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Simulation of electron and photon transport through tumorous and surrounding tissues with 3D Monte Carlo codes

Y.Z. Kandiev, A.A. Malakhov, S.I. Samarin, E.V. Serova, S.G. Spirina

Russian Federal Nuclear Center
Zababakhin Institute of Applied Physics (RFNC-VNIITF)
Snezhinsk, Chelyabinsk Region, Russia
s.g.spirina@vniitf.ru

ABSTRACT

The paper presents results obtained by RFNC-VNIITF scientists in Monte Carlo simulations for the transport of electrons and photons from small sources (seed activities) through tumorous and surrounding tissues. These simulations are used to develop brachytherapy plans for cancer patients. The paper demonstrates capability of the code PRIZMA[1] to reproduce dose depositions from single and several seeds and presents a technique used to optimize seed positions. The technique was implemented in the code SEEDPLAN developed for the selection of optimal conditions for tumor irradiation at least radiation burdens to healthy tissues. The rate of dose from a grid of seeds at one or several points of interest is calculated with an algorithm based on superposition of doses from one seed. The algorithm was verified through calculations with a special model developed in PRIZMA. Our calculations prove that SEEDPLAN quite accurately reproduces dose deposition from seeds in a specified configuration and can be used to optimize treatment plans.

Key Words: brachytherapy, seed, SEEDPLAN, optimization, absorbed energy

1. INTRODUCTION

Recent years have demonstrated growing interest to interstitial brachytherapy as a means of treating prostate, rectal and bladder cancers at early stages. The dose from seed implants and their positioning in a patient are determined from a CT scan. Implants usually consist of ~100 capsules whose positions are chosen in accord with manual examination or with semi-automated software. The cylindrical capsules exhibit strong anisotropy of the dose distribution, especially near “poles” which makes it difficult to achieve uniform irradiation of tumorous tissues. Therefore, seed positioning needs thorough investigation. This poses additional requirements for seed parameters, size, anisotropy and strength parameters, and for dose calculation models used in treatment planning. The paper offers the code PRIZMA for dose calculations associated with seed positioning and a technique implemented in the code SEEDPLAN to optimize seed positioning and provide the best tumor irradiation conditions at the least radiation burden to healthy tissues.

The work we have done in the area basically includes calculations to study dose fields from different seed types in different configurations and the development of a special code (algorithm) to optimize brachytherapy plans. The calculations were done by PRIZMA and compared with similar MCNP results published in the literature. SEEDPLAN calculations for the spatial distribution of absorbed energy from seeds in specified configurations are done with initial data obtained in PRIZMA calculations for a single seed. Comparative PRIZMA calculations were done for several seeds and their total dose fields obtained with SEEDPLAN. The work ended with the implementation of capabilities which help optimize seed positioning for a minimum number of seeds and a minimum number of spokes with respect to prescribed doses to tumorous and healthy tissues. Test calculations were done for a model irradiation geometry. They proved efficiency of seed positioning optimization.

2. INVESTIGATION OF DOSE FIELDS FOR UNIFORMITY

2.1. Calculation of the spatial distribution of absorbed energy near a single seed

Our calculations were done for SEED 6711 shown in Fig.1 (titanium cladding, a thin layer of ^{125}I on a silver bar).

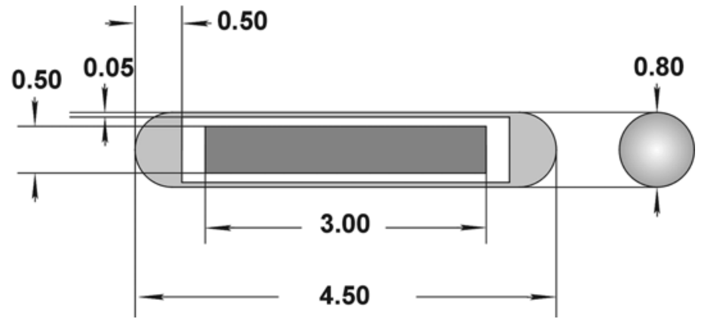


Figure 1 – Dimensions of a standard seed, mm (SEED 6711 of Nicomed Amersham)

We defined a cube 40×40×40 cm^3 filled with a soft biomaterial (SBM) (2.6% of nitrogen, 76.2% of oxygen, 10.1% of hydrogen and 11.1% of carbon, density = 1.0 g/cm^3). A single source (Seed 6711) was placed in its center. The energy distribution of the source was taken from the input deck of an MCNP calculation:

E(MeV)	3.770e-3	4.090e-3	2.720e-2	2.750e-2	3.090e-2	3.100e-2	3.120e-2	3.170e-2	3.550e-2
F	6.140e-2	5.930e-2	3.980e-1	7.410e-1	7.200e-2	1.400e-1	1.440e-3	4.300e-2	6.670e-2

PRIZMA calculations were compared with results obtained by TG-43. A detector was placed on the Y axis at different distances from the center of the seed. Results were normalized to the result obtained for the detector at a distance of 1 cm from the center of the seed (Table I, Figure 2).

Table I. TG-43 and PRIZMA calculations for different detector positions

Distance to detector (cm)	TG-43	PRIZMA	Relative error %
0.50	1.035	1.017	0.43
0.75	1.022	1.016	0.43
1.00	1.000	1.000	0.45
1.50	0.934	0.961	0.42
2.00	0.851	0.891	0.47
2.50	0.760	0.813	0.49
3.00	0.671	0.745	0.41
3.50	0.587	0.678	0.48
4.00	0.511	0.606	0.44
4.50	0.446	0.539	0.47
5.00	0.390	0.486	0.48
5.50	0.343	0.428	0.48
6.00	0.303	0.379	0.48
6.50	0.270	0.335	0.50
7.00	0.237	0.299	0.55
7.50	0.209	0.261	0.55
8.00	0.181	0.232	0.62

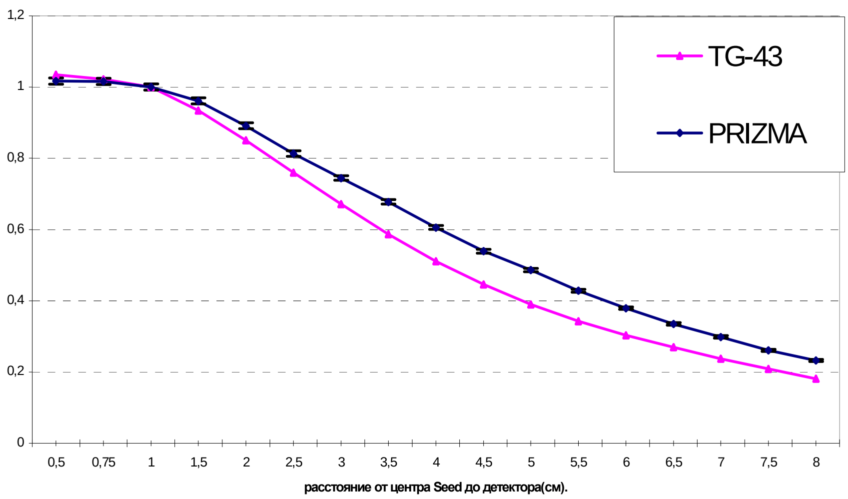


Figure 2. Results for Seed 6711

Particles were tracked in a cubic lattice 12×12×12 cm^3 at a step of 1 mm along X, Y and Z axes. The lattice was centered at the center of the system. The seed was oriented along the Z axis. Calculations were done by PRIZMA. All results are given in MeV/g per disintegration.

