GATE-RTion TPSPencilBeam Source validation procedure

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Test specifications

Test Name: TPS source

Type of test: Functional testing (acceptance)

Test developer: Loïc Grevillot, MedAustron

Configuration: GATEv8.0 (develop branch), GEANT4-10.3, ROOTv6.08.06

Background

The **TPSPencilBeam** source is used to simulated pencil beam scanning treatment plans (like in a TPS). It contains a collection of pencil beams, which are described by the **PencilBeam** source.

For details, please read the GATE manual.

Purpose of the test

To test that the TPSPencilBeam source works as specified:

- The simulated plan (number of particles per spot, spot positions at isocenter) shall be as specified in the **treatment plan file**
- The simulated energy properties (mean energy and energy spread) and optics properties (beam size, divergence and emittance) shall be as specified in the **source description file and treatment plan file** (the **planned energy** is provided in the treatment plan file, but the properties (mean energy and energy spread) of the delivered beam are parametrized in the source description file as a function of the planned energy)
- The various **options** available to configure the **TPSPencilBeam** source work as specified.

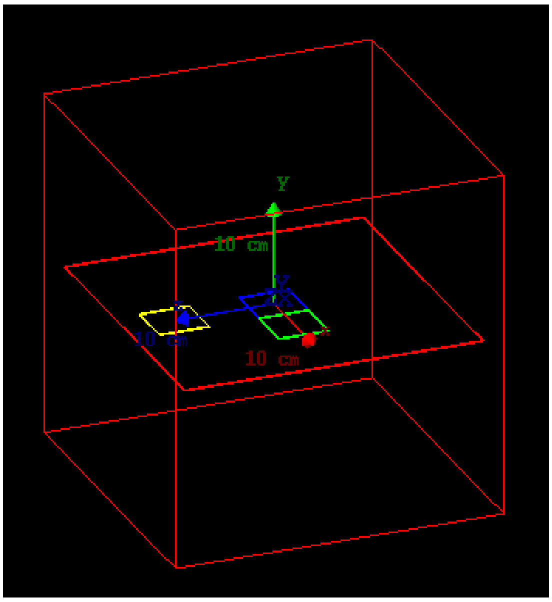
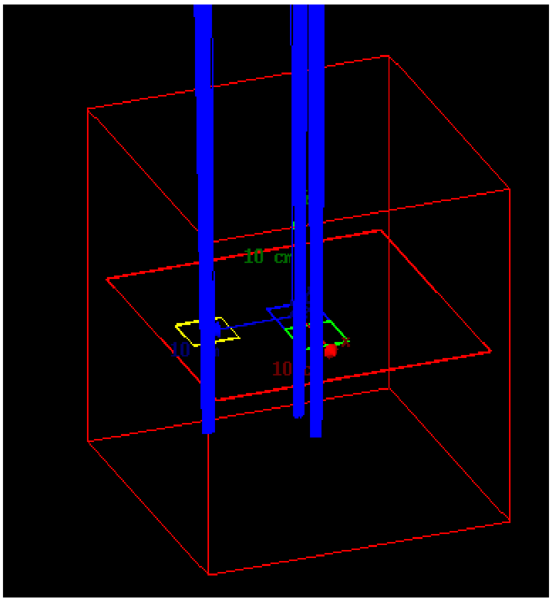
Disclaimer

- This validation test aims at providing confidence that the **TPSPencilBeam** source works as specified and the installation is correct.
- This validation test does not cover all the possibilities offered by the **TPSPencilBeam** source.

- It is recommended that the user adapt the test macros as closely as possible to its intended use, if different from the one proposed here.

