Example: Photon Treatment Plan

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In this example we will show (i) how to load patient data into matRad (ii) how to setup a photon dose calculation and (iii) how to inversly optimize beamlet intensities (iv) how to visually and quantitatively evalute the result

Patient Data Import

Let's begin with a clear Matlab environment. First, import the TG119 phantom into your workspace. The phantom is comprised of a 'ct' and 'cst' structure defining the CT images and the structure set. Make sure the matRad root directory with all its SUBDIRECTORIES is added to the Matlab search path.

```
clc,clear,close all
load('TG119.mat');
```

Let's check the two variables, we have just imported. First, the 'ct' variable comprises the ct cube along with some meta information describing properties of the ct cube (cube dimensions, resolution, number of CT scenarios). Please note that mutiple ct cubes (e.g. 4D CT) can be stored in the cell array ct.cube{}

```
ct
```

```
ct = 

  struct with fields:

           cube: {[167×167×129 double]}
     resolution: [1×1 struct]
```

```
        cubeDim: [167 167 129]
    numOfCtScen: 1
```

The 'cst' cell array defines volumes of interests along with information required for optimization. Each row belongs to one certain VOI, whereas each column defines different proprties. Specifically, the second and third column show the name and the type of the structure. The tpe can be set to OAR, TARGET or IGNORED. The fourth column depicts a linear index vector depicting voxels in the CT cube that are covered by the corresponding VOI. In total, 3 structures are defined in the cst

```
cst
```

```
cst =

  3×6 cell array

  Columns 1 through 5

    [0]    'BODY'           'OAR'       {1×1 cell}    [1×1 struct]
    [1]    'Core'           'OAR'       {1×1 cell}    [1×1 struct]
    [2]    'OuterTarget'    'TARGET'    {1×1 cell}    [1×1 struct]

  Column 6

    [1×1 struct]
    [1×1 struct]
    [1×1 struct]
```

The fifth column represents meta parameters used for optimization such as the overlap priority, which can be specified in double presision. A lower overlap priority indicates increased importance. In contrast, a higher overlap priority indicatets a strcture with lower importance. The parameters alphaX and betaX depict the tissue's photon-radiosensitivity parameter of the linear quadratic model. These parameter are required for biological treatment planning using a variable RBE. Let's output the meta optimization parameter of the target structure:

```
ixTarget = 3;
cst{ixTarget,5}
```

```
ans =

  struct with fields:

    TissueClass: 1
         alphaX: 0.1000
          betaX: 0.0500
       Priority: 1
        Visible: 1
```

The sixth column contains optimization information such as objectives and constraints which are required to calculate the objective function value. Please note, that multiple objectives/constraints can be defined for individual structures. Here, we have defined a squared deviation objective making it 'expensive/costly' for the optimizer to over and underdose the target structure (both are equaly important).

```
cst{ixTarget,6}


ans =

  struct with fields:

          type: 'square deviation'
       penalty: 1000
          dose: 50
           EUD: NaN
        volume: NaN
    robustness: 'none'
```

Treatment Plan

The next step is to define your treatment plan labeld as 'pln'. This structure requires input from the treatment planner and defines the most important cornerstones of your treatment plan.

First of all, we need to define what kind of radiation modality we would like to use. Possible values are photons, protons or carbon. In this case we want to use photons. Then, we need to define a treatment machine to correctly load the corresponding base data. Since we provide generic base data we set the machine to 'Genereric. By this means matRad will look for 'photons_Generic.mat' in our root directory and will use the data provided in there for dose calculation

```
pln.radiationMode = 'photons';
pln.machine       = 'Generic';
```

Define the flavour of biological optimization along with the quantity that should be used for optimizaion. Possible values are (none: physical optimization; const_RBExD: constant RBE of 1.1; LEMIV_effect: effect-based optimization; LEMIV_RBExD: optimization of RBE-weighted dose. As we are using photons, we simply set the parameter to 'none' thereby indicating the physical dose should be optimized.

```
pln.bioOptimization = 'none';
```

Now we have to set some beam parameters. We can define multiple beam angles for the treatment and pass these to the plan as a vector. matRad will then interpret the vector as multiple beams. In this case, we define linear spaced beams from 0 degree to 359 degree in 30 degree steps. This results in 12 beams. All corresponding couch angles are set to 0 at this point. Moreover, we set the bixelWidth to 5, which results in a beamlet size of 5 x 5 mm in the isocenter plane. The number of fractions is set to 30. Be advised that matRad is always optimizing the fraction dose.

```
pln.gantryAngles    = [0:30:359];
pln.couchAngles     = zeros(1,numel(pln.gantryAngles));
pln.bixelWidth      = 5;
pln.numOfFractions  = 30;
```

Obtain the number of beams and voxels from the existing variables and calculate the iso-center which is per default the mass of gravity of all target voxels.

```
pln.numOfBeams      = numel(pln.gantryAngles);
pln.numOfVoxels     = prod(ct.cubeDim);
pln.voxelDimensions = ct.cubeDim;
pln.isoCenter       = ones(pln.numOfBeams,1) *
 matRad_getIsoCenter(cst,ct,0);
```

Enable sequencing and disable direct aperture optimization (DAO) for now. A DAO optimization is shown in a seperate example. The multileaf collimator leaf sequencing algorithm stratifies each beam in N static shape segments.

```
pln.runSequencing = 1;
pln.runDAO        = 0;
```

and et voila our treatment plan is ready. Lets have a look at it:

```
pln
```

```

pln =

  struct with fields:

      radiationMode: 'photons'
            machine: 'Generic'
    bioOptimization: 'none'
       gantryAngles: [0 30 60 90 120 150 180 210 240 270 300 330]
        couchAngles: [0 0 0 0 0 0 0 0 0 0 0 0]
         bixelWidth: 5
     numOfFractions: 30
         numOfBeams: 12
        numOfVoxels: 3597681
    voxelDimensions: [167 167 129]
          isoCenter: [12×3 double]
      runSequencing: 1
             runDAO: 0
```

Generatet Beam Geometry STF

This acronym stands for steering file and comprises the complet beam geomtry along with ray position, beamlet positions, source to axis distance (SAD) etc.

```
stf = matRad_generateStf(ct,cst,pln);
```

```
matRad: Generating stf struct... Progress: 100.00 %
```

Let's display the beam geomtry information of the 6th beam

```
stf(6)
```

```

ans =

  struct with fields:

        gantryAngle: 150
         couchAngle: 0
         bixelWidth: 5
      radiationMode: 'photons'
                SAD: 1000
          isoCenter: [250.7385 236.3393 162.6736]
          numOfRays: 304
```

```
                  ray: [1×304 struct]
       sourcePoint_bev: [0 -1000 0]
           sourcePoint: [500.0000 866.0254 0]
     numOfBixelsPerRay: [1×304 double]
      totalNumOfBixels: 304
```

Dose Calculation

Lets generate dosimetric information by pre-computing dose influence matrices for unit beamlet intensities. Having dose influences available allows then later on inverse optimization.

```
dij       = matRad_calcPhotonDose(ct,stf,pln,cst);
```

```
matRad: Photon dose calculation...
Beam 1 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 939mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 939 mm ...
Progress: 100.00 %
Beam 2 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 930mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 930 mm ...
Progress: 100.00 %
Beam 3 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 884mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 884 mm ...
Progress: 100.00 %
Beam 4 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 850mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 850 mm ...
Progress: 100.00 %
Beam 5 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 827mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 827 mm ...
Progress: 100.00 %
Beam 6 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 894mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 894 mm ...
Progress: 100.00 %
Beam 7 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 908mm
```

```
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 908 mm ...
Progress: 100.00 %
Beam 8 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 897mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 897 mm ...
Progress: 100.00 %
Beam 9 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 827mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 827 mm ...
Progress: 100.00 %
Beam 10 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 850mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 850 mm ...
Progress: 100.00 %
Beam 11 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 878mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 878 mm ...
Progress: 100.00 %
Beam 12 of 12:
matRad: calculate radiological depth cube...done
                   SSD = 930mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 930 mm ...
Progress: 100.00 %
```