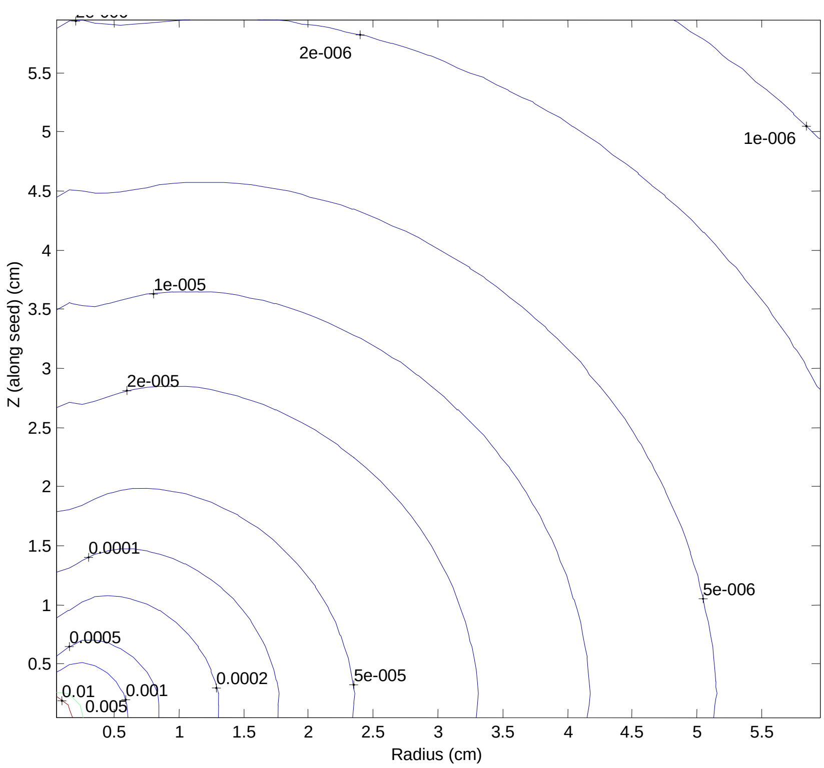


Figure 3. Absorbed dose isolines in the plane Z=0; single Seed 6711

2.2. Calculations for different seed types

Energy absorption by SBM was calculated for three types of seeds (Seed 6711, Seed I-Plant 3500 and ^{100}Pd Seed) which differed in geometry and materials.

For each seed type we considered three configurations of spokes (a spoke is a set of seeds located one after another along one line). The Cartesian frame XYZ creates the right triad of vectors and the X axis is pointed along a seed (spoke). For the purpose of comparison, detectors were at the same points near the central seed placed at the point (0;0;0) of the system.

The following seed configurations were considered:

A quadrilateral lattice where distances between spokes and centers of two neighbor seeds in one spoke were 0.5 cm (see Figures 4a and 4b); the total number of seeds was 1183.

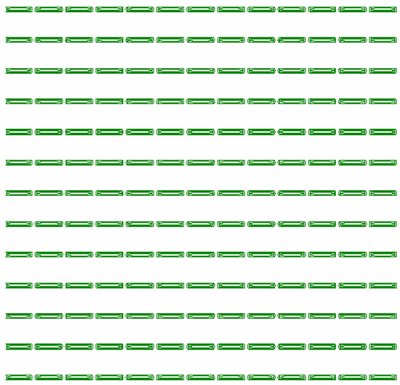
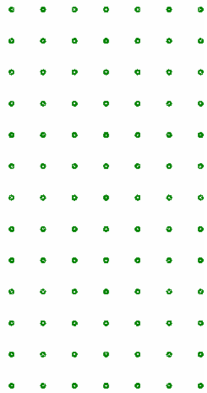



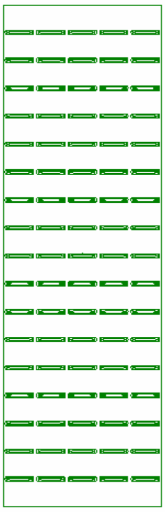
Figure 4a. Seeds in the plane Y=0 Figure 4b. Seeds in the plane Z=0

Calculated results are presented in Table II (hereafter bracketed is standard deviation in %).

Table II. Absorbed energy for different positions of detectors

Detector coordinates (x;y;z)	Absorbed energy (MeV/g per disintegration)	
	I-Plant 3500	6711
(0;0.0411;0)	$3.008\ 10^{-4}$ (0.983)	$1.909\ 10^{-4}$ (0.445)
(0;0.0625;0)	$2.058\ 10^{-4}$ (0.791)	$1.303\ 10^{-4}$ (0.330)
(0;0.125;0)	$1.788\ 10^{-4}$ (0.131)	$1.021\ 10^{-4}$ (0.662)
(0;0.25;0)	$1.676\ 10^{-4}$ (0.088)	$9.195\ 10^{-5}$ (0.419)
(0.25;0.25;0)	$1.687\ 10^{-4}$ (0.059)	$9.187\ 10^{-5}$ (0.390)
(0;0.25;0)	$2.674\ 10^{-4}$ (0.264)	$6.889\ 10^{-5}$ (0.512)

A hexagonal lattice where distances between spokes are 0.5 cm. The distance between centers of two neighbor seeds in one spoke is 0.5cm for Seed 6711 and Seed I-Plant 3500, and 0.75cm for ^{100}Pd Seed. The calculation was done for 1265 seeds. Figures 5a and 5b show spokes of seeds in sectional planes. Calculated results for three seed types are presented in Table III.