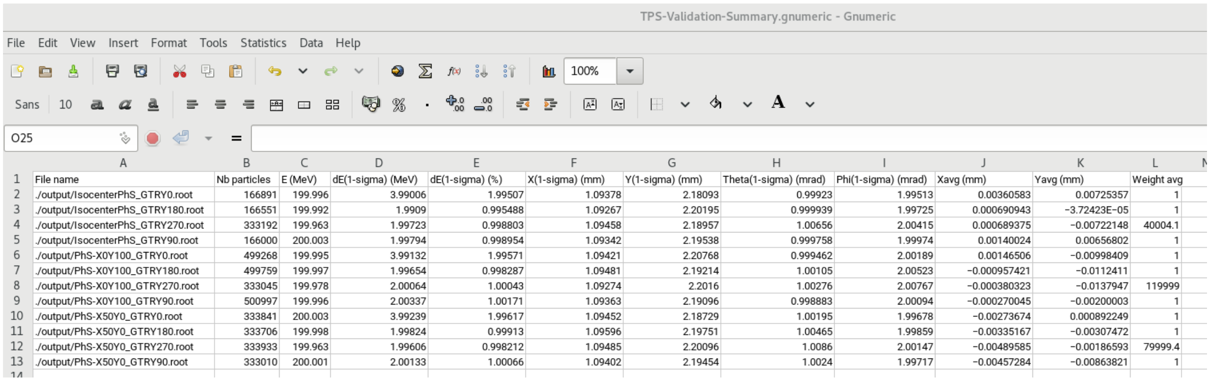
Overview of the test

Three spots starting 100 mm upstream the iso-center are delivered at 3 different positions at isocenter for an energy layer of 200 MeV (planned energy). The optics properties (spot sizes and divergence) in x and y are different. The simulation occurs in vacuum in order to neglect scattering in air. Three phase spaces are set-up at isocenter perpendicularly to the beam axis, one per spot, and analyzed separately. The simulation is performed for the 4 cardinal gantry angles. For each gantry angle, different **options** are used in order to test different functionalities. Scripts are provided to run the simulations and analyze the differences between simulated and expected spot parameters at iso-center. The evaluated spot parameters at iso-center are the following: number of particles, mean energy, energy spread, spot size (x and y), divergence (theta and phi), position (x and y). An illustration of the simulated set-up for gantry 0 (GTRY0) is illustrated below with and without beam. For details, look into the mac and data folders.

Test procedure and validation example: part1

- run the script "./OrientationTestRun.sh" in order to automatically run the 4 simulations for each cardinal angle of the gantry (make sure the script is executable, otherwise execute the following command in the terminal "chmod + X OrientationTestRun.sh") - alterantively you could run each simulation separately (Gate mac/main_orientation_GTRYX.mac) – the simulation time should be around 1 minute.
- When the simulations are finished, list all the phase spaces in a text file, e.g. using the following command "ls output/*.root > listPhS.txt"
- run the script "root LGPhSListProcess.C" in order to automatically analyze all the phase spaces (Line 22 in the script, adapt the input "FileListName=./listPhS.txt" if different)
- open the analysis summary "results/AnalysePhSs.txt" and verify that the outputs are correct. To support the evaluation process, a template spreadsheet based on the Gnumeric software (must be installed if you do not have it) is provided. Copy/paste the values from the analysis summary "results/AnalysePhSs.txt" into the tab "Input" from the spreadsheet "TPS-Validation-Summary.gnumeric" as below.