Inverse Optimizaiton for IMRT

The goal of the fluence optimization is to find a set of beamlet/pencil beam weights which yield the best possible dose distribution according to the clinical objectives and constraints underlying the radiation treatment. Once the optimization has finished, trigger once the GUI to visualize the optimized dose cubes.

```
resultGUI = matRad_fluenceOptimization(dij,cst,pln);
matRadGUI
```

```

******************************************************************************
This program contains Ipopt, a library for large-scale nonlinear
 optimization.
 Ipopt is released as open source code under the Eclipse Public
 License (EPL).
         For more information visit http://projects.coin-or.org/Ipopt
******************************************************************************

This is Ipopt version 3.11.8, running with linear solver ma57.
```

```
Number of nonzeros in equality constraint Jacobian...:        0
Number of nonzeros in inequality constraint Jacobian.:        0
Number of nonzeros in Lagrangian Hessian.............:        0

Total number of variables............................:     3324
                     variables with only lower bounds:     3324
                variables with lower and upper bounds:        0
                     variables with only upper bounds:        0
Total number of equality constraints.................:        0
Total number of inequality constraints...............:        0
        inequality constraints with only lower bounds:        0
   inequality constraints with lower and upper bounds:        0
        inequality constraints with only upper bounds:        0

iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
   0 1.7261147e+002 0.00e+000 5.54e+000   0.0 0.00e+000    -  0.00e
+000 0.00e+000   0
   1 2.4690415e+002 0.00e+000 5.94e+000  -0.4 6.80e-001    -
 9.51e-001 2.78e-001f  1
   2 2.5570216e+001 0.00e+000 3.80e+000  -0.8 9.10e-002    -  1.00e
+000 1.00e+000f  1
   3 1.7599984e+001 0.00e+000 7.45e-001  -1.7 1.89e-002    -
 9.96e-001 1.00e+000f  1
   4 7.6233696e+000 0.00e+000 6.41e-001  -2.5 4.12e-002    -  1.00e
+000 1.00e+000f  1
   5 4.2270947e+000 0.00e+000 3.86e-001  -3.5 3.17e-002    -  1.00e
+000 1.00e+000f  1
   6 2.8928632e+000 0.00e+000 4.54e-001  -4.1 4.99e-002    -  1.00e
+000 7.83e-001f  1
   7 2.3212797e+000 0.00e+000 1.42e-001  -4.4 2.63e-002    -  1.00e
+000 6.90e-001f  1
   8 2.2392089e+000 0.00e+000 9.42e-002  -5.7 1.00e-002    -  1.00e
+000 5.35e-001f  1
   9 2.1682098e+000 0.00e+000 1.28e-001  -6.8 1.98e-002    -  1.00e
+000 2.46e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  10 2.1012807e+000 0.00e+000 1.73e-001  -7.6 2.97e-002    -  1.00e
+000 1.38e-001f  1
  11 2.0149822e+000 0.00e+000 2.78e-001  -8.0 3.94e-002    -  1.00e
+000 1.34e-001f  1
  12 1.9515189e+000 0.00e+000 2.92e-001  -7.9 4.19e-002    -  1.00e
+000 9.92e-002f  1
  13 1.9000904e+000 0.00e+000 3.62e-001  -7.8 3.42e-002    -  1.00e
+000 9.61e-002f  1
  14 1.8026719e+000 0.00e+000 4.08e-001  -7.7 3.70e-002    -  1.00e
+000 1.87e-001f  1
  15 1.7528795e+000 0.00e+000 2.31e-001  -7.8 4.92e-002    -  1.00e
+000 8.25e-002f  1
  16 1.7322128e+000 0.00e+000 5.39e-001  -7.9 4.32e-002    -  1.00e
+000 4.01e-002f  1
  17 1.6841204e+000 0.00e+000 3.67e-001  -4.4 4.36e-002    -  1.00e
+000 8.54e-002f  1
```

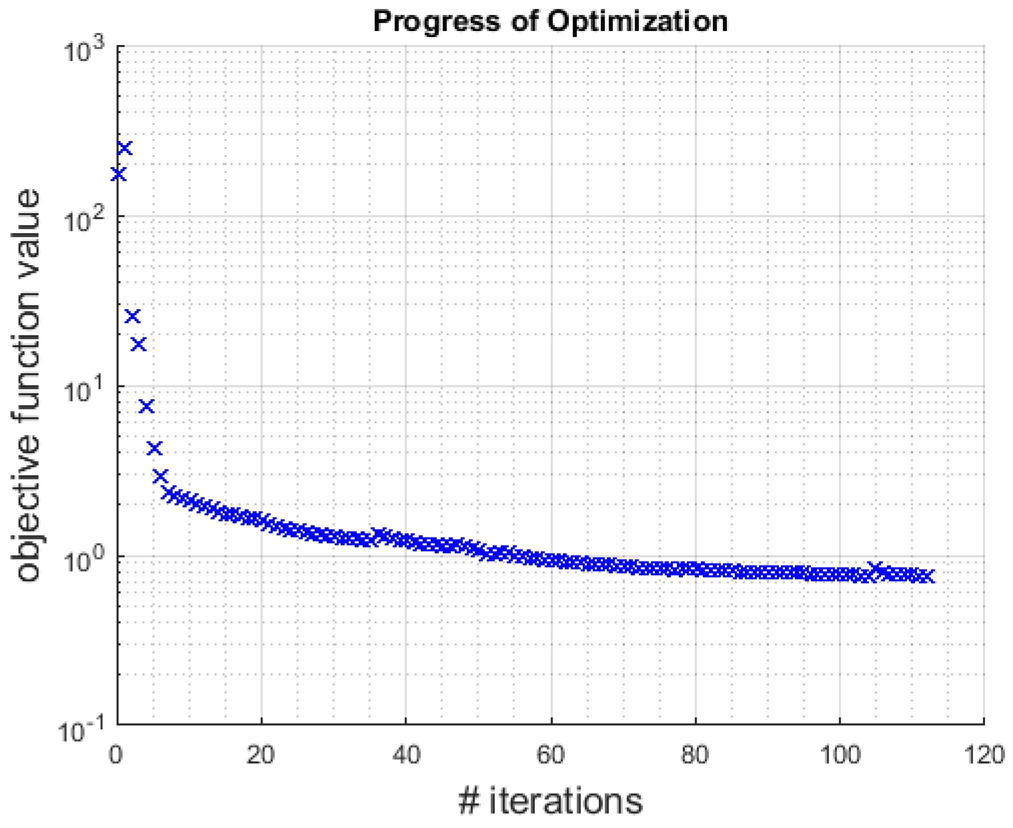
```
  18 1.6326554e+000 0.00e+000 3.28e-001  -3.7 2.41e-002    -  1.00e
+000 1.70e-001f  1
  19 1.6381464e+000 0.00e+000 8.23e-001  -3.2 1.10e-001    -
 8.79e-001 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  20 1.5953433e+000 0.00e+000 1.89e-001  -3.3 8.76e-003    -  1.00e
+000 1.00e+000f  1
  21 1.5261751e+000 0.00e+000 1.30e-001  -4.8 4.08e-002    -  1.00e
+000 8.06e-001f  1
  22 1.4991229e+000 0.00e+000 1.93e-001  -6.4 3.49e-002    -  1.00e
+000 3.89e-001f  1
  23 1.4483759e+000 0.00e+000 7.43e-002  -4.1 5.21e-002    -
 9.99e-001 4.18e-001f  1
  24 1.4156142e+000 0.00e+000 1.10e-001  -5.1 3.21e-002    -  1.00e
+000 3.21e-001f  1
  25 1.3903776e+000 0.00e+000 1.16e-001  -4.7 3.20e-002    -  1.00e
+000 2.16e-001f  1
  26 1.3609081e+000 0.00e+000 1.07e-001  -5.4 3.37e-002    -  1.00e
+000 2.69e-001f  1
  27 1.3375518e+000 0.00e+000 1.29e-001 -11.0 2.92e-002    -
 7.73e-001 2.30e-001f  1
  28 1.3228178e+000 0.00e+000 1.34e-001  -5.7 2.50e-002    -
 7.54e-001 1.67e-001f  1
  29 1.3042292e+000 0.00e+000 9.62e-002  -5.4 3.04e-002    -  1.00e
+000 1.73e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  30 1.2832818e+000 0.00e+000 1.37e-001  -6.2 3.35e-002    -
 9.69e-001 2.03e-001f  1
  31 1.2704239e+000 0.00e+000 1.68e-001  -7.8 3.40e-002    -
 8.40e-001 1.34e-001f  1
  32 1.2544862e+000 0.00e+000 2.16e-001  -6.6 3.28e-002    -  1.00e
+000 2.03e-001f  1
  33 1.2477354e+000 0.00e+000 6.98e-002  -5.6 3.70e-002    -
 8.97e-001 8.21e-002f  1
  34 1.2413335e+000 0.00e+000 2.02e-001  -7.0 1.84e-002    -
 5.06e-001 1.58e-001f  1
  35 1.2305878e+000 0.00e+000 8.26e-002  -5.8 3.44e-002    -  1.00e
+000 1.62e-001f  1
  36 1.3182100e+000 0.00e+000 2.38e-001  -3.7 1.89e-002    -
 5.80e-001 1.00e+000f  1
  37 1.2817816e+000 0.00e+000 8.71e-002  -3.8 1.32e-002    -
 9.86e-001 7.08e-001f  1
  38 1.2460896e+000 0.00e+000 1.67e-001  -3.8 9.41e-003    -
 6.24e-001 1.00e+000f  1
  39 1.2392897e+000 0.00e+000 1.42e-001  -3.8 5.99e-003    -  1.00e
+000 5.71e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  40 1.2143211e+000 0.00e+000 1.40e-001  -3.8 1.37e-002    -
 6.26e-001 1.00e+000f  1
  41 1.1928976e+000 0.00e+000 1.02e-001  -4.0 2.16e-002    -
 9.69e-001 9.97e-001f  1
```

