Mu2e solenoids system magnetic analysis

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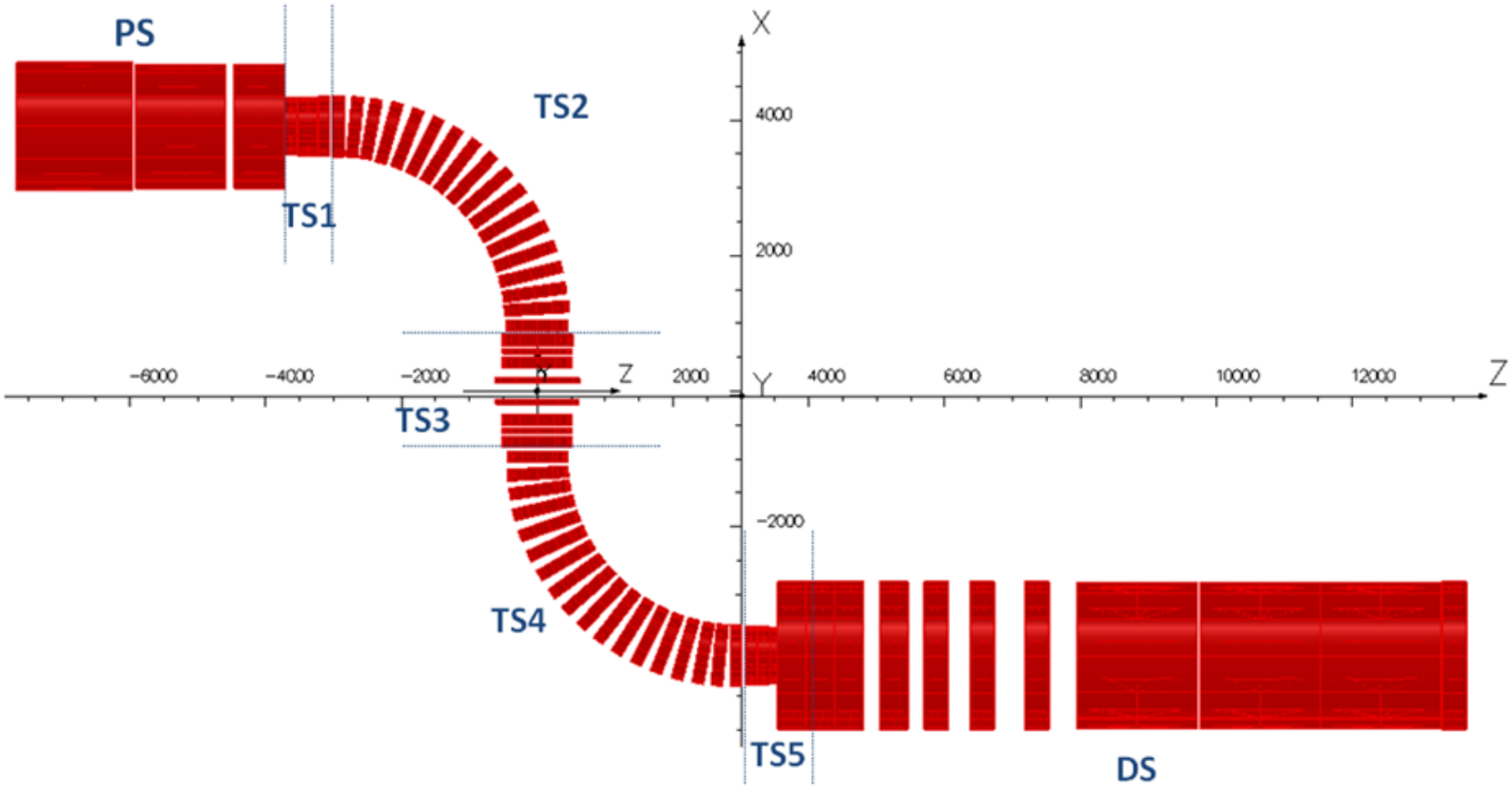
Fermilab

Outline

Mu2e solenoids system



Objectives of the study

1. Verifying the magnetic tolerances of the field and of its gradient for TS-version 7 in presence of coils positioning errors.
2. Studying the misallignments of the magnetic center of TS-version 7 when geometric errors are present.
3. Estimating the magnetic forces on the iron components in the solenoids supports.

