Studies of the fields of the Mu2e Solenoids

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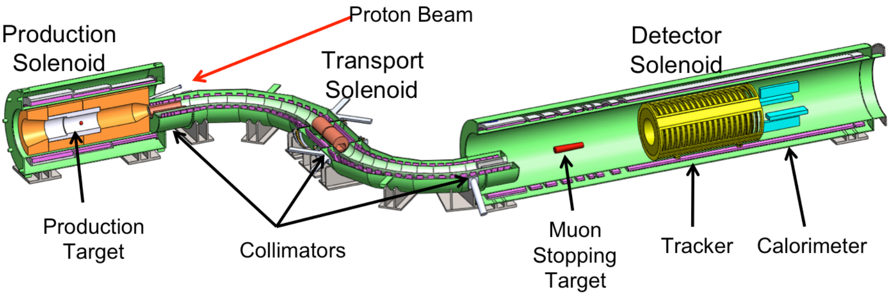
Fermilab Summer Student Program 2015

Final Report

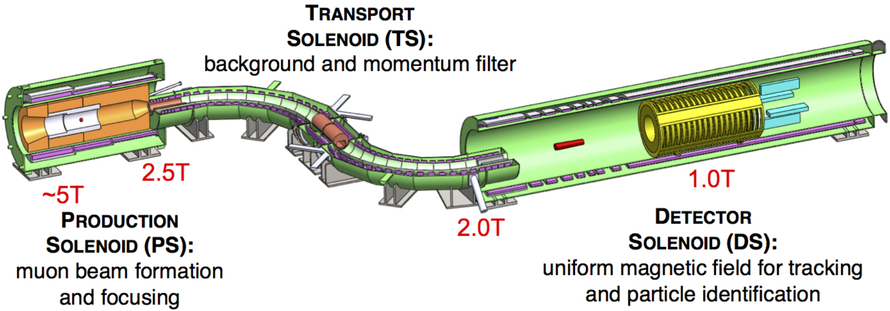
22 September, 2015

Mu2e Experiment

Precision measurement aiming at exploring physics beyond the Standard Model by seeking direct muon to electron conversion in the field of a nucleus, with a sensitivity $10,000$ times better than the previous experiments.



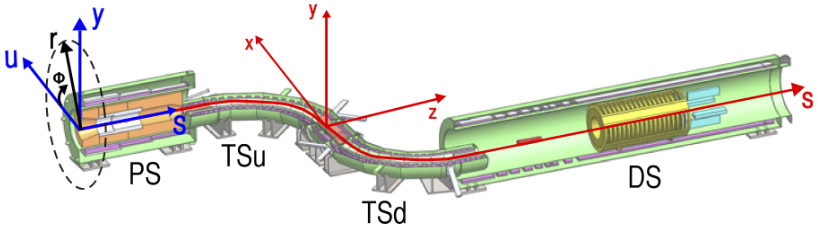
Mu2e Solenoids



Two constructors:

- **General Atomic (GA)** $\rightarrow$ PS and DS
- **Fermilab Technical Division (TD)** $\rightarrow$ TS

Coordinate Systems



- **(X, Y, Z)** Mu2e global cartesian system centered in the middle of TS (in red)
- **(u, y, s)** local cartesian system attached to the Mu2e axis (in blue)
- **(s, r, Φ)** cylindrical coordinate system (in black)

The Field Maps (1)

FIELD MAP

We map the field of each magnet at the points of a 3D grid, which we call Field Map.

- **One-sided maps:** assume XZ-plane symmetry (field values given only at points for $Y \geq 0$). To expand the maps for negative Y, the field is reflected w.r.t. the XZ-plane using:

$$\begin{aligned} B_x(X,-Y,Z) &= B_x(X,Y,Z) \\ B_y(X,-Y,Z) &= -B_y(X,Y,Z) \\ B_z(X,-Y,Z) &= B_z(X,Y,Z) \end{aligned}$$

- **Double-sided maps:** no XZ-plane symmetry (field values given at all Y points)

The Field Maps (2)

Technical Division Maps (Mau9)

- Default set of maps for current simulation
- Solenoid Model
- Symmetric wrt the XZ plane $\Rightarrow$ one-sided map

General Atomics Maps (GA)

- **GA00:** Solenoid Model, double-sided map
- **GA01:** Solenoid Model, one-sided map
- **GA02:** Solenoid Model, double-sided map
- **GA03:** Helical DS Model, double-sided map
- **GA04:** Helical DS Model, double-sided map

Map comparisons (1)

We need to compare in detail the field maps provided by GA and TD.