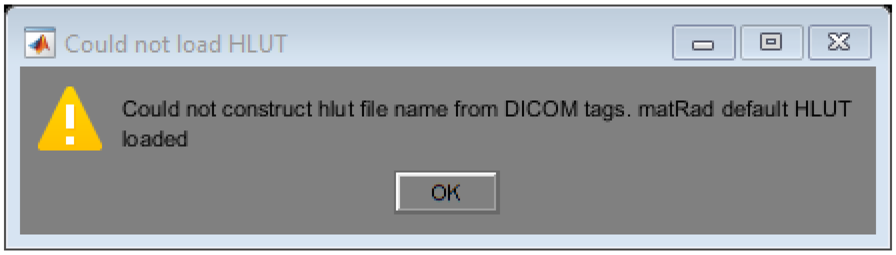
```
  42 1.1596081e+000 0.00e+000 9.20e-002  -4.3 5.15e-003    -  1.00e
+000 1.00e+000f  1
  43 1.1563170e+000 0.00e+000 6.10e-002  -4.0 3.11e-003    -
 8.65e-001 1.00e+000f  1
  44 1.1523144e+000 0.00e+000 2.73e-002  -3.8 1.40e-002    -
 7.45e-001 1.00e+000f  1
  45 1.1331420e+000 0.00e+000 4.66e-002  -4.1 1.25e-002    -
 9.99e-001 8.76e-001f  1
  46 1.1207105e+000 0.00e+000 1.25e-001  -4.6 2.52e-002    -  1.00e
+000 2.63e-001f  1
  47 1.1568149e+000 0.00e+000 3.60e-002  -3.6 1.76e-002    -
 9.32e-001 1.00e+000f  1
  48 1.1251905e+000 0.00e+000 7.68e-002  -3.7 1.74e-002    -  1.00e
+000 1.00e+000f  1
  49 1.1051387e+000 0.00e+000 8.45e-002  -3.7 6.93e-003    -
 9.68e-001 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  50 1.0649431e+000 0.00e+000 1.15e-001  -4.5 2.18e-002    -  1.00e
+000 7.40e-001f  1
  51 1.0214169e+000 0.00e+000 5.22e-002  -4.7 2.53e-002    -  1.00e
+000 9.18e-001f  1
  52 1.0145612e+000 0.00e+000 5.66e-002  -5.3 4.07e-002    -  1.00e
+000 9.81e-002f  1
  53 1.0550545e+000 0.00e+000 8.54e-002  -3.7 1.24e-002    -
 6.02e-001 1.00e+000f  1
  54 1.0320485e+000 0.00e+000 7.27e-002  -3.9 2.33e-002    -  1.00e
+000 3.35e-001f  1
  55 9.9691958e-001 0.00e+000 2.46e-001  -3.9 1.12e-002    -  1.00e
+000 8.85e-001f  1
  56 9.8533963e-001 0.00e+000 1.99e-001  -5.6 1.09e-002    -
 8.10e-001 3.25e-001f  1
  57 9.6549072e-001 0.00e+000 1.28e-001  -5.7 2.05e-002    -  1.00e
+000 3.69e-001f  1
  58 9.5270746e-001 0.00e+000 1.56e-001  -6.1 2.63e-002    -  1.00e
+000 2.33e-001f  1
  59 9.4392188e-001 0.00e+000 1.65e-001  -6.1 3.06e-002    -  1.00e
+000 1.54e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  60 9.2896030e-001 0.00e+000 1.39e-001  -5.7 3.73e-002    -
 9.76e-001 2.59e-001f  1
  61 9.2317698e-001 0.00e+000 9.41e-002  -5.5 3.28e-002    -
 4.01e-001 1.08e-001f  1
  62 9.1609001e-001 0.00e+000 1.27e-001  -5.7 3.50e-002    -
 8.09e-001 1.41e-001f  1
  63 9.0587386e-001 0.00e+000 6.92e-002  -5.6 4.29e-002    -
 9.29e-001 1.79e-001f  1
  64 8.9841529e-001 0.00e+000 1.61e-001  -5.4 2.36e-002    -
 5.44e-001 2.45e-001f  1
  65 8.9038232e-001 0.00e+000 7.99e-002  -5.1 3.99e-002    -  1.00e
+000 1.79e-001f  1
  66 8.8141667e-001 0.00e+000 6.17e-002  -4.7 4.70e-002    -
 4.17e-001 1.78e-001f  1
```

```
  67 8.7980337e-001 0.00e+000 1.50e-001  -5.4 2.55e-002    -
 4.39e-001 5.84e-002f  1
  68 8.7487671e-001 0.00e+000 1.13e-001  -4.7 3.64e-002    -
 3.93e-001 1.39e-001f  1
  69 8.6665189e-001 0.00e+000 6.31e-002  -4.6 4.33e-002    -
 3.47e-001 1.88e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  70 8.6429129e-001 0.00e+000 8.92e-002  -4.5 2.81e-002    -
 5.29e-001 9.38e-002f  1
  71 8.5558594e-001 0.00e+000 5.72e-002  -4.9 3.32e-002    -
 6.07e-001 2.37e-001f  1
  72 8.4918804e-001 0.00e+000 4.64e-002 -10.8 3.40e-002    -
 3.31e-001 1.54e-001f  1
  73 8.4654527e-001 0.00e+000 5.14e-002  -4.6 9.39e-003    -
 1.94e-001 2.35e-001f  1
  74 8.4034601e-001 0.00e+000 4.40e-002 -10.8 3.00e-002    -
 1.89e-001 1.76e-001f  1
  75 8.3758916e-001 0.00e+000 6.30e-002  -4.9 2.34e-002    -
 4.37e-001 9.63e-002f  1
  76 8.3233821e-001 0.00e+000 5.77e-002  -5.6 2.14e-002    -
 2.78e-001 2.10e-001f  1
  77 8.2726643e-001 0.00e+000 3.61e-002  -5.1 2.47e-002    -
 2.64e-001 2.02e-001f  1
  78 8.3793107e-001 0.00e+000 5.54e-002  -4.1 1.29e-002    -
 5.36e-001 1.00e+000f  1
  79 8.3077276e-001 0.00e+000 3.98e-002  -4.4 5.33e-003    -
 9.26e-001 7.94e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  80 8.2851625e-001 0.00e+000 5.17e-002  -4.4 2.07e-003    -  1.00e
+000 1.00e+000f  1
  81 8.2715592e-001 0.00e+000 2.07e-002  -4.4 3.62e-003    -
 8.99e-001 1.00e+000f  1
  82 8.2228808e-001 0.00e+000 2.25e-002  -4.5 4.69e-003    -  1.00e
+000 1.00e+000f  1
  83 8.1410503e-001 0.00e+000 2.30e-002  -5.1 7.32e-003    -  1.00e
+000 7.65e-001f  1
  84 8.0880794e-001 0.00e+000 2.51e-002  -5.2 1.37e-002    -  1.00e
+000 4.65e-001f  1
  85 8.0666478e-001 0.00e+000 4.73e-002  -4.6 6.31e-003    -
 6.51e-001 7.06e-001f  1
  86 8.0324300e-001 0.00e+000 5.22e-002  -4.8 1.25e-002    -
 7.14e-001 3.84e-001f  1
  87 8.0038261e-001 0.00e+000 5.34e-002  -4.9 1.24e-002    -
 5.18e-001 2.97e-001f  1
  88 7.9723259e-001 0.00e+000 5.53e-002  -5.2 1.70e-002    -
 7.25e-001 2.39e-001f  1
  89 7.9349011e-001 0.00e+000 5.03e-002 -11.0 1.97e-002    -
 4.59e-001 2.56e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  90 7.9054692e-001 0.00e+000 6.87e-002  -6.2 2.23e-002    -
 8.68e-001 1.98e-001f  1
```