TS field tolerances analysis

Background

- Requirements on the magnetic field and on the gradient in the different sections are present.
- Two type of geometrical errors in the coils positioning are possible:
  (a) Random errors
  (b) Systematic errors
- It is necessary to check if, in presence of some type of error, violations on the field requirements are present.

Methodolgy

- The geometrical deviations of the coils positions and the data processing are managed with Matlab.
- The linear magnetic calculation of the field is performed with Opera3D-post processor.

Types of errors

Random errors

They affect ach of the coils. Many possible configurations ⇒ several simulations are required for each configuration

- Radial, Vertical, Longitudinal displacements
- Pitch and Yaw Rotations

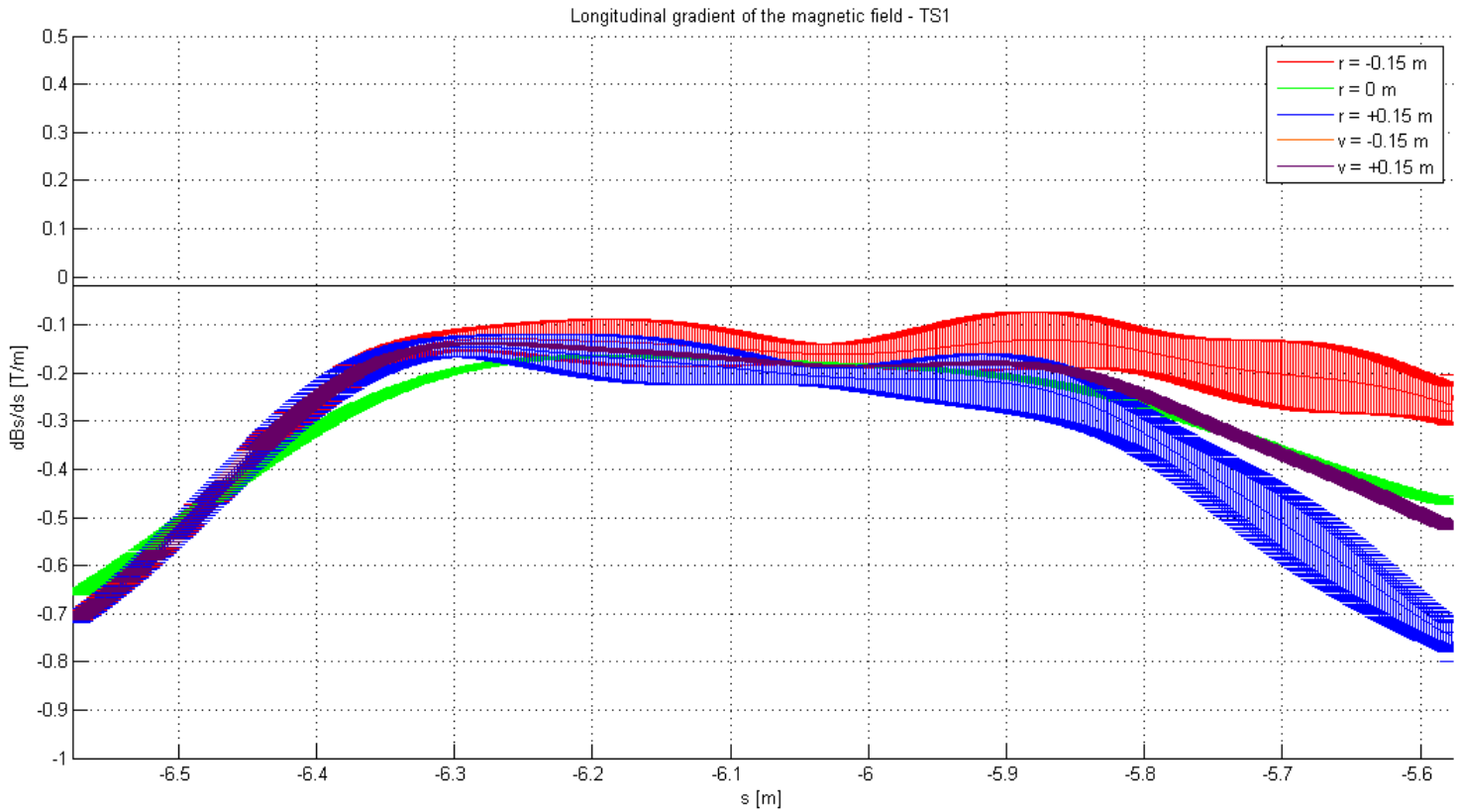
Systematic errors

Only a particular section of the TS is affected. The signs of the displacements are fixed

- Bendings in TS1 or TS5
- TS1, TS3 or TS5 displaced toward a certain direction
- TS3up and TS3down bent in opposite directions
- ...