- **Null Test (benchmark):** GA-DS solenoid model (i.e. GA00, GA01, GA02) compared to Mau9 maps
- if differences are below the design tolerance ($\leq 10^{-4}$) $\Rightarrow$ **Helical Test**
- **Helical Test:** DS helical model compared with DS solenoid model
- GA-DS solenoid model will be used as reference for comparisons with GA - DS helical model

Map comparisons (2)

The comparisons made so far are:

1. GA01 vs Mau9 (1^{st} Null Test) [Mu2e-doc-5865]
2. GA03 vs Mau9 (1^{st} Helical Test) [Mu2e-doc-5888]
3. GA03 vs GA02 (2^{nd} Helical Test) [Mu2e-doc-5957]
4. GA00 vs Mau9 (2^{nd} Null Test) [Mu2e-doc-5999]
5. GA04 vs GA00 (3^{rd} Helical Test) [Mu2e-doc-6025]

- The first three numerical comparisons revealed inconsistencies between Mau9 and GA calculations
  $\rightarrow$ eventually traced to the fact that the two maps had a few coils in slightly different positions
- GA provided two more maps with the inconsistencies fixed:
  - GA00 (for Null Test with Mau9 maps)
  - GA04 (identical to Mau9 except new DS model) to be compared with GA00

How we make comparisons: the tools

- **ContourTool.C** makes plots of the field components B_x, B_y, B_z and of the field gradient $\frac{dB}{ds}$ on a circle centered at a given point on the Mu2e symmetry axis.
- **EasyTest.C** scans all grid points in a given set of field maps and do calculations with the input field.
- **test_maps.C** makes plots of the results from `EasyTest.C`, computed along paths parallel to the Mu2e axis.
- **test_grid.C** makes plots of the results from `EasyTest.C` on the grid points, without interpolation.

How we make comparisons: the analysis

1. Plots of the magnetic fields components:
   - Along the magnetic axis;
   - Moving from the axis in steps of 5cm, until 90cm;
   - For azimuth of $0^\circ, 90^\circ, 180^\circ, 270^\circ$
2. Plots of the magnitude and derivative of B_s:

$$B_s = \sqrt{B_x^2 + B_y^2 + B_z^2}$$

$\rightarrow |B_z|$ in the straight sections (PS, DS)

Overlay plots (eyeball inspection)

3. Histograms of absolute differences of the magnetic field components, in linear and decimal logarithm scale
4. Histograms of logarithmic absolute and relative differences of the field magnitude at all grid points
5. Scatter plots of points where dB$= |B_2 - B_1|$ is above a specified threshold
6. Numerical tables of relative differences of field components and of field gradients