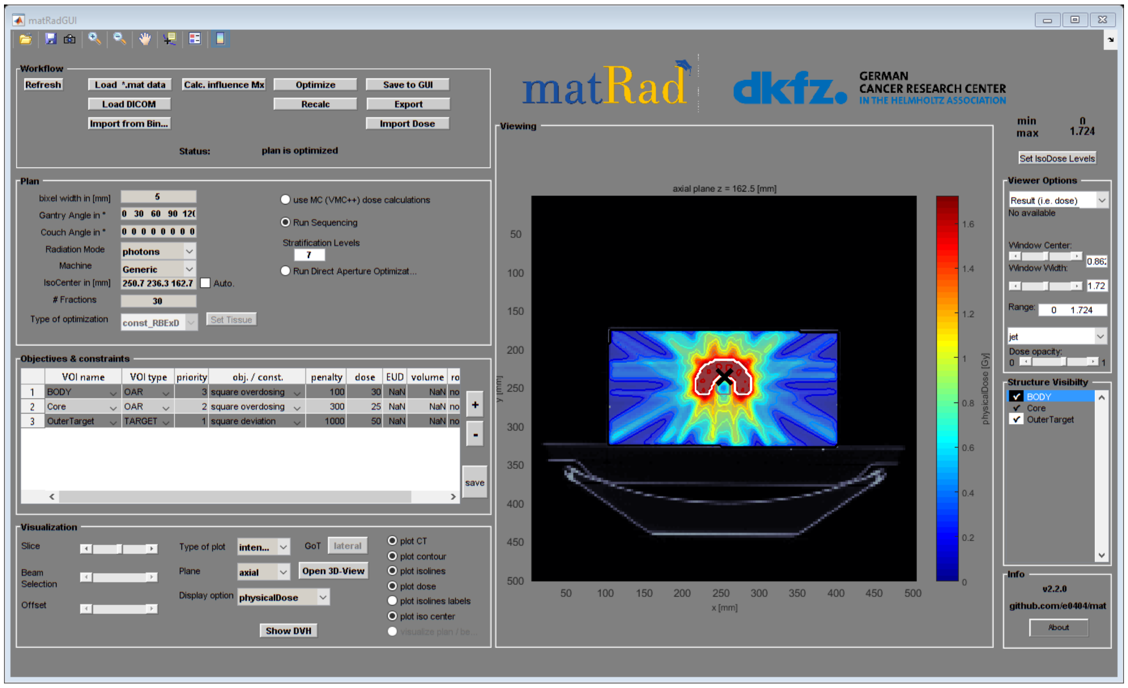
```
  91 7.8730530e-001 0.00e+000 5.57e-002  -5.2 1.74e-002    -
 4.39e-001 3.28e-001f  1
  92 7.9322592e-001 0.00e+000 1.82e-001  -4.4 3.14e-002    -
 5.01e-001 1.00e+000f  1
  93 7.8866756e-001 0.00e+000 2.68e-002  -4.6 1.70e-002    -
 8.73e-001 5.06e-001f  1
  94 7.8566156e-001 0.00e+000 5.63e-002  -4.6 5.92e-003    -
 7.38e-001 1.00e+000f  1
  95 7.8421618e-001 0.00e+000 8.49e-002  -5.2 1.41e-002    -
 7.75e-001 1.90e-001f  1
  96 7.7987146e-001 0.00e+000 4.32e-002  -5.1 1.91e-002    -
 8.83e-001 3.25e-001f  1
  97 7.7575353e-001 0.00e+000 3.67e-002  -5.2 2.78e-002    -
 5.29e-001 2.52e-001f  1
  98 7.7396226e-001 0.00e+000 6.01e-002  -6.6 1.99e-002    -
 3.41e-001 1.34e-001f  1
  99 7.7097100e-001 0.00e+000 5.05e-002  -5.5 2.85e-002    -
 4.59e-001 1.62e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 100 7.6834081e-001 0.00e+000 4.30e-002  -5.0 2.85e-002    -
 3.15e-001 1.52e-001f  1
 101 7.6577124e-001 0.00e+000 4.89e-002  -7.3 3.02e-002    -
 2.50e-001 1.36e-001f  1
 102 7.6319828e-001 0.00e+000 9.32e-002  -5.4 4.72e-002    -
 8.24e-001 9.63e-002f  1
 103 7.6143305e-001 0.00e+000 8.10e-002  -6.2 1.76e-002    -
 9.78e-002 1.55e-001f  1
 104 7.5795280e-001 0.00e+000 5.04e-002  -5.5 3.79e-002    -
 4.84e-001 1.53e-001f  1
 105 8.4623252e-001 0.00e+000 1.51e-001  -4.0 9.04e-002    -
 4.93e-001 1.00e+000f  1
 106 7.9071269e-001 0.00e+000 7.54e-002  -4.3 4.02e-002    -  1.00e
+000 5.91e-001f  1
 107 7.6627662e-001 0.00e+000 1.26e-001  -4.3 1.73e-002    -  1.00e
+000 1.00e+000f  1
 108 7.6481776e-001 0.00e+000 2.73e-002  -4.3 2.25e-003    -  1.00e
+000 1.00e+000f  1
 109 7.6368214e-001 0.00e+000 2.83e-002  -4.3 7.67e-003    -
 9.33e-001 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 110 7.6338675e-001 0.00e+000 1.92e-002  -4.3 8.44e-003    -  1.00e
+000 1.00e+000f  1
 111 7.6259789e-001 0.00e+000 1.78e-002  -4.3 1.03e-002    -  1.00e
+000 1.00e+000f  1
 112 7.6162777e-001 0.00e+000 8.89e-003  -4.3 1.72e-003    -  1.00e
+000 1.00e+000f  1

Number of Iterations....: 112

                                   (scaled)                 (unscaled)
Objective...............:  7.6162777376635393e-001
 7.6162777376635393e-001
```

```
Dual infeasibility......:  8.8915524124589442e-003
 8.8915524124589442e-003
Constraint violation....:  0.0000000000000000e+000
 0.0000000000000000e+000
Complementarity.........:  5.9235295952830844e-005
 5.9235295952830844e-005
Overall NLP error.......:  8.8915524124589442e-003
 8.8915524124589442e-003


Number of objective function evaluations             = 113
Number of objective gradient evaluations             = 113
Number of equality constraint evaluations            = 0
Number of inequality constraint evaluations          = 0
Number of equality constraint Jacobian evaluations   = 0
Number of inequality constraint Jacobian evaluations = 0
Number of Lagrangian Hessian evaluations             = 0
Total CPU secs in IPOPT (w/o function evaluations)   =      2.923
Total CPU secs in NLP function evaluations           =     60.239

EXIT: Solved To Acceptable Level.
Calculating final cubes...
Warning: matRad default HLUT loaded
Reconversion of HU values could not be done because HLUT is not
 bijective.
```




Could not load HLUT

Could not construct hlut file name from DICOM tags. matRad default HLUT loaded



Status: plan is optimized

Plan	
bixel width in [mm]	5
Gantry Angle in °	0 30 60 90 120
Couch Angle in °	0 0 0 0 0 0 0 0
Radiation Mode	photons
Machine	Generic
IsoCenter in [mm]	250.7 236.3 162.7
# Fractions	30
Type of optimization	const_RBExD

use MC (VMC++) dose calculations
Run Sequencing
Stratification Levels: 7
Run Direct Aperture Optimizat...

	VOI name	VOI type	priority	obj. / const.	penalty	dose	EUD	volume	ro
1	BODY	OAR	3	square overdosing	100	30	NaN	NaN	no
2	Core	OAR	2	square overdosing	300	25	NaN	NaN	no
3	OuterTarget	TARGET	1	square deviation	1000	50	NaN	NaN	no

Type of plot: inten... GoT lateral
Plane: axial
Display option: physicalDose
plot CT, plot contour, plot isolines, plot dose, plot isolines labels, plot iso center

axial plane z = 162.5 [mm]

min 0
max 1.724

Result (i.e. dose)
Window Center: 0.862
Window Width: 1.72
Range: 0 1.724
jet
Dose opacity: 0 1

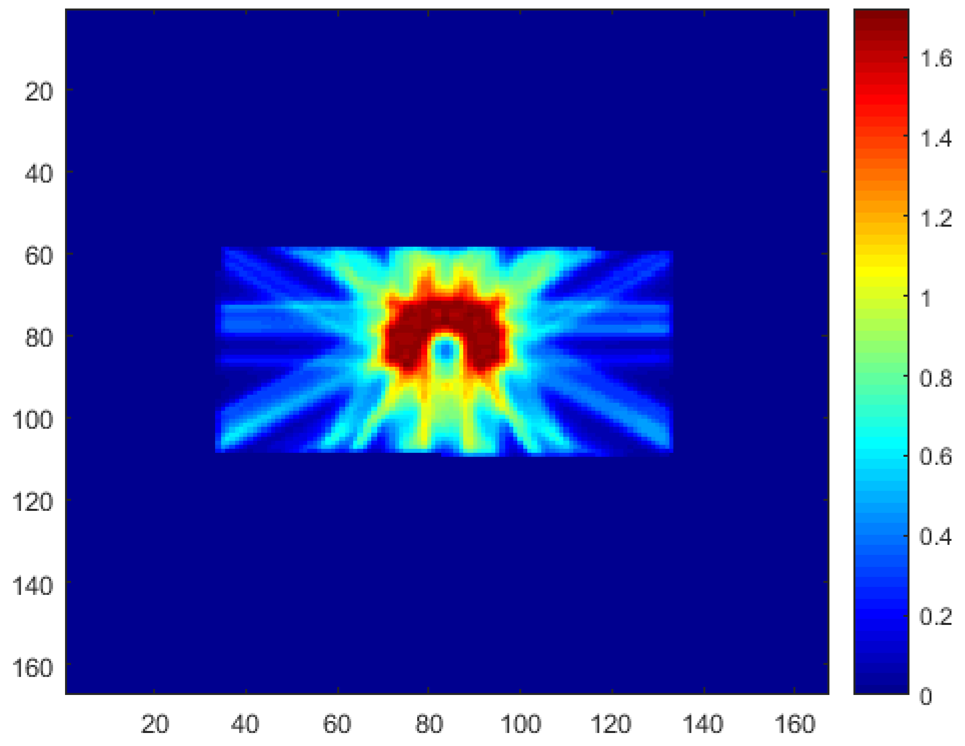
Structure Visibility: ✓ BODY, ✓ Core, ✓ OuterTarget

v2.2.0
github.com/e0404/mat

Plot the Resulting Dose Slice

Let's plot the transversal iso-center dose slice

```
slice = round(pln.isoCenter(1,3)./ct.resolution.z);
figure
imagesc(resultGUI.physicalDose(:,:,slice)),colorbar, colormap(jet)
```



Now let's create another treatment plan but this time use a coarser beam spacing.