An example of random error

Radial displacements of 10 mm - **TS1 gradient**

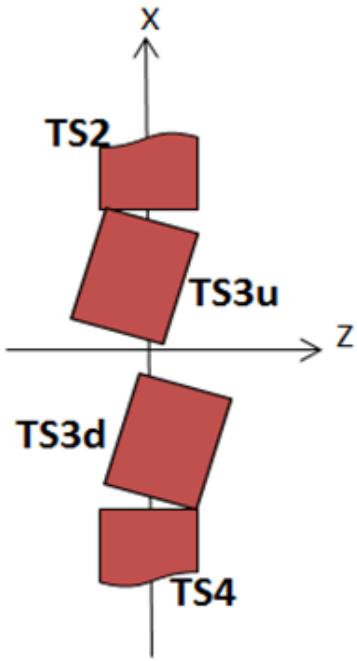


An example of systematic error

TS3up bent toward -Z, TS3down bent toward +Z

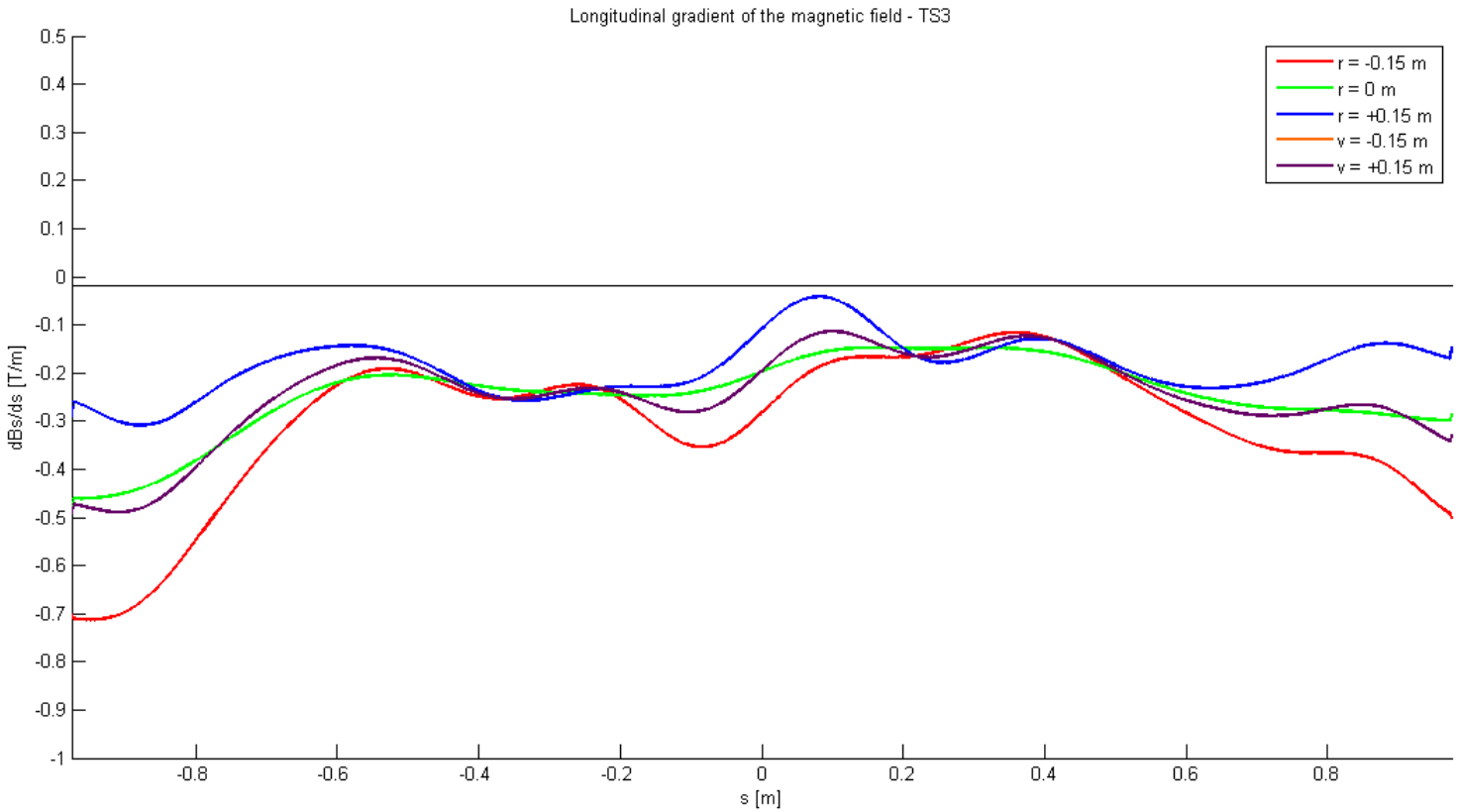
TS3 geometry

- A large air gap is present in the middle of TS3.
- The gap divides TS3 into 2 parts: TSup and TSdown.
- One of the most critical systematic errors is when TS3up and TS3down are bent in opposite directions.



An example of systematic error

TS3up bent 1 ° toward -Z, TS3down bent 1 ° toward +Z - **TS3 longitudinal field gradient**



Results

Findings

- New version 7 of TS is very robust to geometrical deviations of the coils positioning.
- Most critical sections are TS1, where the field is maximum, and TS3, due to the presence of the gap.
- No violations have been detected even considering higher displacements than the real expected ones.

Records

- A list of possible errors with corresponding graphs was produced.
- A new Mu2e database document was written (Mu2e-doc-2156-V3).