TPS-Validation-Summary.gnumeric - Gnumeric

File name	Nb particles	E (MeV)	dE(1-sigma) (MeV)	dE(1-sigma) (%)	X(1-sigma) (mm)	Y(1-sigma) (mm)	Theta(1-sigma) (mrad)	Phi(1-sigma) (mrad)	Xavg (mm)	Yavg (mm)	Weight avg
./output/IsocenterPhS_GTRY0.root	166891	199.996	3.99006	1.99507	1.09378	2.18093	0.99923	1.99513	0.00360583	0.00725357	1
./output/IsocenterPhS_GTRY180.root	166551	199.992	1.9909	0.995488	1.09267	2.20195	0.999939	1.99725	0.000690943	−3.72423E−05	1
./output/IsocenterPhS_GTRY270.root	333192	199.963	1.99723	0.998803	1.09458	2.18957	1.00656	2.00415	0.000689375	−0.00722148	40004.1
./output/IsocenterPhS_GTRY90.root	166000	200.003	1.99794	0.998954	1.09342	2.19538	0.999758	1.99974	0.00140024	0.00656802	1
./output/PhS-X0Y100_GTRY0.root	499268	199.995	3.99132	1.99571	1.09421	2.20768	0.999462	2.00189	0.00146506	−0.00998409	1
./output/PhS-X0Y100_GTRY180.root	499759	199.997	1.99654	0.998287	1.09481	2.19214	1.00105	2.00523	−0.000957421	−0.0112411	1
./output/PhS-X0Y100_GTRY270.root	333045	199.978	2.00064	1.00043	1.09274	2.2016	1.00276	2.00767	−0.000380323	−0.0137947	119999
./output/PhS-X0Y100_GTRY90.root	500997	199.996	2.00337	1.00171	1.09363	2.19096	0.998883	2.00094	−0.000270045	−0.00200003	1
./output/PhS-X50Y0_GTRY0.root	333841	200.003	3.99239	1.99617	1.09452	2.18729	1.00195	1.99678	−0.00273674	0.000892249	1
./output/PhS-X50Y0_GTRY180.root	333706	199.998	1.99824	0.99913	1.09596	2.19751	1.00465	1.99859	−0.00335167	−0.00307472	1
./output/PhS-X50Y0_GTRY270.root	333933	199.963	1.99606	0.998212	1.09485	2.20096	1.0086	2.00147	−0.00489585	−0.00186593	79999.4
./output/PhS-X50Y0_GTRY90.root	333010	200.001	2.00133	1.00066	1.09402	2.19454	1.0024	1.99717	−0.00457284	−0.00863821	1

- Evaluate the results for each gantry angle in the respective tabs and make sure the observed deviations are statistically acceptable (e.g. <0.5% in number of particles, <0.05mm in size and <0.05mrad in divergence, etc.) - the evaluation data shall turn green if they are within tolerances or red otherwise (see example below for the gantry angle 0). The evaluation concerns the number of particles delivered, the energy, the energy spread, the spot size, position and divergence in x and y, the particle weight. Additional specificities are tested for each gantry angle separately and require additional check as described in the following section.