Instead of 30 degree spacing use a 50 degree geantry beam spacing

```
pln.gantryAngles = [0:50:359];
pln.couchAngles  = zeros(1,numel(pln.gantryAngles));
pln.numOfBeams   = numel(pln.gantryAngles);
stf              = matRad_generateStf(ct,cst,pln);
pln.isoCenter    = stf.isoCenter;
dij              = matRad_calcPhotonDose(ct,stf,pln,cst);
resultGUI_coarse = matRad_fluenceOptimization(dij,cst,pln);
```

```
matRad: Generating stf struct... Progress: 100.00 %
matRad: Photon dose calculation...
Beam 1 of 8:
matRad: calculate radiological depth cube...done
                   SSD = 939mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 939 mm ...
Progress: 100.00 %
Beam 2 of 8:
matRad: calculate radiological depth cube...done
                   SSD = 905mm
```

```
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 905 mm ...
Progress: 100.00 %
Beam 3 of 8:
matRad: calculate radiological depth cube...done
                   SSD = 848mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 848 mm ...
Progress: 100.00 %
Beam 4 of 8:
matRad: calculate radiological depth cube...done
                   SSD = 894mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 894 mm ...
Progress: 100.00 %
Beam 5 of 8:
matRad: calculate radiological depth cube...done
                   SSD = 905mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 905 mm ...
Progress: 100.00 %
Beam 6 of 8:
matRad: calculate radiological depth cube...done
                   SSD = 840mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 840 mm ...
Progress: 100.00 %
Beam 7 of 8:
matRad: calculate radiological depth cube...done
                   SSD = 878mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 878 mm ...
Progress: 100.00 %
Beam 8 of 8:
matRad: calculate radiological depth cube...done
                   SSD = 938mm
matRad: Uniform primary photon fluence -> pre-compute kernel
 convolution for SSD = 938 mm ...
Progress: 100.00 %

******************************************************************************
This program contains Ipopt, a library for large-scale nonlinear
 optimization.
 Ipopt is released as open source code under the Eclipse Public
 License (EPL).
         For more information visit http://projects.coin-or.org/Ipopt
******************************************************************************

This is Ipopt version 3.11.8, running with linear solver ma57.

Number of nonzeros in equality constraint Jacobian...:        0
Number of nonzeros in inequality constraint Jacobian.:        0
Number of nonzeros in Lagrangian Hessian.............:        0
```

```
Total number of variables............................:     2207
                     variables with only lower bounds:     2207
                variables with lower and upper bounds:        0
                     variables with only upper bounds:        0
Total number of equality constraints.................:        0
Total number of inequality constraints...............:        0
        inequality constraints with only lower bounds:        0
   inequality constraints with lower and upper bounds:        0
        inequality constraints with only upper bounds:        0

iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
   0 1.6835152e+002 0.00e+000 5.54e+000   0.0 0.00e+000    -  0.00e
+000 0.00e+000   0
   1 9.0229894e+001 0.00e+000 5.64e+000  -0.3 1.03e+000    -
 9.77e-001 2.67e-001f  1
   2 7.2225245e+001 0.00e+000 4.15e+000  -6.6 1.45e-001    -  1.00e
+000 1.00e+000f  1
   3 1.5886846e+001 0.00e+000 2.49e+000  -1.6 6.87e-002    -
 9.99e-001 1.00e+000f  1
   4 1.2711254e+001 0.00e+000 6.60e-001  -1.7 2.21e-002    -
 9.28e-001 1.00e+000f  1
   5 7.5346485e+000 0.00e+000 4.25e-001  -2.0 5.31e-002    -
 9.98e-001 1.00e+000f  1
   6 4.3820387e+000 0.00e+000 3.54e-001  -2.8 6.10e-002    -  1.00e
+000 1.00e+000f  1
   7 3.2914364e+000 0.00e+000 5.76e-001  -3.4 8.20e-002    -  1.00e
+000 1.00e+000f  1
   8 2.3991188e+000 0.00e+000 1.84e-001  -3.8 2.75e-002    -  1.00e
+000 8.41e-001f  1
   9 2.2613266e+000 0.00e+000 1.46e-001  -4.8 9.15e-003    -  1.00e
+000 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  10 2.1628239e+000 0.00e+000 1.46e-001  -5.8 2.27e-002    -  1.00e
+000 3.33e-001f  1
  11 2.0423020e+000 0.00e+000 1.37e-001  -4.6 4.60e-002    -  1.00e
+000 2.25e-001f  1
  12 1.9278596e+000 0.00e+000 5.51e-001  -4.0 5.47e-002    -  1.00e
+000 1.98e-001f  1
  13 1.8476477e+000 0.00e+000 8.75e-001  -2.9 1.32e-001    -
 6.38e-001 1.00e+000f  1
  14 1.7538306e+000 0.00e+000 1.58e-001  -4.2 2.31e-002    -
 9.90e-001 1.00e+000f  1
  15 1.6968139e+000 0.00e+000 7.91e-002  -4.4 3.37e-002    -  1.00e
+000 1.00e+000f  1
  16 1.6593228e+000 0.00e+000 5.78e-002  -5.7 3.13e-002    -  1.00e
+000 6.94e-001f  1
  17 1.6351462e+000 0.00e+000 1.14e-001  -6.2 2.83e-002    -  1.00e
+000 2.83e-001f  1
  18 1.6021937e+000 0.00e+000 9.55e-002  -7.1 4.55e-002    -  1.00e
+000 2.10e-001f  1
  19 1.5710715e+000 0.00e+000 5.16e-002  -7.4 3.70e-002    -  1.00e
+000 1.75e-001f  1
```

```
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  20 1.5499955e+000 0.00e+000 2.04e-001  -4.2 5.32e-002    -
 9.31e-001 9.40e-002f  1
  21 1.4927035e+000 0.00e+000 4.58e-001  -3.7 9.24e-002    -
 8.51e-001 3.20e-001f  1
  22 1.5233347e+000 0.00e+000 4.25e-001  -3.3 7.05e-002    -
 8.15e-001 1.00e+000f  1
  23 1.4751530e+000 0.00e+000 1.02e-001  -3.3 1.23e-002    -  1.00e
+000 1.00e+000f  1
  24 1.4515605e+000 0.00e+000 9.01e-002  -4.0 1.94e-002    -
 9.99e-001 1.00e+000f  1
  25 1.4320297e+000 0.00e+000 1.03e-001  -5.3 2.17e-002    -  1.00e
+000 6.07e-001f  1
  26 1.4112400e+000 0.00e+000 6.73e-002  -5.8 2.85e-002    -  1.00e
+000 3.49e-001f  1
  27 1.4043540e+000 0.00e+000 1.38e-001  -5.2 1.59e-002    -
 7.77e-001 1.71e-001f  1
  28 1.3872250e+000 0.00e+000 5.48e-002  -5.6 3.60e-002    -  1.00e
+000 2.05e-001f  1
  29 1.3571939e+000 0.00e+000 9.36e-002  -5.2 5.12e-002    -  1.00e
+000 3.43e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  30 1.3490060e+000 0.00e+000 7.56e-002  -4.4 3.66e-002    -  1.00e
+000 1.51e-001f  1
  31 1.3307865e+000 0.00e+000 6.89e-002  -4.0 3.94e-002    -
 7.81e-001 4.97e-001f  1
  32 1.3193885e+000 0.00e+000 2.22e-001  -3.8 1.21e-002    -
 8.77e-001 1.00e+000f  1
  33 1.3126632e+000 0.00e+000 1.27e-001  -9.8 1.36e-002    -
 7.87e-001 3.78e-001f  1
  34 1.2993745e+000 0.00e+000 1.22e-001  -4.7 2.45e-002    -
 7.16e-001 4.56e-001f  1
  35 1.2922290e+000 0.00e+000 1.23e-001  -5.4 2.75e-002    -
 7.82e-001 2.03e-001f  1
  36 1.2803522e+000 0.00e+000 7.92e-002 -11.0 4.21e-002    -
 3.33e-001 2.09e-001f  1
  37 1.2674119e+000 0.00e+000 9.50e-002  -5.5 6.16e-002    -
 8.71e-001 1.64e-001f  1
  38 1.2622395e+000 0.00e+000 9.00e-002  -5.1 3.41e-002    -
 6.76e-001 1.17e-001f  1
  39 1.2463301e+000 0.00e+000 7.60e-002  -4.9 4.27e-002    -
 7.32e-001 2.61e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  40 1.2400471e+000 0.00e+000 1.31e-001  -4.3 1.40e-002    -
 6.61e-001 2.50e-001f  1
  41 1.2325859e+000 0.00e+000 1.16e-001  -4.2 1.88e-002    -
 4.38e-001 2.61e-001f  1
  42 1.2276620e+000 0.00e+000 1.02e-001 -10.3 2.19e-002    -
 5.80e-001 1.47e-001f  1
  43 1.2139467e+000 0.00e+000 1.05e-001  -5.2 3.63e-002    -  1.00e
+000 2.69e-001f  1
```