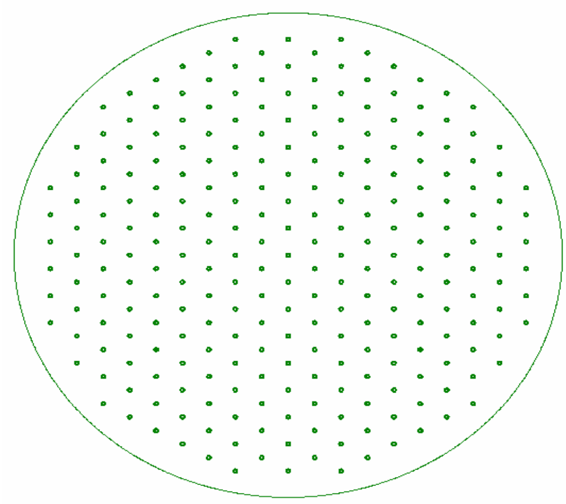


Figure 5a. The plane Y=0 Figure 5b. The plane Z=0

Table III. Absorbed energy for different positions of detectors

Detector coordinates (x;y;z)	**Absorbed energy (MeV/g per disintegration)**					
	I-Plant 3500		**6711**		**^{100}Pd**	
(0;0.0411;0)	$2.991\ 10^{-4}$	(0.955)	$1.954\ 10^{-4}$	(0.947)	$7.480\ 10^{-5}$	(0.629)
(0;0.0625;0)	$2.122\ 10^{-4}$	(0.462)	$1.353\ 10^{-4}$	(0.453)	$8.664\ 10^{-5}$	(0.573)
(0;0.125;0)	$1.809\ 10^{-4}$	(0.086)	$1.049\ 10^{-4}$	(0.423)	$9.566\ 10^{-5}$	(0.714)
(0;0.25;0)	$1.712\ 10^{-4}$	(0.061)	$9.532\ 10^{-5}$	(0.265)	$9.522\ 10^{-5}$	(0.260)
(0.25;0.1;0)					$9.590\ 10^{-5}$	(0.258)
(0.25;0.25;0)	$1.706\ 10^{-4}$	(0.061)	$9.465\ 10^{-5}$	(0.250)	$9.747\ 10^{-5}$	(0.510)
(0.25;0;0)	$2.714\ 10^{-4}$	(0.318)	$7.544\ 10^{-5}$	(0.324)	$9.201\ 10^{-5}$	(0.524)
(0;0.2511;0)					$1.454\ 10^{-4}$	(0.353)
(0;0.275;0)					$1.076\ 10^{-4}$	(0.588)

A hexagonal lattice where distances between spokes and centers of two neighbor seeds in one spoke are 1 cm (the same configuration as earlier). The calculation was done for 185 seeds. Spokes are configured as previously. Results are presented in Table IV.

Table IV. **Absorbed energy for different positions of detectors**

Detector coordinates (x;y;z)	Absorbed energy (MeV/g per disintegration)		
	I-Plant 3500	6711	^{100}Pd
(0;0.0411;0)	$1.933\ 10^{-4}$ (1.316)	$1.377\ 10^{-4}$ (0.634)	$1.784\ 10^{-5}$ (0.544)
(0;0.125;0)	$4.848\ 10^{-5}$ (0.043)	$3.570\ 10^{-5}$ (0.620)	$2.680\ 10^{-5}$ (0.246)
(0;0.25;0)	$3.269\ 10^{-5}$ (0.025)	$2.048\ 10^{-5}$ (0.350)	$2.692\ 10^{-5}$ (0.134)
(0;0.5;0)	$2.772\ 10^{-5}$ (0.021)	$1.654\ 10^{-5}$ (0.280)	$1.863\ 10^{-5}$ (0.108)
(0.5;0.5;0)	$2.642\ 10^{-5}$ (0.021)	$1.565\ 10^{-5}$ (0.274)	$1.756\ 10^{-5}$ (0.106)
(0.5;0;0)	$2.889\ 10^{-5}$ (0.045)	$1.360\ 10^{-5}$ (0.295)	$1.814\ 10^{-5}$ (0.117)

Our calculations suggest that a hexagonal lattice of spokes provides the most uniform distribution of absorbed energy for all seed types.

3. DEVELOPMENT OF A SPECIAL CODE TO OPTIMIZE BRACHYTHERAPY PLANS

3.1. Dose fields predicted by PRIZMA and SEEDPLAN for a specified seed configuration

SEEDPLAN (its description is given below) predicts the distribution of absorbed energy for a specified seed configuration and gives absorbed dose isolines for specified sections. As initial data, it uses results of PRIZMA calculations for a single seed.

To verify SEEDPLAN, we made an additional PRIZMA calculation for several seeds.

For this purpose we defined 16 spokes of seeds (6711) oriented along OZ at distances of 1cm along OX and OY. Each spoke had 4 seeds (1 cm distant). The total number of seeds was 64. They were configured as a quadrilateral lattice.

All seeds were in a 40×40×40-cm^3 cube filled with SBM.

Particles were tracked in a cubic lattice 12×12×12 cm^3 at a step of 1 mm along the axes OX, OY and OZ.

PRIZMA results for the specified seeds were used to obtain absorbed dose isolines for specified sections in Z (spokes are parallel to OZ). They are shown in Figs. 6a-6i for the 1/8 space created by positive axes.

