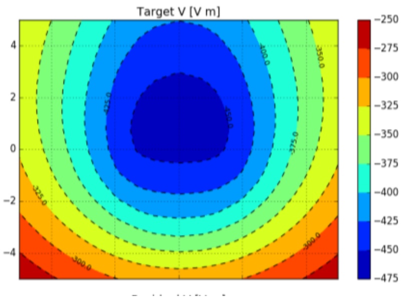


Residuals vs fitting order do not show big changes for N>10;
→ The same applies to the fitting of the other maps;

Chebyshev Lens: SixTrack Implementation

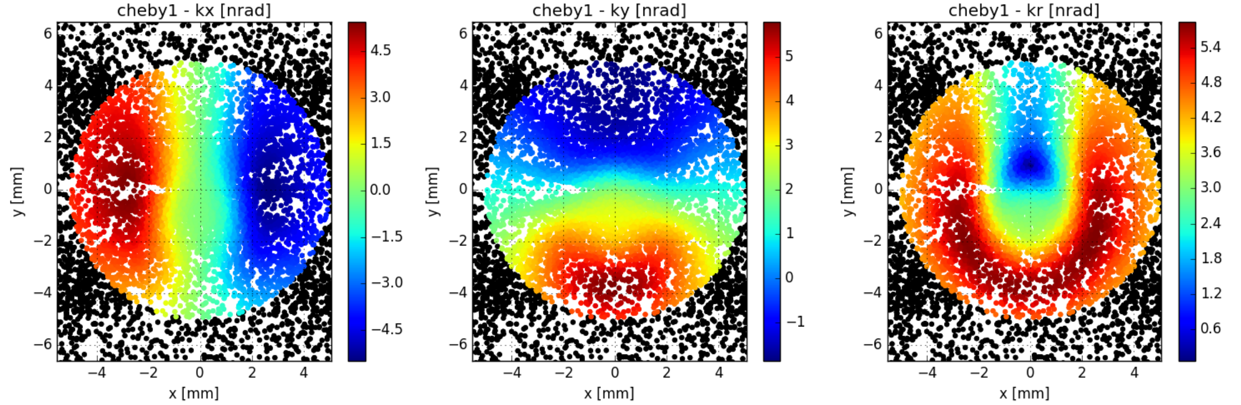


Original potential map

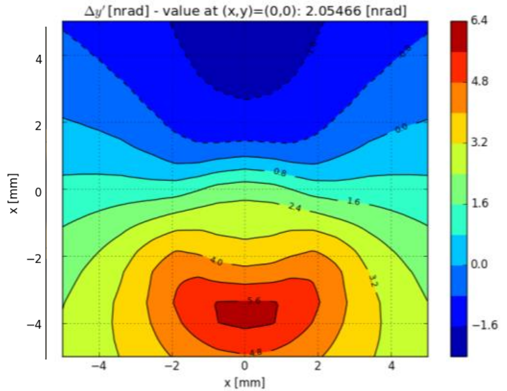


- Chebyshev polynomials implemented;
- Compatible with all species tracked by SixTrack;
- Echo of integrated potential map as from read Chebyshev coefficients;
- Possibility to rotate and offset original maps;
- Dynamic allocation of memory, i.e. no hard-coded limit in number of elements or dimension of map;
- Lenses are DYNK-able (i.e. kick can be varied with time);
- Foxification (i.e. 6D closed orbit calculation via Taylor maps) almost done;

Kick applied to 7 TeV protons (test with 60, 400 turns)



Original integrated map of vertical field

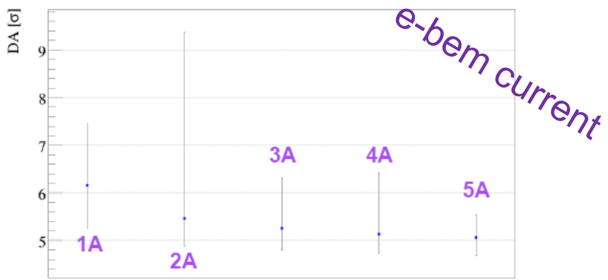


Examples of Tracking Studies

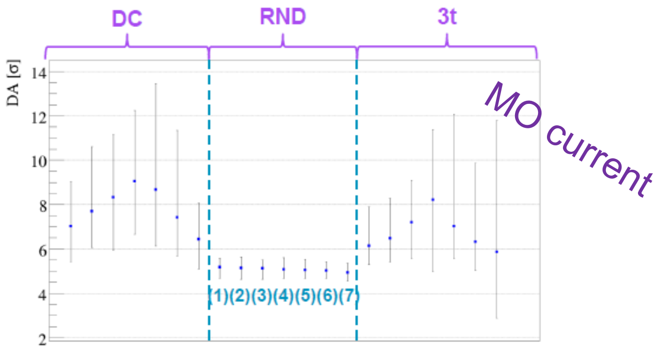
Parameters explored

- *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)

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



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

Courtesy of D. Mirarchi, 9th HL-LHC Annual Meeting;