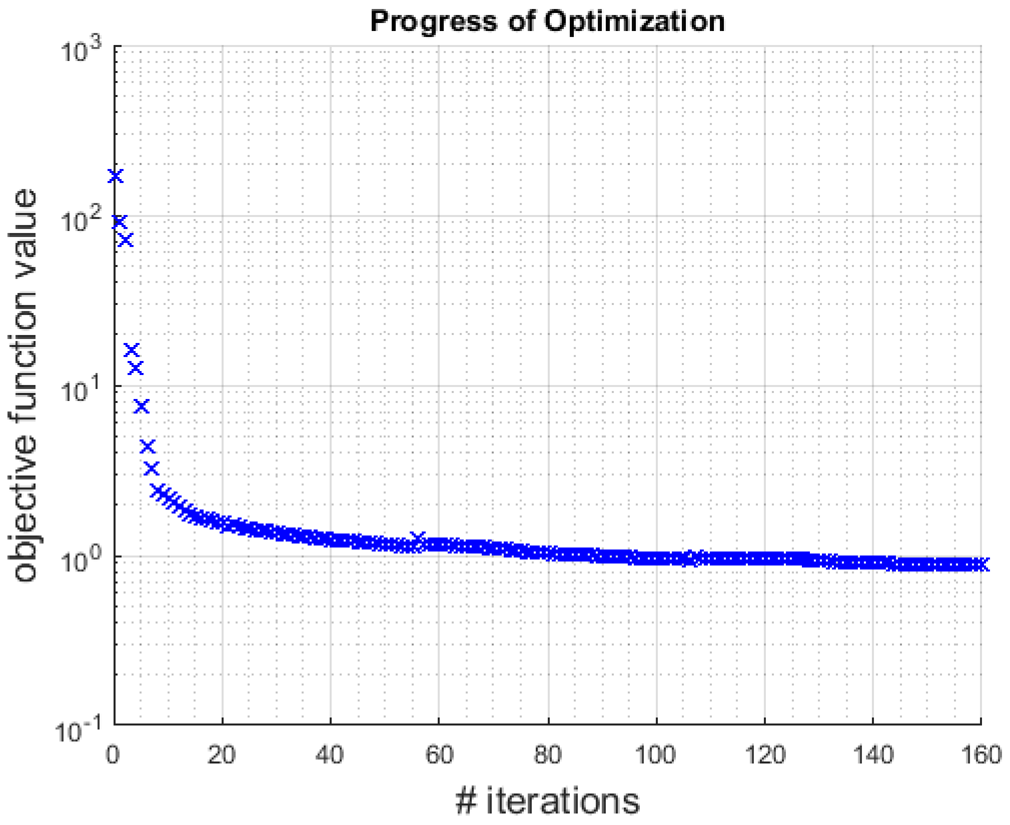
```
  44 1.2092307e+000 0.00e+000 2.04e-001  -5.7 2.76e-002    -
 7.76e-001 1.18e-001f  1
  45 1.2025930e+000 0.00e+000 1.27e-001  -6.7 2.58e-002    -
 6.64e-001 1.64e-001f  1
  46 1.1918803e+000 0.00e+000 1.49e-001  -5.4 3.25e-002    -  1.00e
+000 2.49e-001f  1
  47 1.1811352e+000 0.00e+000 3.80e-002  -4.5 3.64e-002    -  1.00e
+000 2.92e-001f  1
  48 1.1765723e+000 0.00e+000 8.13e-002  -4.8 2.33e-002    -
 8.55e-001 2.03e-001f  1
  49 1.1704586e+000 0.00e+000 6.06e-002  -5.4 3.19e-002    -  1.00e
+000 2.01e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  50 1.1597742e+000 0.00e+000 2.92e-002  -4.6 3.54e-002    -
 4.98e-001 4.10e-001f  1
  51 1.1565150e+000 0.00e+000 1.99e-001  -4.2 1.10e-002    -  1.00e
+000 4.55e-001f  1
  52 1.1532504e+000 0.00e+000 8.96e-002  -6.3 1.78e-002    -
 5.69e-001 1.64e-001f  1
  53 1.1398902e+000 0.00e+000 4.16e-002  -4.8 3.75e-002    -
 5.61e-001 3.97e-001f  1
  54 1.1308042e+000 0.00e+000 2.79e-002  -4.3 3.85e-002    -
 8.22e-001 3.60e-001f  1
  55 1.1223989e+000 0.00e+000 1.25e-001  -4.7 2.04e-002    -
 7.23e-001 5.16e-001f  1
  56 1.2717907e+000 0.00e+000 1.59e-001  -3.4 1.47e-001    -  1.00e
+000 1.00e+000f  1
  57 1.1685623e+000 0.00e+000 9.65e-002  -3.4 4.54e-002    -  1.00e
+000 1.00e+000f  1
  58 1.1578186e+000 0.00e+000 7.16e-002  -3.4 1.25e-002    -  1.00e
+000 1.00e+000f  1
  59 1.1514750e+000 0.00e+000 3.91e-002  -3.4 8.81e-003    -  1.00e
+000 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  60 1.1495486e+000 0.00e+000 6.27e-002  -3.4 1.05e-002    -  1.00e
+000 1.00e+000f  1
  61 1.1480513e+000 0.00e+000 3.68e-002  -3.4 1.09e-002    -  1.00e
+000 1.00e+000f  1
  62 1.1467486e+000 0.00e+000 2.48e-002  -3.4 5.57e-003    -  1.00e
+000 1.00e+000f  1
  63 1.1428323e+000 0.00e+000 4.21e-002  -3.4 1.80e-002    -  1.00e
+000 1.00e+000f  1
  64 1.1390424e+000 0.00e+000 3.00e-002  -3.4 8.28e-003    -  1.00e
+000 1.00e+000f  1
  65 1.1357442e+000 0.00e+000 2.13e-002  -3.4 1.92e-003    -  1.00e
+000 1.00e+000f  1
  66 1.1309438e+000 0.00e+000 1.76e-002  -3.4 5.23e-003    -  1.00e
+000 1.00e+000f  1
  67 1.1269752e+000 0.00e+000 2.58e-002  -3.4 5.71e-003    -  1.00e
+000 1.00e+000f  1
  68 1.1206528e+000 0.00e+000 3.37e-002  -3.4 1.20e-002    -  1.00e
+000 1.00e+000f  1
```

```
  69 1.1120263e+000 0.00e+000 3.22e-002  -4.2 1.07e-002    -  1.00e
+000 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  70 1.1017197e+000 0.00e+000 3.40e-002  -5.6 7.69e-003    -  1.00e
+000 1.00e+000f  1
  71 1.0900689e+000 0.00e+000 2.89e-002  -6.2 1.87e-002    -  1.00e
+000 3.64e-001f  1
  72 1.0848965e+000 0.00e+000 6.03e-002  -6.4 1.52e-002    -  1.00e
+000 1.55e-001f  1
  73 1.0776577e+000 0.00e+000 6.15e-002  -4.0 4.50e-003    -
 9.60e-001 8.37e-001f  1
  74 1.0662697e+000 0.00e+000 1.17e-001  -4.7 1.14e-002    -  1.00e
+000 5.27e-001f  1
  75 1.0570152e+000 0.00e+000 4.08e-002  -5.8 1.34e-002    -  1.00e
+000 4.43e-001f  1
  76 1.0527430e+000 0.00e+000 4.43e-002  -4.1 1.14e-002    -
 9.96e-001 7.81e-001f  1
  77 1.0421556e+000 0.00e+000 1.25e-001  -5.0 1.09e-002    -  1.00e
+000 7.47e-001f  1
  78 1.0396648e+000 0.00e+000 6.81e-002 -10.9 1.23e-002    -
 8.66e-001 1.86e-001f  1
  79 1.0334545e+000 0.00e+000 6.59e-002  -5.2 2.23e-002    -
 7.48e-001 2.97e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  80 1.0283782e+000 0.00e+000 8.19e-002  -5.6 2.35e-002    -
 5.66e-001 2.65e-001f  1
  81 1.0266396e+000 0.00e+000 1.23e-001  -7.3 2.37e-002    -
 8.62e-001 9.36e-002f  1
  82 1.0220485e+000 0.00e+000 9.63e-002  -6.7 3.19e-002    -
 9.03e-001 2.00e-001f  1
  83 1.0177696e+000 0.00e+000 6.27e-002  -7.4 3.55e-002    -  1.00e
+000 1.74e-001f  1
  84 1.0154361e+000 0.00e+000 1.05e-001  -5.4 2.34e-002    -
 7.51e-001 1.51e-001f  1
  85 1.0115662e+000 0.00e+000 4.47e-002  -4.8 3.74e-002    -
 7.93e-001 1.73e-001f  1
  86 1.0097005e+000 0.00e+000 7.91e-002  -7.0 2.66e-002    -
 3.71e-001 1.04e-001f  1
  87 1.0062117e+000 0.00e+000 7.76e-002  -4.4 4.86e-002    -
 6.03e-001 1.32e-001f  1
  88 1.0022194e+000 0.00e+000 6.78e-002  -4.3 3.64e-002    -
 5.30e-001 1.89e-001f  1
  89 9.9783179e-001 0.00e+000 8.94e-002 -10.4 3.03e-002    -
 4.30e-001 2.33e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
  90 9.9526408e-001 0.00e+000 1.80e-001  -5.0 1.93e-002    -
 8.31e-001 2.06e-001f  1
  91 9.9309042e-001 0.00e+000 1.70e-001  -5.5 2.31e-002    -
 6.17e-001 1.32e-001f  1
  92 9.8856582e-001 0.00e+000 8.44e-002  -4.6 2.53e-002    -
 5.15e-001 2.72e-001f  1
```

```
  93 9.8498654e-001 0.00e+000 5.97e-002  -4.9 2.45e-002    -
 4.22e-001 1.95e-001f  1
  94 9.8110315e-001 0.00e+000 4.79e-002 -10.8 3.71e-002    -
 2.77e-001 1.37e-001f  1
  95 9.7828877e-001 0.00e+000 7.91e-002  -4.7 3.19e-002    -
 6.41e-001 1.20e-001f  1
  96 9.7319549e-001 0.00e+000 7.35e-002  -4.8 4.12e-002    -
 4.27e-001 1.74e-001f  1
  97 9.7125917e-001 0.00e+000 7.10e-002 -10.8 4.10e-002    -
 4.44e-001 6.38e-002f  1
  98 9.6717406e-001 0.00e+000 9.47e-002  -5.8 3.02e-002    -
 5.27e-001 1.91e-001f  1
  99 9.6232298e-001 0.00e+000 5.40e-002  -5.2 2.88e-002    -
 6.20e-001 2.69e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 100 9.6117072e-001 0.00e+000 7.34e-002  -5.2 7.63e-003    -
 4.30e-001 1.95e-001f  1
 101 9.5866235e-001 0.00e+000 6.79e-002  -4.4 1.38e-002    -
 6.48e-001 3.40e-001f  1
 102 9.5725853e-001 0.00e+000 5.68e-002  -4.6 7.50e-003    -
 4.70e-001 2.90e-001f  1
 103 9.5563347e-001 0.00e+000 6.05e-002 -10.6 1.12e-002    -
 3.15e-001 1.72e-001f  1
 104 9.5348679e-001 0.00e+000 9.81e-002  -5.0 1.77e-002    -
 8.45e-001 1.64e-001f  1
 105 9.4842063e-001 0.00e+000 6.63e-002  -4.6 1.90e-002    -
 6.27e-001 4.98e-001f  1
 106 9.4617285e-001 0.00e+000 4.40e-002  -5.3 2.20e-002    -
 6.76e-001 1.85e-001f  1
 107 9.9103016e-001 0.00e+000 8.35e-002  -3.8 2.16e-002    -
 8.70e-001 1.00e+000f  1
 108 9.7220512e-001 0.00e+000 3.09e-002  -3.9 1.50e-002    -  1.00e