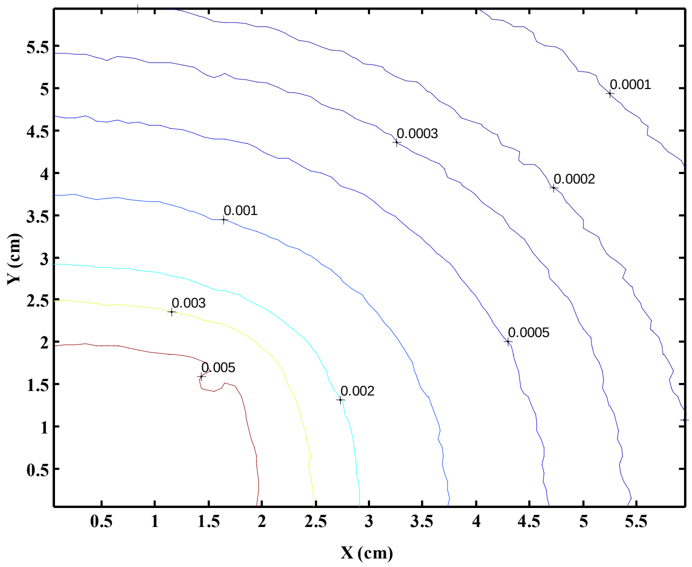


Figure 6a. Absorbed dose isolines for the plane Z=0.1 cm

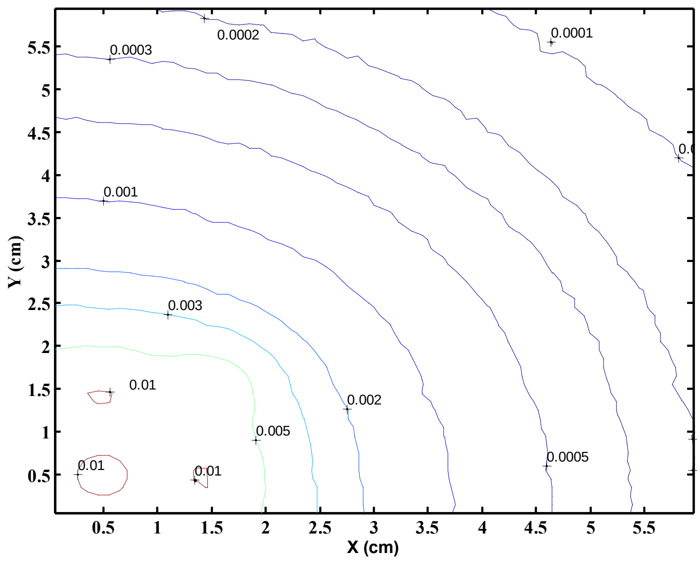


Figure 6b. Absorbed dose isolines for the plane Z=0.3 cm

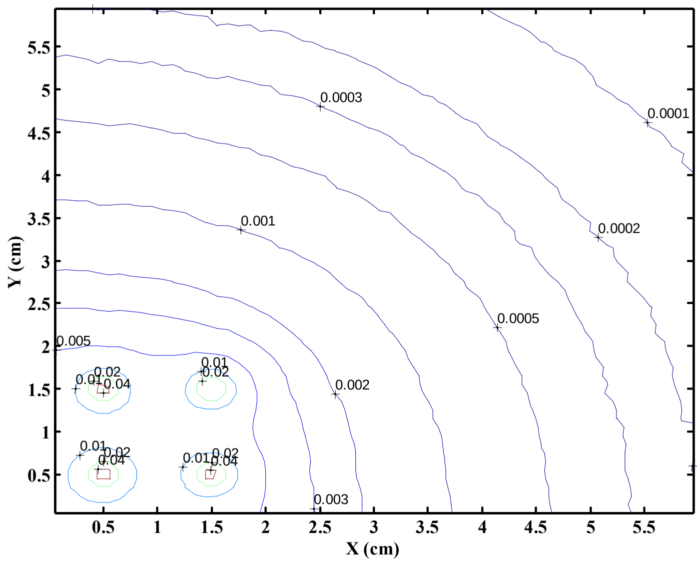


Figure 6c. Absorbed dose isolines for the plane Z=0.5 cm

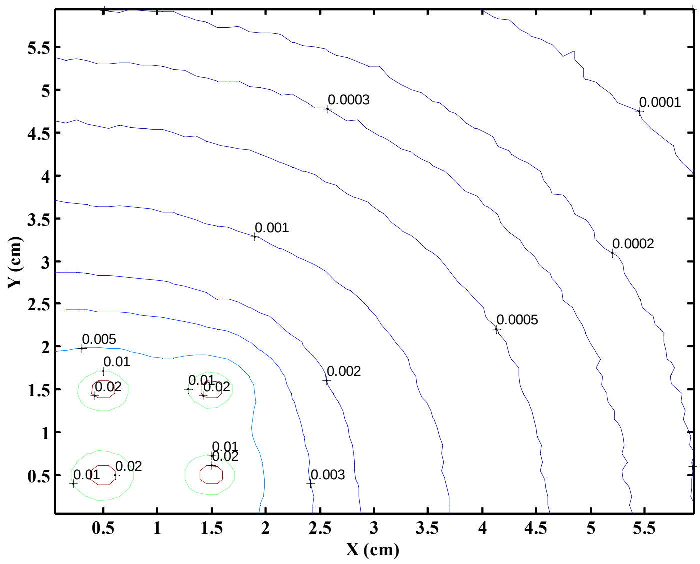


Figure 6d. Absorbed dose isolines for the plane Z=0.7 cm

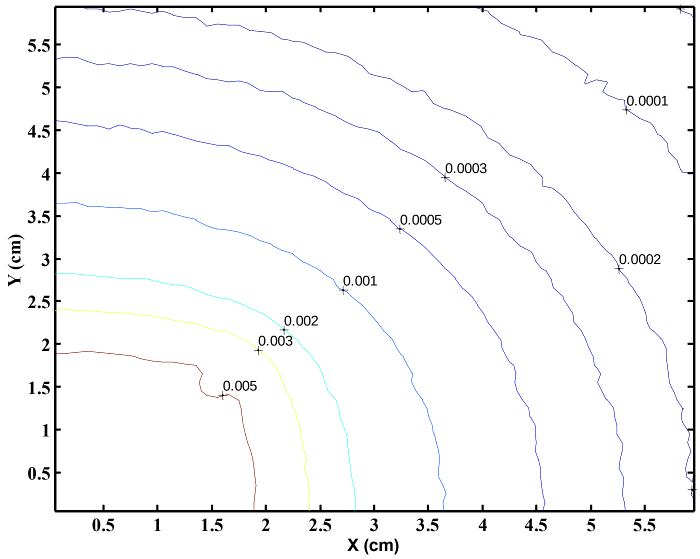


Figure 6e. Absorbed dose isolines for the plane Z=1cm

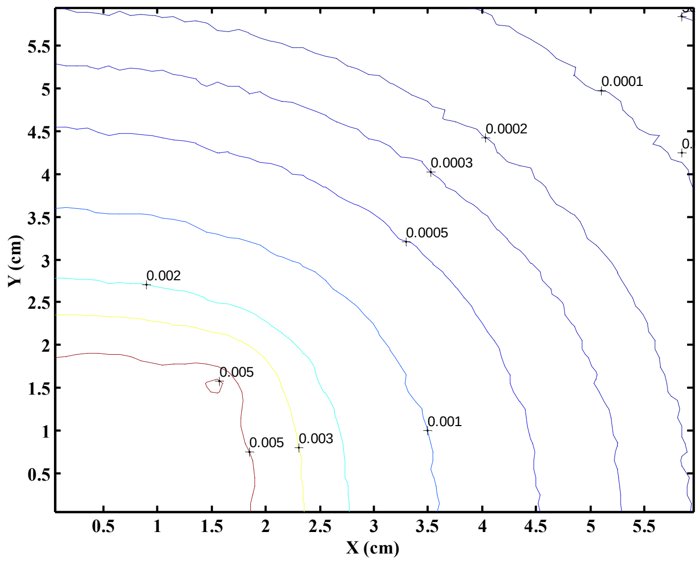


Figure 6f. Absorbed dose isolines for the plane Z=1.2cm

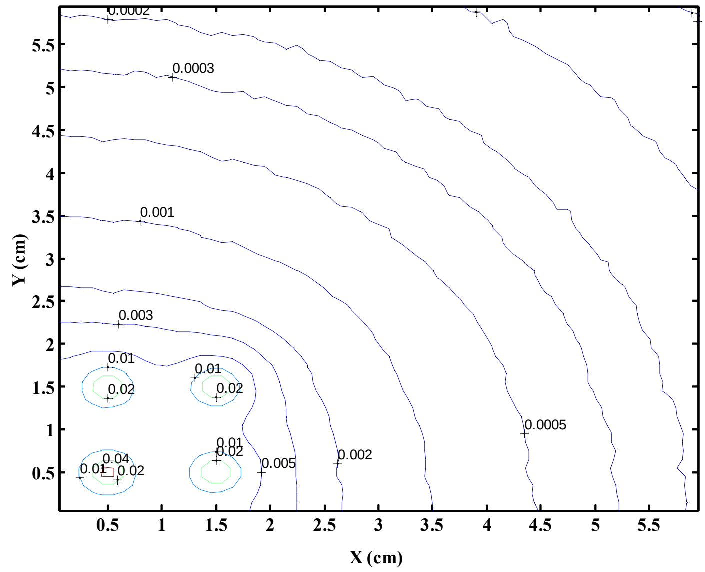


Figure 6g. Absorbed dose isolines for the plane Z=1.5 cm

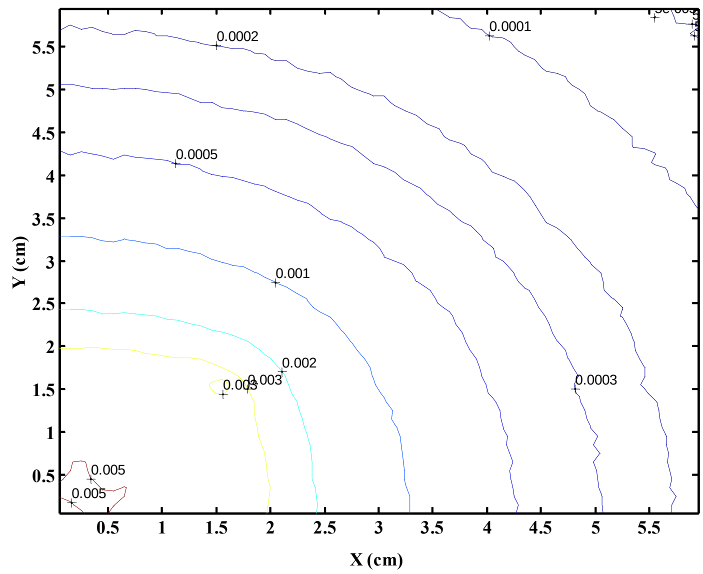


Figure 6h. Absorbed dose isolines for the plane Z=2 cm

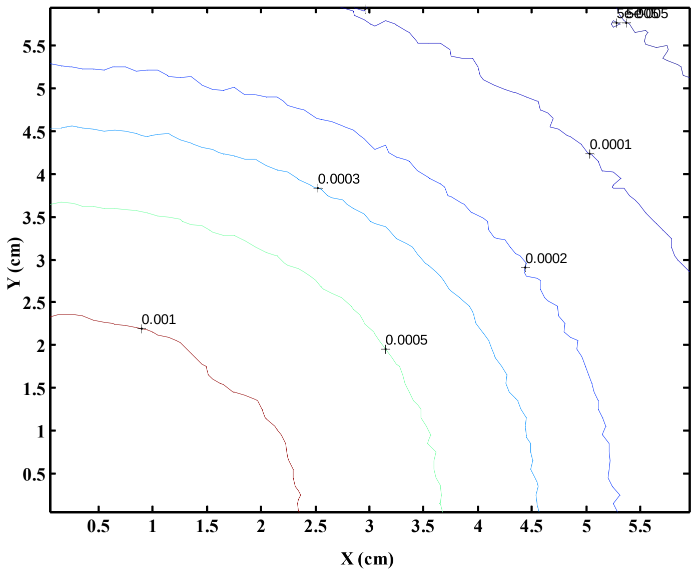


Figure 6i. Absorbed dose isolines for the plane Z=3 cm

SEEDPLAN modeled seeds in the same configuration as PRIZMA. SEEDPLAN assumes additivity of seeds, i.e., it sums contributions from all seeds to dose, neglecting their mutual shielding and using the dose field from a single seed predicted by PRIZMA.