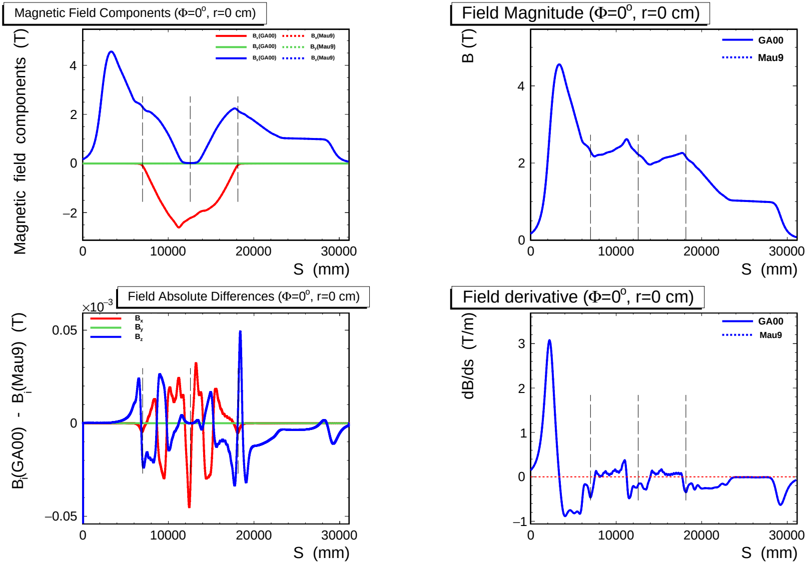
To quantify the differences

Null Test GA00 vs Mau9

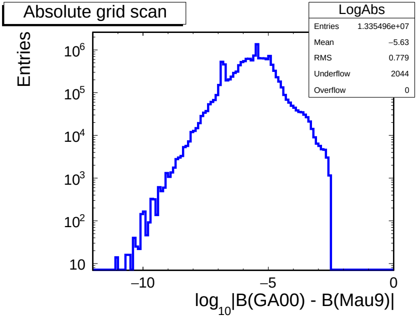
Mu2e-doc-5999

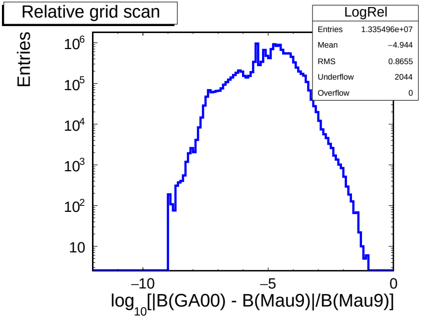
+ additional files with tables and histograms

Numerical Comparisons (along axis)



Histogram of the decimal logarithm of absolute field magnitude differences over all grid points

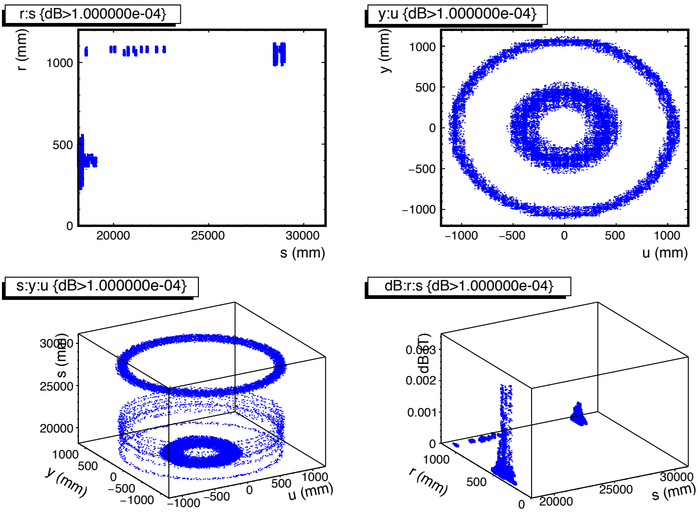




Absolute differences go up to $10^{-2.5}$T (∼30-40 G)

Relative differences go up to 10^{-1} (∼ 10%)

Mapping of max dB (> 1 G) points for DS



Significant differences (> 1 G) in $|B|$ were detected near the coils.

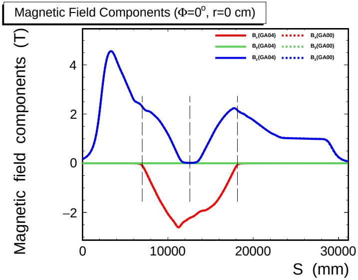
No effect on physics. Likely associated with details of numerical integration.

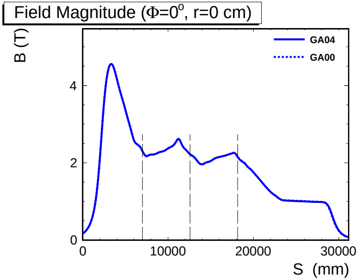
Helical Test GA04 vs GA00

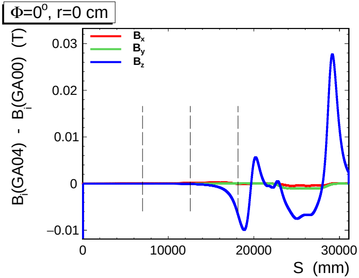
Mu2e-doc-6025

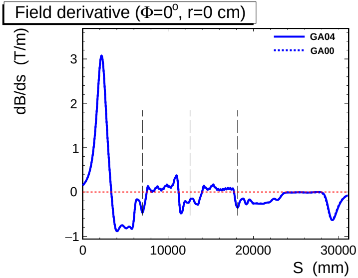
+ additional files with tables and histograms