+000 8.38e-001f  1
 109 9.6632343e-001 0.00e+000 2.12e-001  -3.9 7.15e-003    -  1.00e
+000 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 110 9.6287428e-001 0.00e+000 1.42e-002  -3.9 8.17e-003    -
 9.73e-001 1.00e+000f  1
 111 9.6354708e-001 0.00e+000 2.58e-002  -3.9 8.90e-003    -  1.00e
+000 1.00e+000f  1
 112 9.6275569e-001 0.00e+000 1.57e-002  -3.9 3.30e-003    -  1.00e
+000 1.00e+000f  1
 113 9.6411641e-001 0.00e+000 8.58e-003  -3.9 3.09e-003    -  1.00e
+000 1.00e+000f  1
 114 9.6496170e-001 0.00e+000 9.81e-003  -3.9 2.33e-003    -  1.00e
+000 1.00e+000f  1
 115 9.6544646e-001 0.00e+000 1.34e-002  -3.9 4.57e-003    -  1.00e
+000 1.00e+000f  1
 116 9.6395176e-001 0.00e+000 9.50e-003  -3.9 3.21e-003    -  1.00e
+000 1.00e+000f  1
 117 9.6240002e-001 0.00e+000 9.36e-003  -3.9 2.70e-003    -  1.00e
+000 1.00e+000f  1
```

```
 118 9.6022179e-001 0.00e+000 1.17e-002  -3.9 5.04e-003    -  1.00e
+000 1.00e+000f  1
 119 9.5834308e-001 0.00e+000 1.01e-002  -3.9 6.28e-003    -  1.00e
+000 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 120 9.5692798e-001 0.00e+000 1.02e-002  -3.9 6.15e-003    -  1.00e
+000 1.00e+000f  1
 121 9.5631828e-001 0.00e+000 9.43e-003  -3.9 2.57e-003    -  1.00e
+000 1.00e+000f  1
 122 9.5589146e-001 0.00e+000 9.12e-003  -3.9 2.75e-003    -  1.00e
+000 1.00e+000f  1
 123 9.5460755e-001 0.00e+000 1.25e-002  -3.9 4.73e-003    -  1.00e
+000 1.00e+000f  1
 124 9.5356639e-001 0.00e+000 8.97e-003  -3.9 5.00e-003    -  1.00e
+000 1.00e+000f  1
 125 9.5200129e-001 0.00e+000 7.66e-003  -3.9 4.14e-003    -  1.00e
+000 1.00e+000f  1
 126 9.5026339e-001 0.00e+000 8.59e-003  -3.9 4.80e-003    -  1.00e
+000 1.00e+000f  1
 127 9.4736202e-001 0.00e+000 1.45e-002  -3.9 8.28e-003    -  1.00e
+000 1.00e+000f  1
 128 9.4458164e-001 0.00e+000 1.01e-002  -3.9 8.02e-003    -  1.00e
+000 1.00e+000f  1
 129 9.3746848e-001 0.00e+000 1.60e-002  -4.5 1.96e-002    -  1.00e
+000 1.00e+000f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 130 9.3042564e-001 0.00e+000 1.71e-002  -5.5 3.35e-002    -  1.00e
+000 4.50e-001f  1
 131 9.2861860e-001 0.00e+000 8.88e-002  -6.1 1.48e-002    -  1.00e
+000 1.31e-001f  1
 132 9.2292080e-001 0.00e+000 3.43e-002 -11.0 1.47e-002    -
 5.63e-001 3.58e-001f  1
 133 9.1881489e-001 0.00e+000 2.61e-002  -5.2 1.03e-002    -
 5.53e-001 2.69e-001f  1
 134 9.1625790e-001 0.00e+000 8.07e-002  -5.8 1.20e-002    -  1.00e
+000 1.81e-001f  1
 135 9.1240944e-001 0.00e+000 4.97e-002  -7.6 1.42e-002    -
 4.05e-001 2.51e-001f  1
 136 9.0989065e-001 0.00e+000 3.01e-002  -5.4 1.35e-002    -
 4.33e-001 1.65e-001f  1
 137 9.0875589e-001 0.00e+000 3.23e-002 -11.0 1.14e-002    -
 4.26e-001 9.94e-002f  1
 138 9.0651262e-001 0.00e+000 3.72e-002  -6.3 1.50e-002    -  1.00e
+000 1.65e-001f  1
 139 9.0420033e-001 0.00e+000 2.63e-002  -5.7 1.48e-002    -
 9.29e-001 1.98e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 140 9.0300141e-001 0.00e+000 7.30e-002  -5.8 8.12e-003    -
 9.36e-001 2.08e-001f  1
 141 9.0058145e-001 0.00e+000 5.36e-002  -5.1 1.31e-002    -
 9.96e-001 3.26e-001f  1
 142 8.9954983e-001 0.00e+000 3.09e-002  -5.4 1.42e-002    -
 6.63e-001 1.23e-001f  1
 143 8.9807712e-001 0.00e+000 5.16e-002  -5.6 9.59e-003    -
 7.45e-001 2.63e-001f  1
 144 8.9639926e-001 0.00e+000 4.59e-002  -5.1 1.13e-002    -
 8.20e-001 3.47e-001f  1
 145 8.9499442e-001 0.00e+000 4.16e-002  -5.9 1.16e-002    -
 5.68e-001 2.23e-001f  1
 146 8.9383728e-001 0.00e+000 2.83e-002  -5.1 1.18e-002    -
 6.35e-001 2.34e-001f  1
 147 8.9237924e-001 0.00e+000 3.19e-002  -5.0 1.39e-002    -
 8.53e-001 4.46e-001f  1
 148 8.9159228e-001 0.00e+000 4.37e-002  -5.3 3.47e-003    -
 9.06e-001 3.70e-001f  1
 149 8.9053598e-001 0.00e+000 3.51e-002 -11.0 6.22e-003    -
 4.21e-001 2.63e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 150 8.8968815e-001 0.00e+000 4.40e-002  -6.9 8.64e-003    -
 7.56e-001 1.77e-001f  1
 151 8.8889024e-001 0.00e+000 5.08e-002  -7.1 1.00e-002    -
 9.36e-001 1.58e-001f  1
 152 8.8784494e-001 0.00e+000 5.08e-002  -5.6 8.97e-003    -
 7.42e-001 2.58e-001f  1
 153 8.8938157e-001 0.00e+000 1.26e-001  -4.8 1.86e-002    -
 5.65e-001 9.14e-001f  1
 154 8.8805800e-001 0.00e+000 1.04e-001  -5.0 2.05e-003    -  1.00e
+000 9.84e-001f  1
 155 8.8761731e-001 0.00e+000 5.06e-002  -5.0 3.64e-003    -
 7.33e-001 1.00e+000f  1
 156 8.8708058e-001 0.00e+000 2.76e-002  -5.6 3.26e-003    -
 8.48e-001 2.94e-001f  1
 157 8.8602966e-001 0.00e+000 5.33e-002  -6.1 5.01e-003    -
 8.43e-001 3.43e-001f  1
 158 8.8544657e-001 0.00e+000 5.82e-002  -5.5 4.78e-003    -
 9.74e-001 2.68e-001f  1
 159 8.8471922e-001 0.00e+000 3.82e-002  -6.4 7.62e-003    -
 6.93e-001 2.19e-001f  1
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du
 alpha_pr  ls
 160 8.8393186e-001 0.00e+000 3.39e-002  -6.6 1.34e-002    -
 9.10e-001 1.61e-001f  1

Number of Iterations....: 160

                                   (scaled)                 (unscaled)
Objective...............:  8.8393185574438515e-001
 8.8393185574438515e-001
Dual infeasibility......:  3.3948503162460439e-002
 3.3948503162460439e-002
Constraint violation....:  0.0000000000000000e+000
 0.0000000000000000e+000
Complementarity.........:  7.8777891974112479e-006
 7.8777891974112479e-006
```

```
Overall NLP error.......:  3.3948503162460439e-002
 3.3948503162460439e-002


Number of objective function evaluations             = 161
Number of objective gradient evaluations             = 161
Number of equality constraint evaluations            = 0
Number of inequality constraint evaluations          = 0
Number of equality constraint Jacobian evaluations   = 0
Number of inequality constraint Jacobian evaluations = 0
Number of Lagrangian Hessian evaluations             = 0
Total CPU secs in IPOPT (w/o function evaluations)   =      4.776
Total CPU secs in NLP function evaluations           =     60.473

EXIT: Solved To Acceptable Level.
Calculating final cubes...
```