Magnetic center allignment and particles tracking

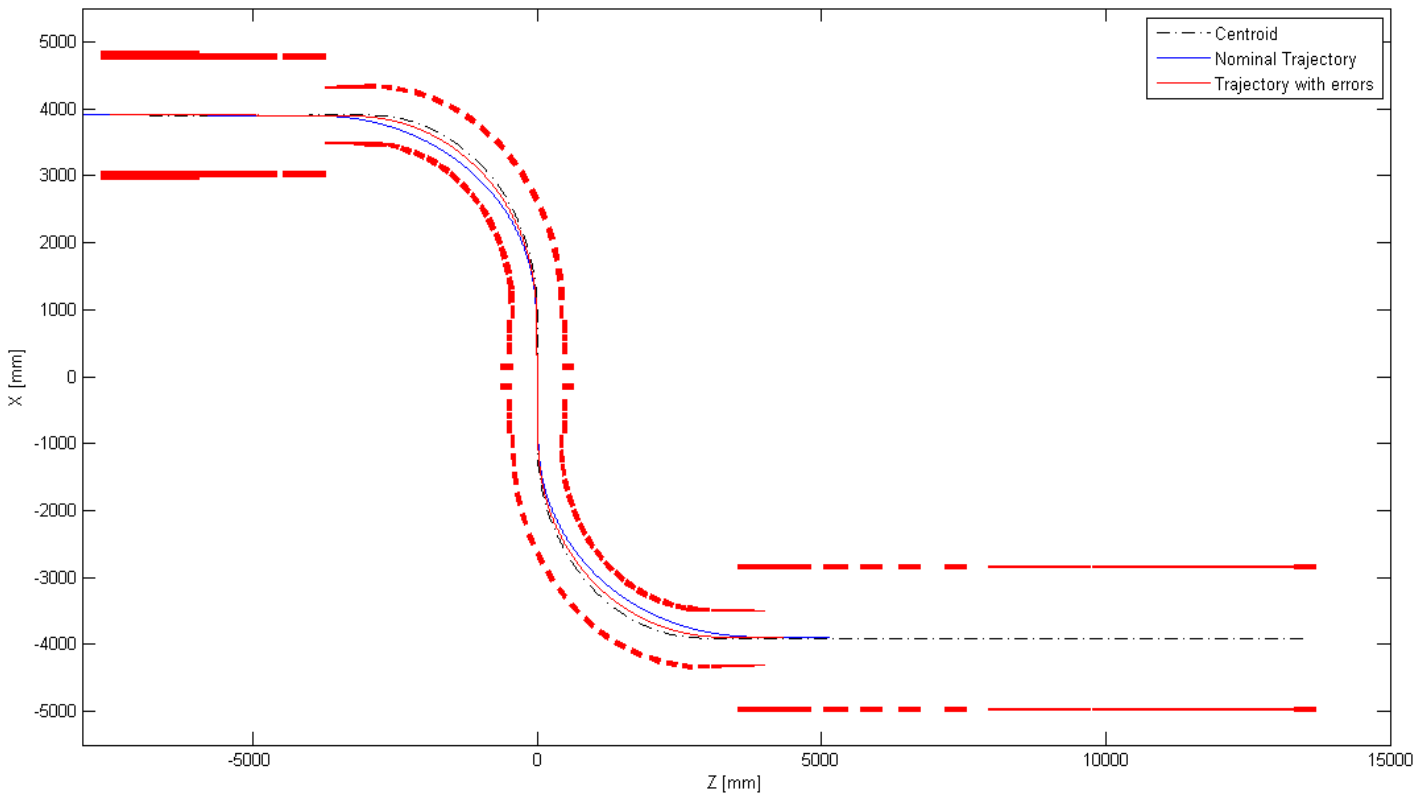
Background

Due to the S-shape of the TS, the magnetic center of the TS does not overlap with the geometric central line.

Methodology

- The magnetic center can be defined through the trajectory of a low energy charged particle (1 MeV e^-).
- Deviations of the trajectories from the nominal track can be read as displacements of the magnetic center.
- Again, random errors and systematic errors were considered.
- Matlab and Opera-3D softwares were used for the calculations.