Numerical Comparisons (along axis)

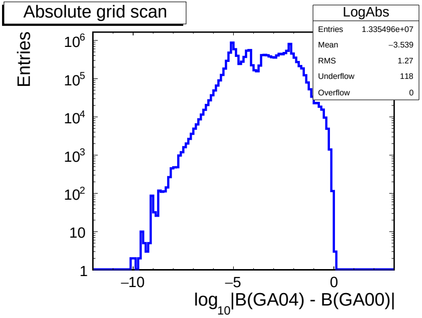


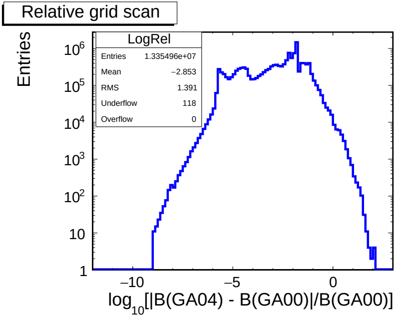






Histogram of the decimal log of field magnitude differences over all grid points (no interpolation)

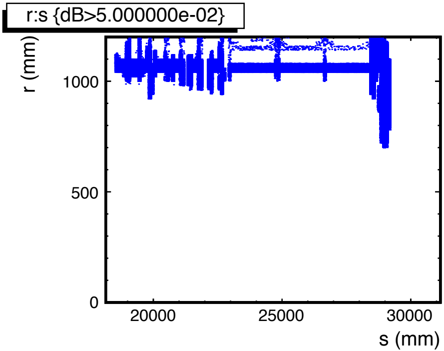


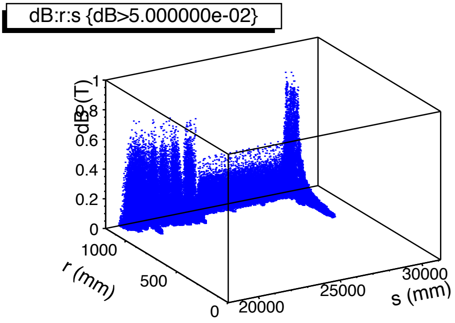


Absolute differences go up to 1T ($\sim$10000 G)

Log10 of relative differences goes up to 2 (a factor of $\sim$ 100)

Mapping of max dB (> 0.5 kG) points for DS





Simulation of Electron Source Test of TS Field

Objective:

Test of the magnetic fields of the Mu2e TS after solenoid system commissioning is completed.

Problem:

In contrast to the PS and DS fields, it is difficult to test the TS field using field probes - needs a complicated design of support system, interfering mechanically with the magnetic coils.

Possible solution:

Use a source of charged particles (electrons) emitted into the TS field.

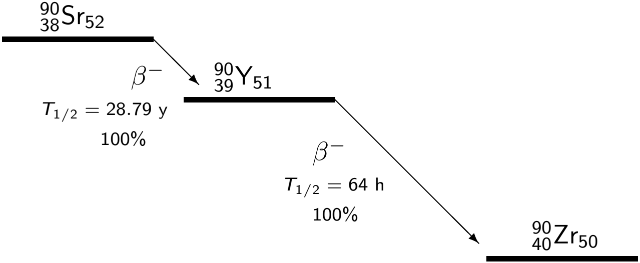
Overview of the β^- source test

- The principle of the test is that low momentum electrons follow paths very close to the field lines, and thus they can help trace the field if they are detected at various positions inside the solenoids
- They can also be used to check the geometry constraints (slits, absorber foils, collimators)
- The idea is to use a commercial beta source and a simple low-momentum electron detector located at various places along the solenoid system
- Two field maps are used in this preliminary simulation, as a way to simulate uncertainties of the field at the commissioning phase
- Eventually, we will use varied maps from TD incorporating field variations from random displacements of the coils

Electron Source

Preliminary studies have shown that the best tradeoff among sufficient momentum range, moderate source activity (to suppress hazard) and lack of background particles (e.g. photons) is ^{90}Sr/^{90}Y.