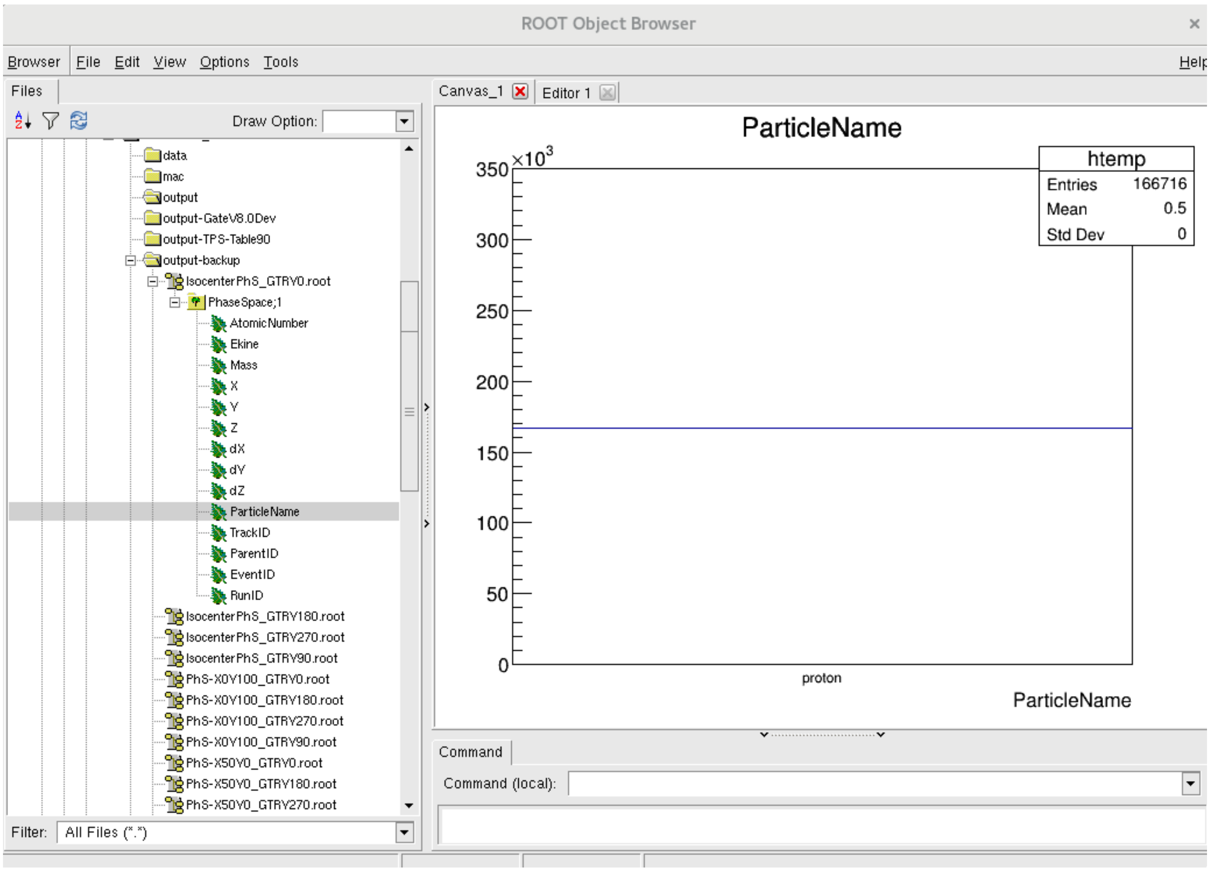
	A	B	C	D	E	F	G	H	I	J	K	L
1	**The treatment plan is made of 1 layer (1 energy) with 3 spots having different MU, positions (X,Y in DICOM coordinates)**											
2	Spot ID	MU	Energy	X	Y							
3	Spot 1	100	200.00	0.00	0.00							
4	Spot 2	300	200.00	0.00	100.00							
5	Spot 3	200	200.00	50.00	0.00							
6												
7	**The beam model describes the optics properties: beam size (x,y), divergence and emittance and the energy properties: mean energy, energy spread, as a function of the prescribed energy in the treatment plan**											
8	**It contains also some important geometric parameters like the scanning magnet positions (SMX, SMY) and the source to isocenter distance (SAD)**											
9	**In this validation example, the emittance can be neglected**											
10	Mean energy (MeV)	Energy spread (%)	SigX	SigY	DivX	DivY	SAD (mm)					
11	200	0.02	1.00	2.00	1.00	2.00	100					
12												
13	**The main simulation file also contains some relevant parameters, like the "setBeamConvergence" parameter, which is by default divergent.**											
14	**The simulation medium is vacuum,therefore no impact of scattering on spot size and divergence**											
15	**The scoring is performed in 3 phase spaces (PhSs) centered at the expected location of each spot, therefore expected psoitions are 0,0,0foreach spotin each PhS.**											
16	Number of primaries simulated	1000000										
17												
18	**Derived reference values for validation, based on the above explanations**											
19	**Specifications for GTRY0 at isocenter**	**Nb particles**	**E (MeV)**	**E-spread (MeV)**	**E-spread (%)**	**X(1-sigma) (mm)**	**Y(1-sigma)**	**Theta(1-sigma)**	**Phi(1-sigma) (mrad)**	**Xavg (mm)**	**Yavg (mm)**	**Weight avg**
20	Spot 1	166667	200.00	4.00	2.00	1.10	2.20	1.00	2.00	0.00	0.00	1.00
21	Spot 2	500000	200.00	4.00	2.00	1.10	2.20	1.00	2.00	50.00	0.00	1.00
22	Spot 3	333333	200.00	4.00	2.00	1.10	2.20	1.00	2.00	0.00	100.00	1.00
23												
24	**Simulation output for GTRY0**											
25	File name	Nb particles	E (MeV)	dE(1-sigma) (MeV	dE(1-sigma) (%	X(1-sigma) (mm)	Y(1-sigma)	Theta(1-sigma)	Phi(1-sigma) (mrad)	Xavg (mm)	Yavg (mm)	Weight avg
26	./output/IsocenterPhS_GTRY0.root	166891	200.00	3.99	2.00	1.09	2.18	1.00	2.00	0.00	0.01	1.00
27	./output/PhS-X0Y100_GTRY0.root	499268	200.00	3.99	2.00	1.09	2.21	1.00	2.00	0.00	−0.01	1.00
28	./output/PhS-X50Y0_GTRY0.root	333841	200.00	3.99	2.00	1.09	2.19	1.00	2.00	0.00	0.00	1.00
29												
30	**differences and validation**	**Nb particles**	**E (MeV)**	**dE(1-sigma) (Me**	**dE(1-sigma) (**	**X(1-sigma) (mm)**	**Y(1-sigma)**	**Theta(1-sigma)**	**Phi(1-sigma) (mrad)**	**Xavg (mm)**	**Yavg (mm)**	**Weight avg**
31	Spot 1	0.13%	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.01	0.00%
32	Spot 2	0.15%	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00%
33	Spot 3	0.15%	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00%