The single-seed dose maps shown in Fig.3 were calculated under the condition that seeds were positioned as shown in Fig.7.

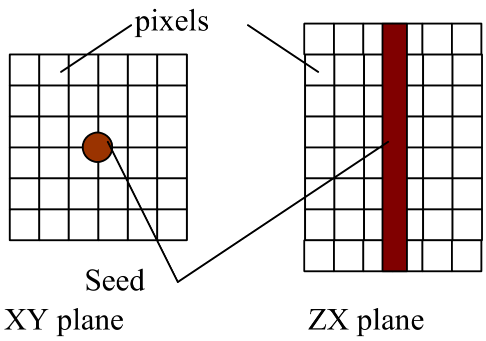


Figure 7. Positions of seeds relative to pixels of the modeled system

Dose fields from several seeds were calculated for each pixel by summing doses from all seeds thus implementing the additive approximation.

Figures 8a-8b show doses predicted by PRIZMA and calculated by SEEDPLAN. In SEEDPLAN calculations we used the spatial distribution of absorbed energy obtained by PRIZMA for a single seed.

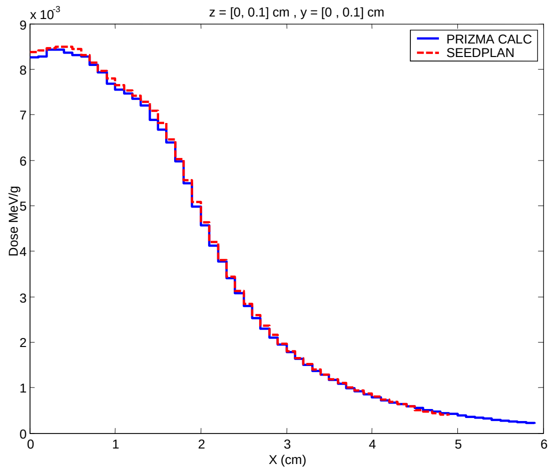


Figure 8a. Absorbed energies obtained by PRIZMA and SEEDPLAN

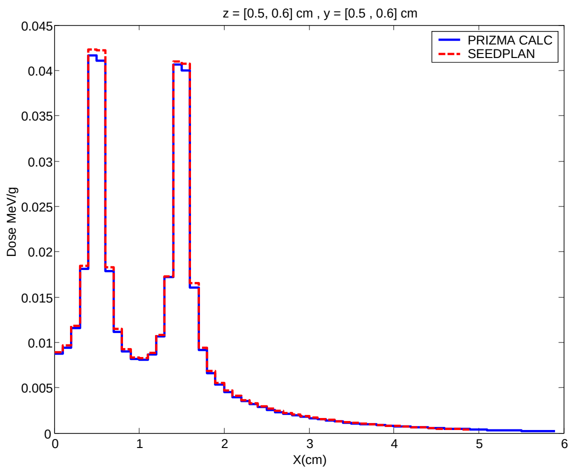


Figure 8b. Absorbed energies obtained by PRIZMA and SEEDPLAN

Our calculations prove that SEEDPLAN quite accurately reproduces the spatial distribution of absorbed energy for specified seed configurations (obtained results differ by no more than 4%). This allows its use for brachytherapy planning.