Difference between Geometric and Magnetic center

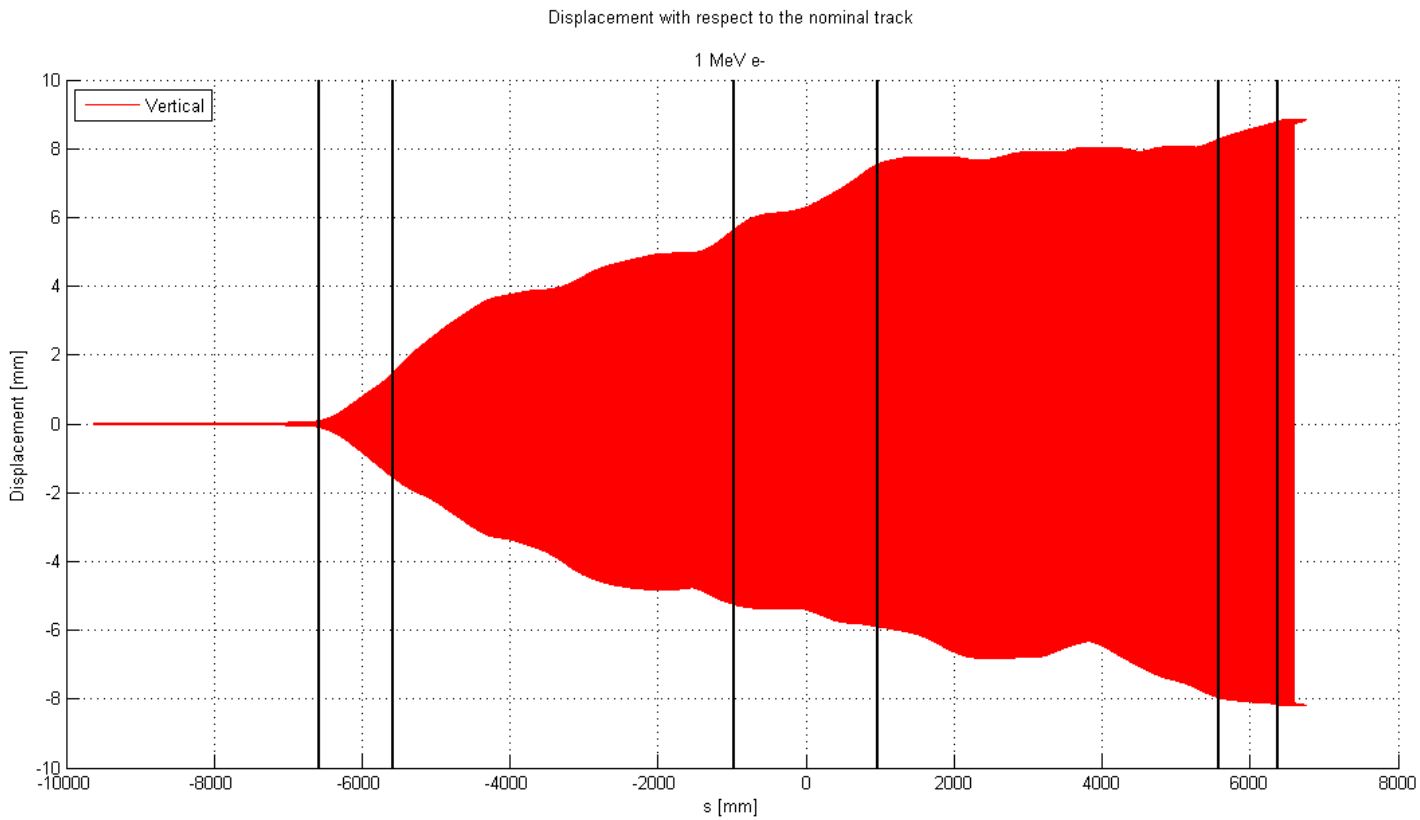


Displacements of the trajectories in the picture are exaggerated for clarity!