1. Test procedure and validation example: part2

- Backup your results by copying the output folder (e.g. cp output output-backup -r)
- Clean the current output folder (e.g. rm output/*)
- The main differences between the 4 GTRYXX simulations are the following:
  - GTRY0
    - /gate/source/PBS/setParticleType proton
    - /gate/source/PBS/setSpotIntensityAsNbIons true
    - /gate/source/PBS/setSigmaEnergyInMeVFlag false
    - /gate/source/PBS/setSortedSpotGenerationFlag false
    - /gate/source/PBS/setFlatGenerationFlag false
    - /gate/source/PBS/setBeamConvergence true
    - /gate/source/PBS/setNotAllowedFieldID 2
  - GTRY90
    - /gate/source/PBS/setParticleType GenericIon
    - /gate/source/PBS/setIonProperties 2 4 2 0
    - /gate/source/PBS/setSpotIntensityAsNbIons false
    - /gate/source/PBS/setSigmaEnergyInMeVFlag true
    - /gate/source/PBS/setSortedSpotGenerationFlag false
    - /gate/source/PBS/setFlatGenerationFlag false
    - /gate/source/PBS/setBeamConvergenceXTheta true
    - /gate/source/PBS/setBeamConvergenceYPhi false
  - GTRY180
    - /gate/source/PBS/setParticleType GenericIon
    - /gate/source/PBS/setIonProperties 3 6 3 0
    - /gate/source/PBS/setSpotIntensityAsNbIons false
    - /gate/source/PBS/setSigmaEnergyInMeVFlag true
    - /gate/source/PBS/setSortedSpotGenerationFlag true
    - /gate/source/PBS/setFlatGenerationFlag false
    - /gate/source/PBS/setBeamConvergenceXTheta false
    - /gate/source/PBS/setBeamConvergenceYPhi true

- GTRY270
  - /gate/source/PBS/setParticleType GenericIon
  - /gate/source/PBS/setIonProperties 3 6 3 0
  - /gate/source/PBS/setSpotIntensityAsNbIons false
  - /gate/source/PBS/setSigmaEnergyInMeVFlag true
  - /gate/source/PBS/setSortedSpotGenerationFlag true
  - /gate/source/PBS/setFlatGenerationFlag true
  - /gate/source/PBS/setBeamConvergence false

- The correct particle type delivery can be verified using root and Tbrowser (e.g. root [0] TBrowser T). Open the phase space trees from the output-backup folder and look at the particle type. The histogram should show “proton” (GTR0 – see example below), “alpha” (GTRY90), “Li6” (GTRY180) or “C12” (GTRY270).