3.2. SEEDPLAN: purpose and capabilities

SEEDPLAN was developed for brachytherapy planning, specifically, for finding the best seed positioning from data on dose fields from single seeds predicted by PRIZMA. Positions of spokes and seeds can be defined by user with a special editor or automatically in nodes of a cubic lattice with a specified step along X, Y and Z axes. After seed positioning, it is possible to visualize the dose map in a selected layer Z (spokes are in the XY plane), see doses on the map, mark the tumorous region, the region of the specified dose threshold and the region outside the tumor where doses are higher than the minimal dose in the tumorous region.

The code provides for automated determination of coordinates for spokes and seeds which correspond to the minimum of a functional chosen. Functionals are chosen from a number of options so as to satisfy the condition that doses must be as close as possible to a prescribed value inside the tumorous region and to a prescribed minimum outside the region. Results of optimization can also be visualized and damped in a special file.

3.2.1. Structure of data used in the code

The code uses the following data.

Seed data: dose fields around single seeds predicted by PRIZMA and other information such as size and number of pixels along axes which define the size of specified data on dose fields and dose arrays

Image data (from CT scanning) which briefly describe an image – the region that completely covers the tumor in a 3D pixel representation. These also include information on the minimum value of each coordinate, size and number of pixels along each axis, and the array of image options. Two options are used now: 1 for the tumorous tissue in the pixel and 0 for the usual tissue.

A number of model images are used to adjust the code. ***Data on spoke and seed positioning*** can be stored in text files or developed by SEEDPLAN.

Output data contain resulted doses and seed positions stored in m-files for MATLAB and drw-files for the DataViewer 3D visualization system.

3.2.2. Capabilities

Illustrate some capabilities implemented in the code.
Manual positioning: Gray variances are used for the tumorous region. The greater the number of pixels in Z for the selected coordinate in the projection plane, the darker gray is the projection pixel. This helps measure the “thickness” of the tumor in planning positions of spokes (Figure 9).

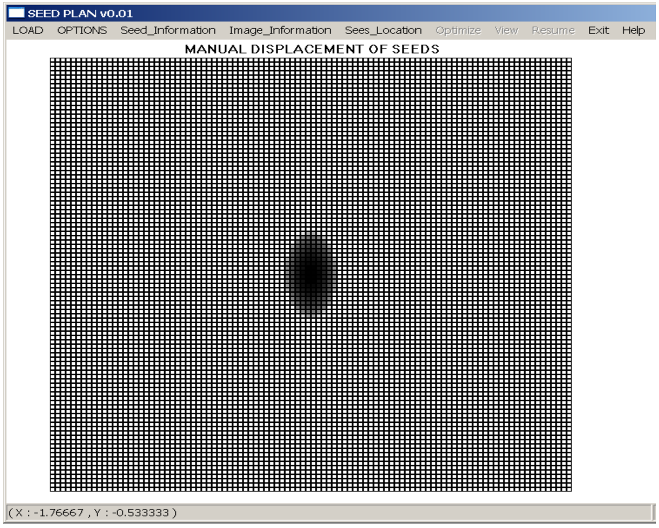


Figure 9. Manual seed positioning: spokes

The spoke which is being positioned at the moment is marked with the darker red circle (Figure 10).

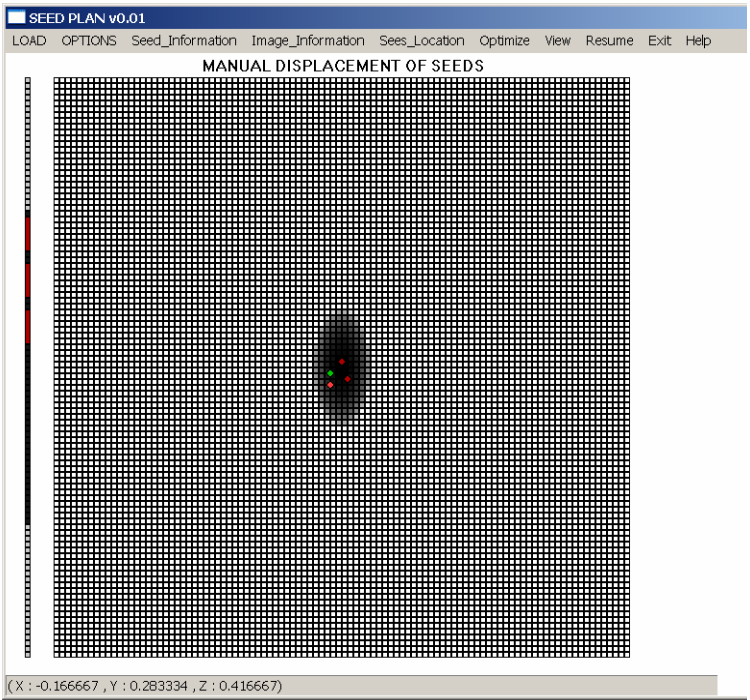


Figure 10. Manual seed positioning: seeds

Spokes can be deleted, copied and displaced.

Manual seed positioning can be done for an existing configuration developed manually or automatically. The dose map for the current seed configuration can be visualized. The dose map is the XY plane for a layer of pixels in the Z axis. It is selected in accord with a scale of vertical layers shown as a column of pixels on the left side of the map (Figure 11). The current vertical layer has a red marker.