- **Activity:** 0.1 μCi (1 μCi = 37,000 decays/s)
- **Half-lifetime:** 28.79 years
- **Emissions:** 100% (β^-, β^-)
- **Decay max Energy:** 546 keV, 2280 keV



Detector

- Detector choice driven by precision requirements of the test
- Several ideas proposed, a scintillator pixel array seems to be the best solution
- Optimized for highest efficiency and uniform response
- Such an array has been built and tested by NIU for ILC

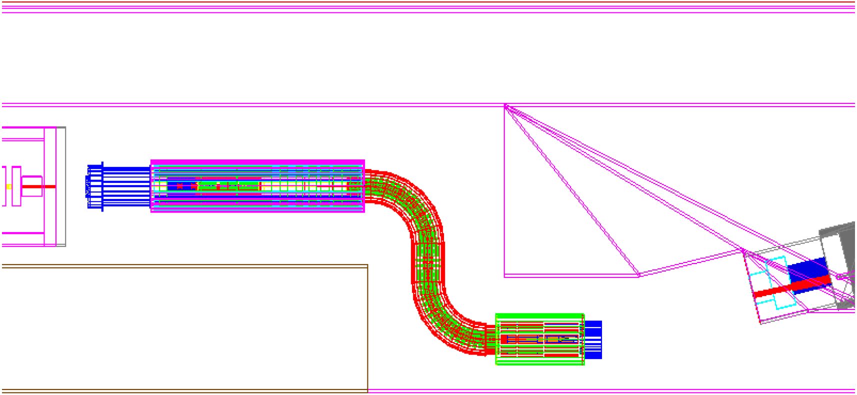
Simulation parameters

- **Number of events:** 50,000
- **Vacuum pressure:** 1Torr
- **Location of the β^- source:**

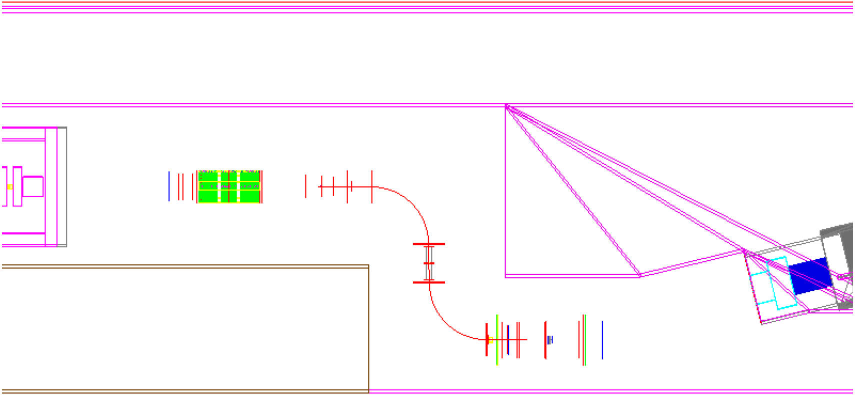
x	y	z
3904	0	-6000
3954	0	-6000
3854	0	-6000
3904	50	-6000
3954	50	-6000
3854	50	-6000
3904	100	-6000
3954	100	-6000
3854	100	-6000