- The specification “setSpotIntensityAsNbIons true or false” can be partly verified in the tabs “GTRY0” and “GTRY90 (or 180 or 270)”. In order to precisely check the influence of the option “setSpotIntensityAsNbIons true”, the user shall open the macro GTRY0 (e.g. gedit mac/main_orientation_GTRY0.mac), turn the option Testflag to true

(/gate/source/PBS/setTestFlag true) and decrease the number of primaries to 10 (/gate/application/setTotalNumberOfPrimaries 10) and run the macro (e.g. Gate mac/main_orientation_GTRY0.mac). In the simulation logs printed in the terminal, one can figure out the prescribed spot metersetweight for each spot (in number of protons). The values should be 100, 200 and 300 for spot 1,2, and 3, respectively.

```
[Beam-0] Configuration of spot No. 0 (out of 3)
[Beam-0] Energy 200
[Beam-0] Spot metersetweight    100

[Beam-0] Configuration of spot No. 1 (out of 3)
[Beam-0] Energy 200
[Beam-0] Spot metersetweight    200

[Beam-0] Configuration of spot No. 2 (out of 3)
[Beam-0] Energy 200
[Beam-0] Spot metersetweight    300
```

- In order to check the influence of the option “setSpotIntensityAsNbIons false” in more details, the user shall open the macro GTRY90 (or 180 or 270), turn the option Testflag to true and decrease the number of primaries to 10 and run the macro. In the simulation logs printed in the terminal, one can figure out the prescribed spot metersetweight for each spot. Since the protons/MU calibration function inserted in the source description file corresponds to N=(2*E+0)*MU, where N stand for number of particles, E for energy and MU for Monitor Unit, the expected spot meterset (number of protons) should be 2*200*100=4E4, 2*200*200=8E4 and 2*200*300=1.2E5 for spot 1,2, and 3, respectively.

```
[Beam-0] Configuration of spot No. 0 (out of 3)
[Beam-0] Energy 200
[Beam-0] Spot metersetweight    40000

[Beam-0] Configuration of spot No. 1 (out of 3)
[Beam-0] Energy 200
[Beam-0] Spot metersetweight    80000

[Beam-0] Configuration of spot No. 2 (out of 3)
[Beam-0] Energy 200
[Beam-0] Spot metersetweight    120000
```

- The specification of the energy spread spread in % or MeV can be verified in the respective tabs “GTRY0” and “GTRY90” from the spreadsheet “TPS-Validation-Summary.gnumeric”.
- The definition of the energy spread in MeV or percent can additionally be defined directly in the source description file. In this case, it will override the command /gate/source/PBS/setSigmaEnergyInMeVFlag true (or false). Just add the symbol “%” or

“PERCENT” or “percent”, or “MeV” in the source description file before the polynomial order in the source description file in order to define the energy spread

```
# energy spread
# polynomial order
%
1
# polynomial parameters (highest to lowest)
0
2.0
```