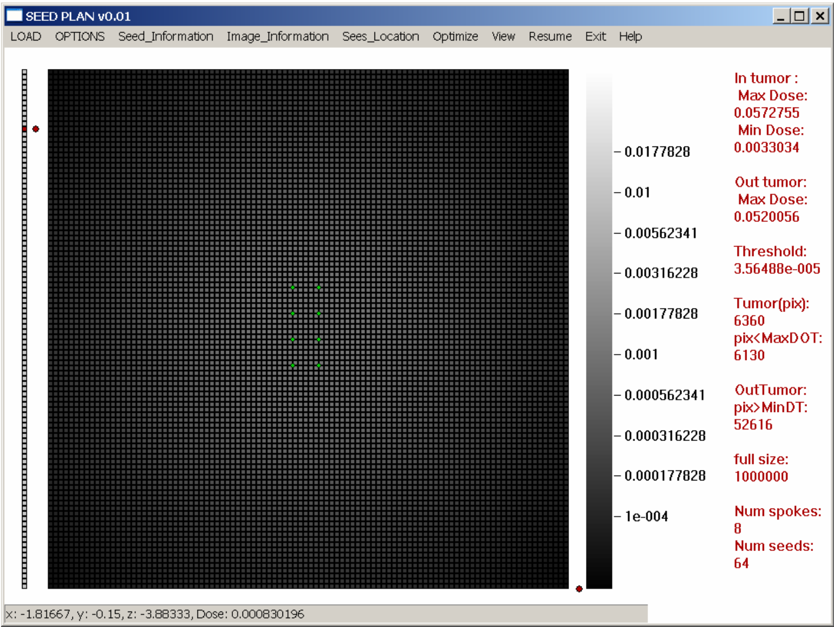


Figure 11. Dose map viewing

The dose map of the current layer is shown in pixels colored with different variances of gray in accord with the total dose in the pixel. Color intensity corresponds to the digital color bar shown on the right.

The red marker to the right of the color box shows the threshold dose which is taken, by default, to be equal to the minimum dose in the object. Minimum and maximum doses in the color box correspond to minimum and maximum doses in the object (not in the current layer). The threshold can easily be changed. Its marker moves opposite the mouth position and all pixels where doses are lower than the threshold are colored in blue (Figure 12).

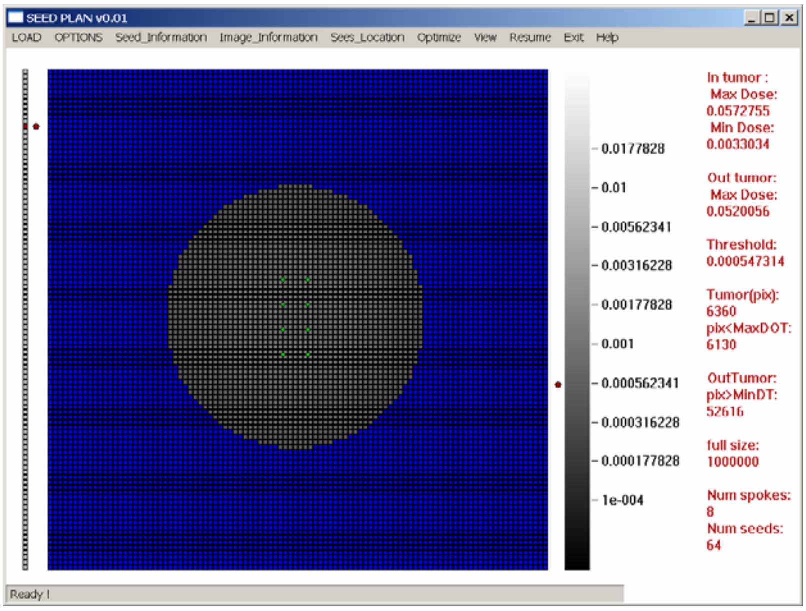


Figure 12. Dose map viewing

If necessary, color intensities can be converted into a log scale and back into a linear one. Spokes are shown by colored circles and a green circle shows that there is no seed in the spoke in the layer. Accordingly, a red marker informs about the presence of a seed in the layer (Figures 12 and 13).

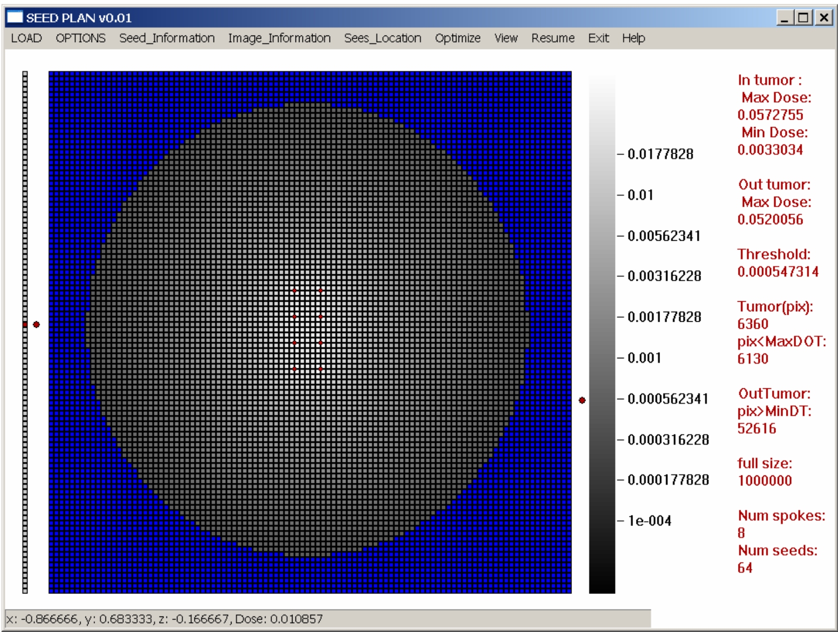


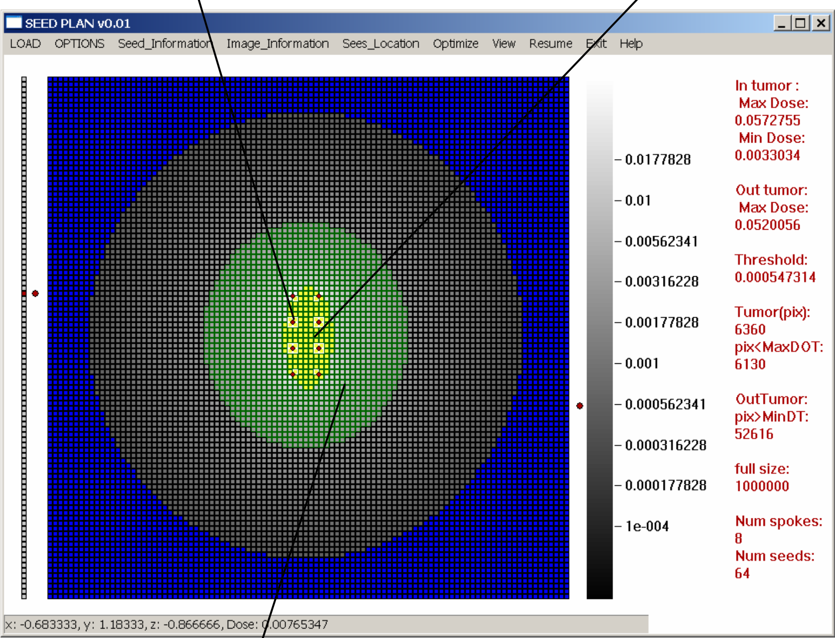
Figure 13. Dose map viewing

The right part of the window displays basic information used for the analysis of irradiation quality:
Maximum dose to tumor (0.05727755)
Minimum dose to tumor (0.0033034)
Maximum dose outside tumor (0.0520056)
Current threshold dose (blue color for doses below the threshold)
Number of pixels in tumor (6360)
Number of pixels in tumor where doses are lower than the maximum dose outside tumor (6130)
Number of pixels outside tumor where doses are higher than the minimum dose in tumor (52616)
Total number of pixels (1000000)
Number of spokes (8)
Number of seeds (64)

This information helps judge on the quality of irradiation. Additional visualization capabilities facilitating the analysis include conversion of the image into a form which is easier to analyze (Figure 14).