- **Phase space:** $0^\circ < \theta < 8^\circ$ wrt the z axis

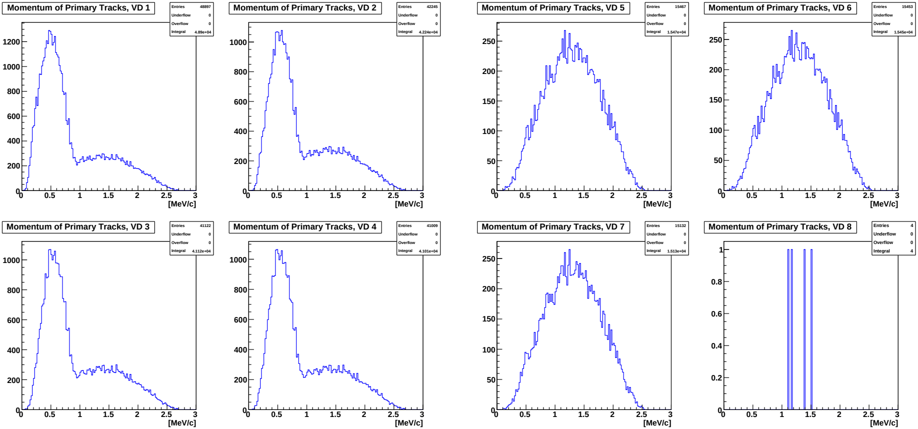
Location of virtual detectors



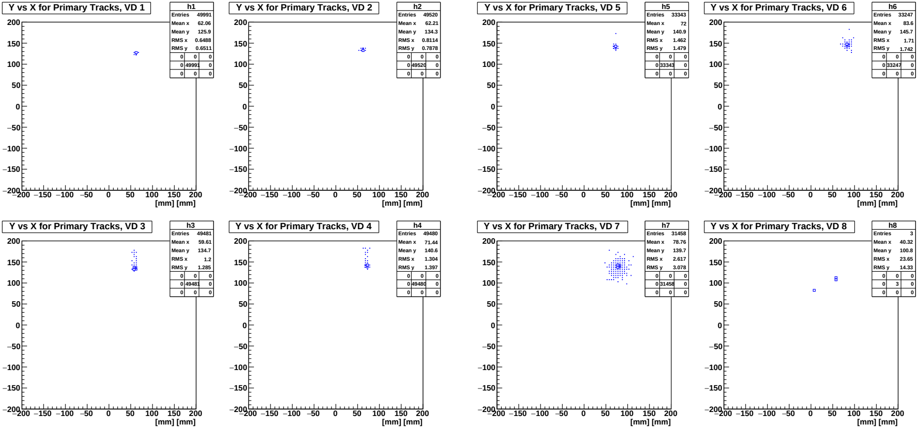
Location of virtual detectors



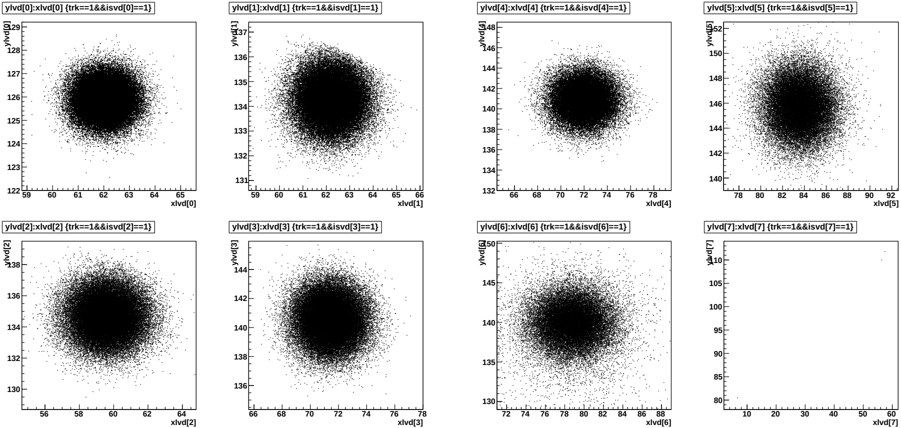
Electron Source Spectrum
$(x, y, z) \equiv (3954, 100, -6000)$



Track plots (x, y, z) $\equiv$ (3954, 100, -6000)

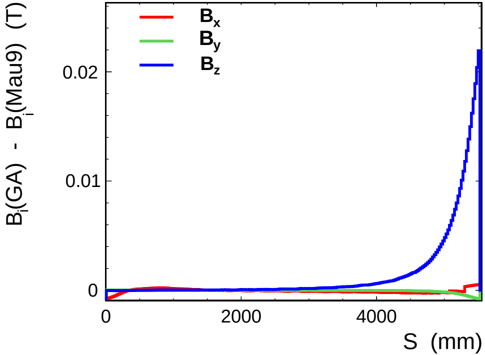


Scatter plots (x, y, z) ≡ (3954, 100, -6000)



Effects of a different field map

GA01 maps used, differing from Mau9 by up to $\sim$ 200 G close to the exit of TS



No changes observed
$\Rightarrow$ β^- test is insensitive to uncertainties of this order

Summary

- I have developed methods and tools for precision testing of the Mu2e design magnetic fields.
- The results of these tests show:
  1. agreement between benchmark maps (Null Test) and small differences in fiducial volume between Mau9 and new GA;
  2. overall consistencies between GA00 and GA04 except in DS (because of the different model)
- I made a preliminary simulation to test TS field using a β^- source model
- Uncertainties of the order of up to ~ 200 G in the exit of TS have no effects on the results of the test
- To be continued...