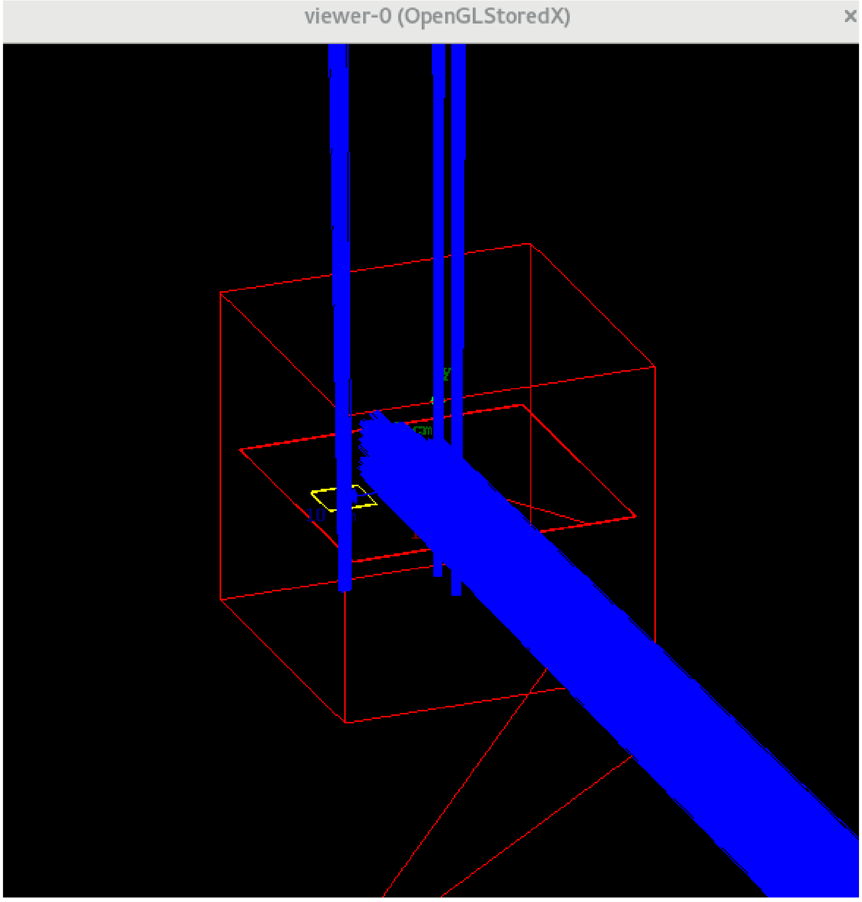
You can then check in the log information of the terminal that the energy spread has been defined as specified in the source description file (see below).

```
[Beam-0] source description file specifies energy spread in PERCENT (%)
[Beam-0] (This overrides whatever you configured for the 'setSigmaEnergyInMeVFlag' in the configuration of TPSPencilBeam.)
```

You can also analyze the simulation output as before using the root macro LGPhSListProcess or simply open the energy histogram with the Tbrowser in root and look at the energy spread.

- The specification of the random or sorted spot delivery “setSortedSpotGenerationFlag false or true” can be verified graphically by activating the display (/control/execute mac/visu.mac) and by reducing the number of primaries. It may be useful to activate or de-activate the accumulation of events in the macro “Visu.mac” (/vis/scene/endOfEventAction accumulate)
- The specification setFlatGenerationFlag true can be verified in the tab “GTRY270” from the spreadsheet “TPS-Validation-Summary.gnumeric”: each spot has the name number of particles and the weight have been modified according to the metersetweight. For the GTR0, 90 and 180, the weight is always 1, since the FlatFlag is false.
- The specification of the beam divergence is tested in all the 4 macros, with x and y converging in GTR0, x and y diverging in GTR270, x converging and y diverging in GTRY90, x diverging and y converging in GTRY180. It can be verified in the tabs “GTRYXX” from the spreadsheet “TPS-Validation-Summary.gnumeric” by looking at the spot size which is increasing (decreasing) if the beam is diverging (converging).
- The specification “setNotAllowedFieldID” and “setAllowedFieldID” can be tested in GTR0 macro (mac/main_orientation_GTRY0.mac). The user should activate the graphical display and by reduce the number of primaries. If both lines are commented, then both beams shall be delivered.

```
#/gate/source/PBS/setNotAllowedFieldID 1
#/gate/source/PBS/setAllowedFieldID 2
```



If only SetAllowedField 1 (or 2) is activated, then only the allowed field shall be delivered. If only SetNotAllowedField 1 (or 2) is activated, then only the not allowed field shall not be delivered.