Highlight of tumor region in which dose value is greater than maximum value out of tumor

Highlight of tumor region



Highlight of region out of tumor in which dose value is greater than minimum value in tumor region

Figure 14. Dose map viewing

Tumorous regions where doses are lower than the selected threshold are shown in orange (Figure 15).

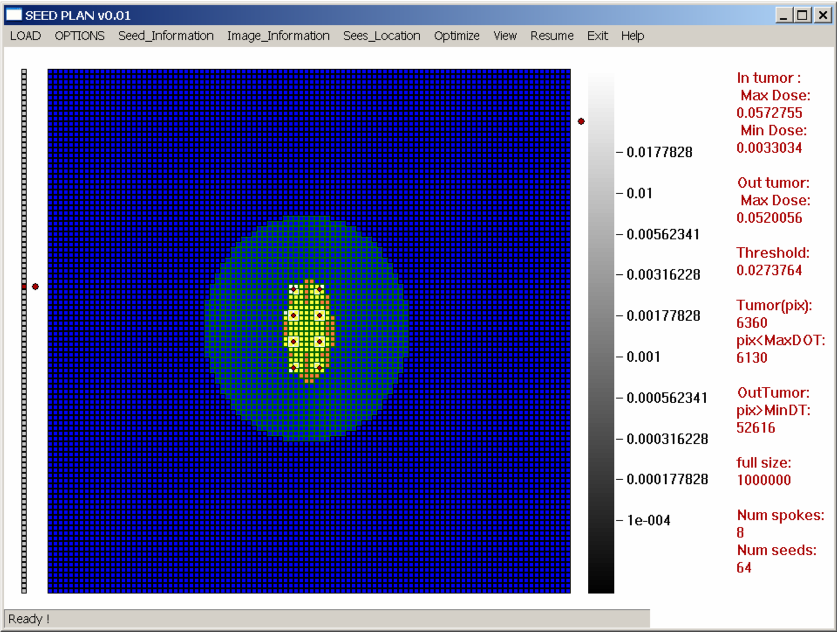


Figure 15. Dose map viewing

The best positions of seeds can be found through optimization.

3.2.3. Optimization

The problem of optimization reduces to finding the functional minimum by Metropolis method. The form of the functional is defined by accumulated discrepancy of doses in the tumorous region to a specified dose and the minimum total dose outside tumor. The importance of each discrepancy contributing to the functional is defined by its weight and functional dependence. The functional may also contain factors which define the optimal numbers of seeds and spokes that allow approximating the functional minimum to almost optimal values specified beforehand.

To find a functional minimum by Metropolis method requires the definition of events which can change the configuration of seeds. A number of such evens are defined in SEEDPLAN.

It is almost always possible to find the form and parameters of a functional and optimization parameters that give acceptable irradiation quality. Figure 16 shows optimization results for seeds automatically positioned in a cubic lattice at steps 0.5, 0.5 and 0.5 (Figures 10 and 11). Dose distributions (for some layers of pixels) are shown in Figs. 12 and 13. With the selected functional and optimization procedure, the quality of irradiation became ~15 times better if follow from the number of off-site pixels where doses are lower than minimum in tumor. In this case we did not change seed intensity that was taken to be 1.

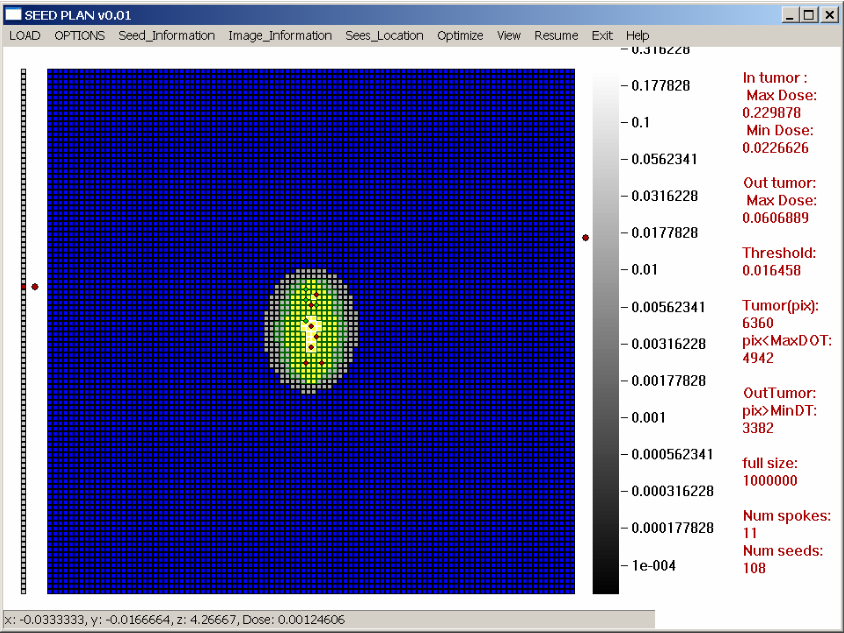


Figure 16. Optimization example

4. CONCLUSION

The paper described calculations made by 3D Monte Carlo codes to characterize electron and photon fields in tumorous and surrounding tissues. PRIZMA was used to predict energy absorption by biotissue for three types of seeds. Obtained results agree with calculations by other codes (for example, MCNP).

The code SEEDPLAN was developed for brachytherapy planning. It uses the spatial distribution of absorbed energy from single Seed 6711. It allows on-line optimization of seed positioning to minimize doses to healthy tissues. Automated optimization makes planning faster and easier. In the future we plan to implement a number of improvements (matching of data on seeds and objects, form and representation of functionals, other seed types).

REFERENCES

1. Arnautova M.A., Kandiev Ya.Z., Lukhminsky B.E., Malishkin G.N., “Monte-Carlo simulation in nuclear geophysics: Comparison of the PRIZMA Monte-Carlo program and benchmark experiments”. Nucl.Geophys., 1993, #3, p. 407-418.