An example of random error

Pitch rotation of 10 mrad

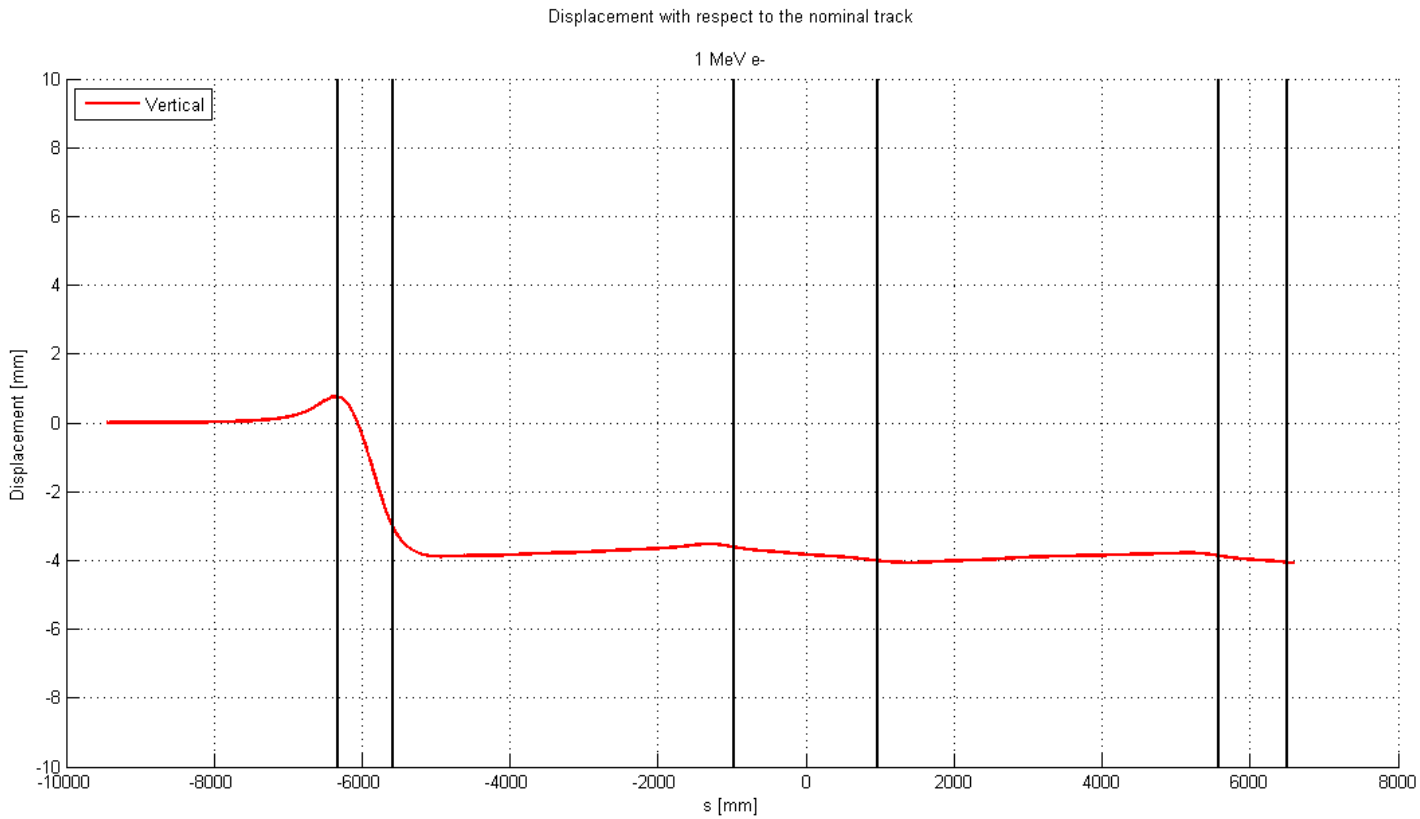
Vertical displacement from the nominal track



An example of systematic error

TS1 bent 1 ° toward +Y

Vertical displacement from the nominal track



Results

Findings

- Most critical random errors are Pitch and Yaw rotations.
- Some systematic errors generate an offset in terms of displacement from the nominal trajectory.

Records

- A list of results was prepared for several geometrical errors.
- A new Mu2e database document was written (Mu2e-doc-2403-V2).

Forces calculation on the iron components of the setup

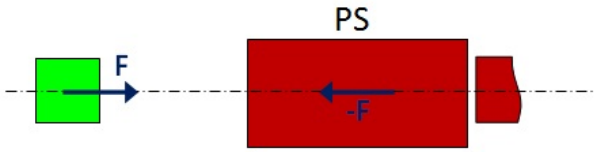
Background

- As the peak field in the solenoids system exceeds 4 T, significant forces may be present on the iron components of the support structures and on the items located around the solenoids (pumps, plugs etc.)
- In most of the cases, components to be verified can be modelled as
  (a) **Full iron blocks**: used to model specific items or to have an overestimation of the forces.
  (b) **Iron wireframes**: used to simulate the rebars of the concrete blocks of the support walls.

Methodology

- The calculation of the magnetic forces on some body can be done by using Maxwell stress tensor.
- Due to the non-linear behaviour of Iron, a FEM simulation with Opera-3D software is required.

Magnetic forces calculation



Force on the block - Maxwell tensor

$$\mathbf{S} = \frac{1}{\mu_0}\begin{bmatrix} B_x^2 - B^2/2 & B_x B_y & B_x B_z \\ B_y B_x & B_y^2 - B^2/2 & B_y B_z \\ B_z B_x & B_z B_y & B_z^2 - B^2/2 \end{bmatrix}$$