- The functionality "/gate/source/PBS/selectLayerID" can be simply tested, for example by selecting the second field (/gate/source/PBS/setAllowedFieldID 2) and selecting a layer ID. Not that the first layer of the field has ID 0, the second has ID 1, etc. if we select the third layer (/gate/source/PBS/selectLayerID 2), increase the verbosity (/gate/verbose Beam 10) and run only 10 primaries (to reduce log info), we could check in the log that the system delivers the layer 3 which has an energy of 183.83 MeV and 37 spots (see below). Please note that a field must be selected to guarantee a proper behavior.

```
[Beam-0] Configuration of spot No. 18 (out of 37)
[Beam-0] Energy 183.83
```

- The functionality "/gate/source/PBS/selectSpotID" can be simply tested, for example by selecting the second field (/gate/source/PBS/setAllowedFieldID 2), the third layer (/gate/source/PBS/selectLayerID 2) and selecting the second spot ID (/gate/source/PBS/selectSpotID 2). Not that the first Spot of the layer has ID 0, the second has ID 1, etc. if we select the third spot (/gate/source/PBS/selectSpotID 2), increase the verbosity (/gate/verbose Beam 10) and run only 10 primaries (to reduce log info), we could check in the log that the system delivers the spot 3 of the layer 3 of the field 2, which has a position -8/32 (x/y) and a meterset of 33.26.

```
[Beam-5]      [TPSPencilBeam] trying to parse line 142 from file data/OrientationTest_PlanDescriptionFileGTRY0.txt
[Beam-1]  TESTREAD Spot No. 2 (for this field)   parameters: -8 32 33.26
```

The proper layer information can also be checked

```
[Beam-0] Configuration of spot (ID) No. 0 (out of 1)
[Beam-0] Energy 183.83
```

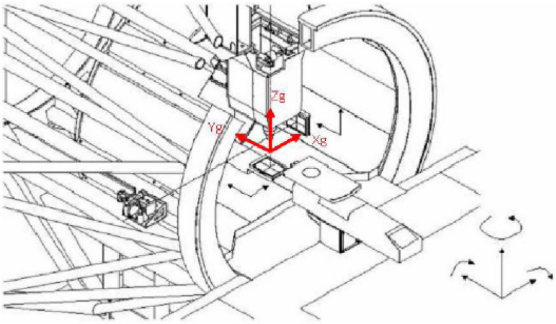
We can also see that all other spots are rejected from the simulation (see example of one spot below).

```
[Beam-1]  TESTREAD Spot No. 4 (for this layer)   parameters: -8 24 0
[Beam-1]  Rejected spot nr 4 (for this layer) for energy=146.25 MeV, layer 27 in field=1 lineno=1765
```

Please note that a field and a layer must be selected to guarantee a proper behavior.

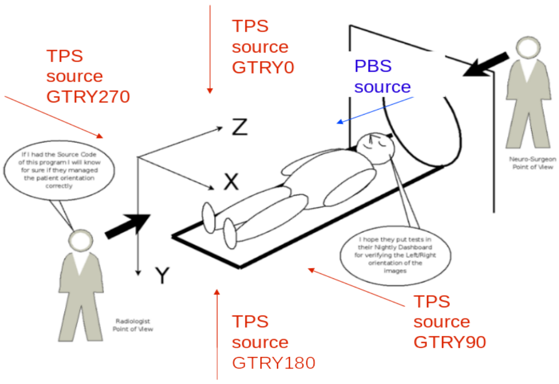
2. Annexes

The **PencilBeam** source is set-up according to IEC coordinate system; i.e. beam direction –Z, spot position in X and Y (see picture below)



(a) IEC Coordinate system

The **TPSPencilBeam** source consists in a collection of **PencilBeam** sources and DICOM image coordinate system is considered as illustrated below



The conversion of each pencil beam coordinate defined as a PencilBeam source in the TPSPencilBeam source, i.e. in the GATE world (or DICOM image coordinate convention) is as follows:

TPS source \ PBS source	X	Y	Beam direction
GTRY0	X	Z	+Y
GTRY90	Y	Z	-X
GTRY180	-X	Z	-Y
GTRY270/-90	-Y	Z	+X