$$B = B_x^2 + B_y^2 + B_z^2$$

$$\vec{F} = \frac{1}{\mu_0}\iint \mathbf{S} \cdot \vec{n} dA$$

Force on the coils - Lorentz force

$$\vec{F} = \oint i \cdot d\vec{\ell} \times \vec{B}$$

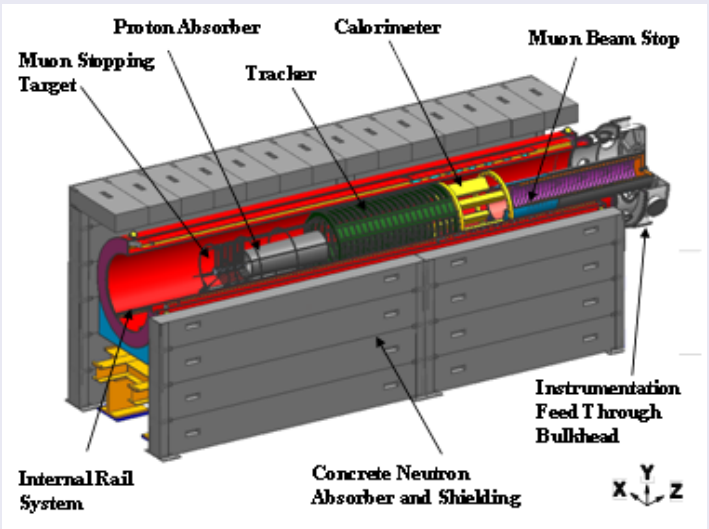
Remarks

- Since an accurate calculation requires very thin mesh, with long computing time, a comprimise has been found between accuracy and calculation time.
- Most of the results are simply estimations of the orders of magnitude of the real forces.

An example of analysis

DS support upper wall

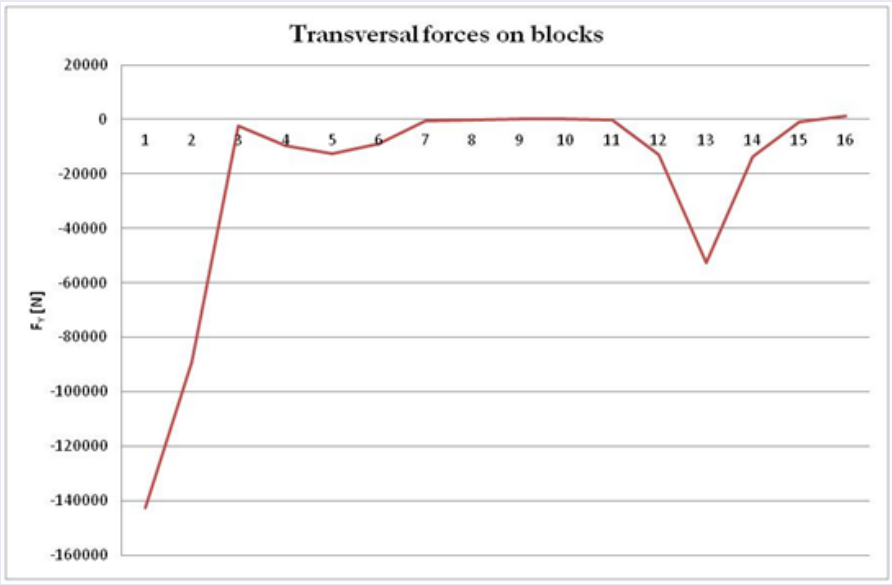
Support structure for the DS



- As a first approximation, the top wall was modelled as a set of iron blocks.

DS support upper wall

Transversal forces on the blocks



Model

Resulting forces on the wall

$$F_Y \simeq -340000N$$

$$F_Z \simeq -6000N$$

Results

Assesments

- PS and DS supports were modelled using blocks and wireframes.
- A simulation of the complex PS support structure was done.
- Orders of magnitude of the forces in the different components are now available for the structural analysis.

Records

- A list of results was prepared for several components of TS and DS support.
- A new Mu2e database is being written (Work in progress . . . !).

Achievements

- The study of the Mu2e TS tolerances has demonstrated that the magnetic design is very robust and effectual.
- The study of the magnetic center allignment has shown that the expected displacements from the nominal tracks are compatible with the positions of the targets and collimators.
- The estimation of the forces on the supports may be a usefull tool for the structural analysis and for the choice of the materials (stainless steel instead of iron).

Thank you for your attention!