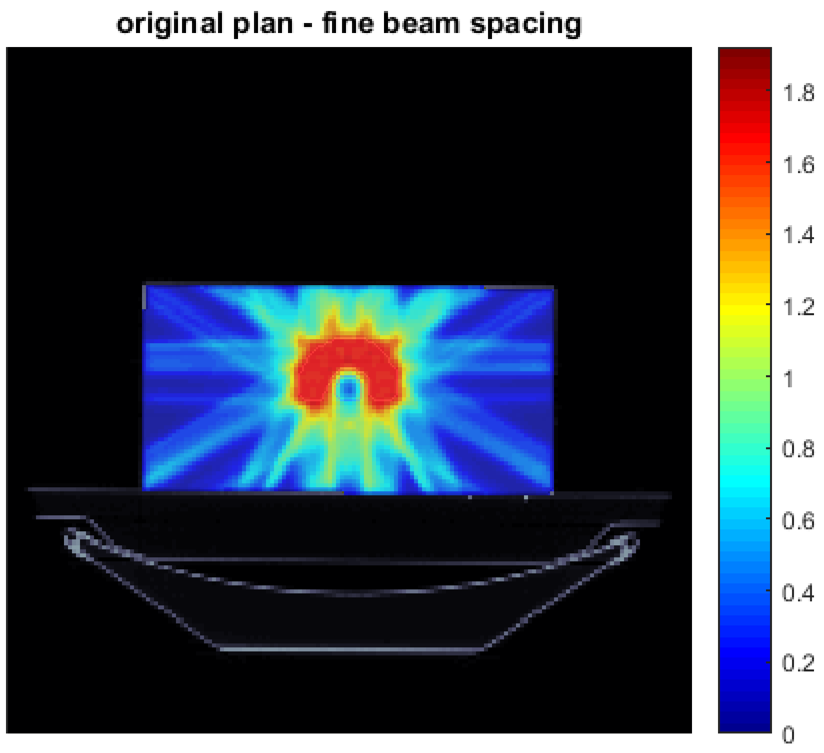


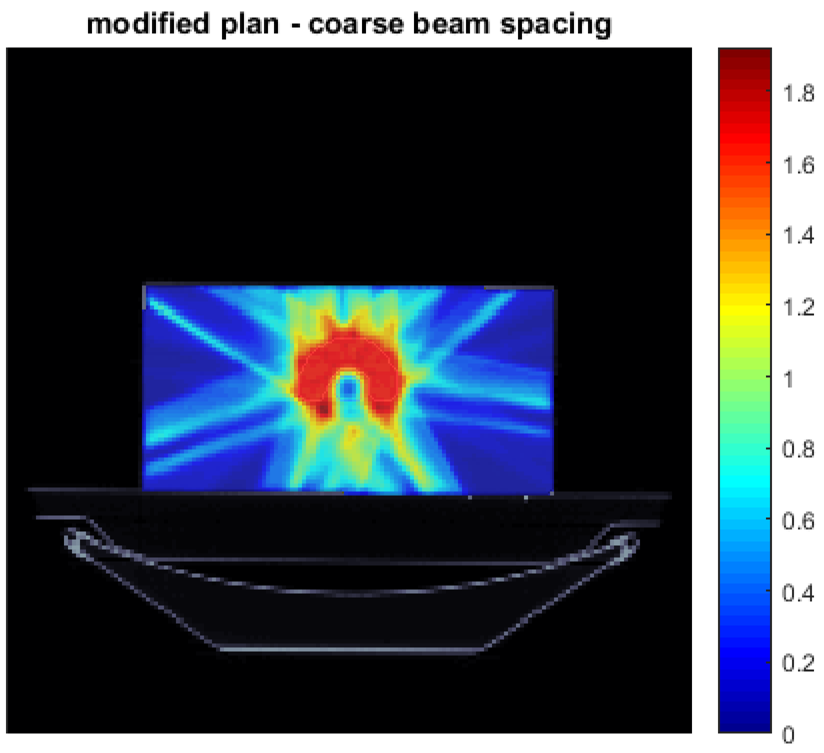
Visual Comparison of results

Let's compare the new recalculation against the optimization result. Check if you have added all SUB-DIRECTORIES to the MATLAB search path, otherwise it will not find the plotting function

```
plane      = 3;
doseWindow = [0 max([resultGUI.physicalDose(:);
 resultGUI_coarse.physicalDose(:)])];
```

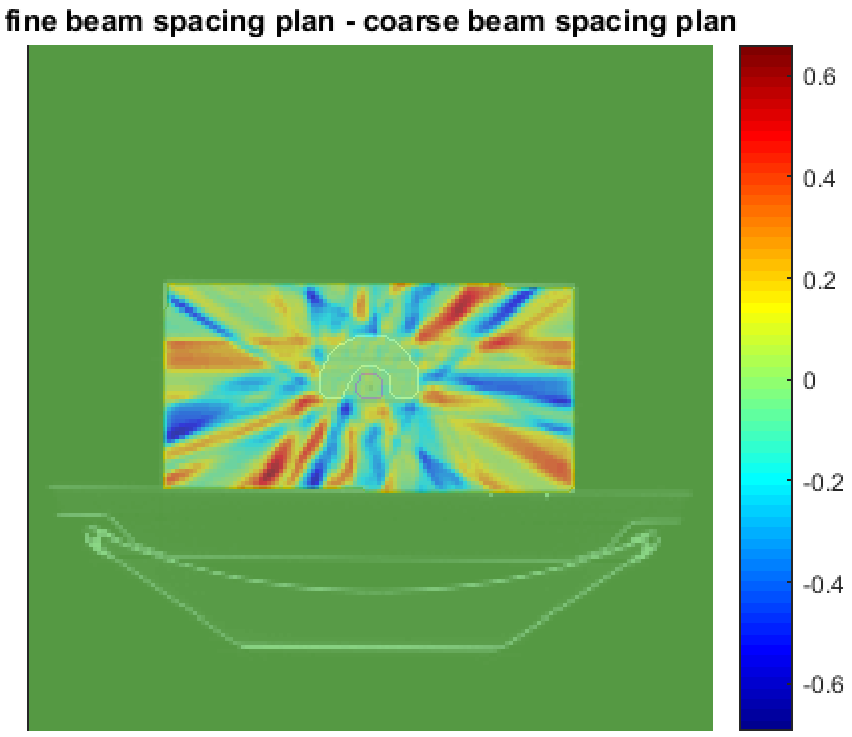
```
figure,title('original plan - fine beam spacing')
[~,~,~,~,~] =
 matRad_plotSliceWrapper(gca,ct,cst,1,resultGUI.physicalDose,plane,slice,
[],0.75,colorcube,[],doseWindow,[]);
figure,title('modified plan - coarse beam spacing')
[~,~,~,~,~] =
 matRad_plotSliceWrapper(gca,ct,cst,1,resultGUI_coarse.physicalDose,plane,slice,
[],0.75,colorcube,[],doseWindow,[]);
```





At this point we would like to see the absolute difference of the first optimization (finer beam spacing) and the second optimization (coarser beam spacing)

```
absDiffCube = resultGUI.physicalDose-resultGUI_coarse.physicalDose;
figure,title( 'fine beam spacing plan - coarse beam spacing plan')
[~,~,~,~,~] =
 matRad_plotSliceWrapper(gca,ct,cst,1,absDiffCube,plane,slice,[],
[],colorcube);
```



Obtain dose statistics

Two more columns will be added to the cst structure depicting the DVH and standard dose statistics such as D95,D98, mean dose, max dose etc.

```
cst        = matRad_indicatorWrapper(cst,pln,resultGUI);
cst_coarse = matRad_indicatorWrapper(cst,pln,resultGUI_coarse);
```

```
 0                  BODY - Mean dose =  0.17 Gy +/-  0.33 Gy (Max dose
 =  1.72 Gy, Min dose =  0.00 Gy)
                          D2% =  1.39 Gy, D5% =  0.90 Gy, D98% =
 0.00 Gy, D95% =  0.00 Gy,
                          V0Gy = 100.00%, V0.345Gy =  17.58%, V0.69Gy
 =   8.17%, V1.03Gy =   3.69%, V1.38Gy =   2.03%, V1.72Gy =   0.00%,

 1                  Core - Mean dose =  0.59 Gy +/-  0.18 Gy (Max dose
 =  0.91 Gy, Min dose =  0.17 Gy)
                          D2% =  0.91 Gy, D5% =  0.86 Gy, D98% =
 0.21 Gy, D95% =  0.29 Gy,
                          V0Gy = 100.00%, V0.345Gy =  91.95%, V0.69Gy
 =  33.28%, V1.03Gy =   0.00%, V1.38Gy =   0.00%, V1.72Gy =   0.00%,

 2           OuterTarget - Mean dose =  1.67 Gy +/-  0.02 Gy (Max dose
 =  1.72 Gy, Min dose =  1.57 Gy)
                          D2% =  1.70 Gy, D5% =  1.69 Gy, D98% =
 1.60 Gy, D95% =  1.63 Gy,
                          V0Gy = 100.00%, V0.345Gy = 100.00%, V0.69Gy
= 100.00%, V1.03Gy = 100.00%, V1.38Gy = 100.00%, V1.72Gy =   0.01%,
                          CI = 0.8581, HI =  3.44 for reference dose
of 1.7 Gy

 0                BODY - Mean dose =  0.17 Gy +/-  0.34 Gy (Max dose
=  1.92 Gy, Min dose =  0.00 Gy)
                          D2% =  1.45 Gy, D5% =  0.94 Gy, D98% =
0.00 Gy, D95% =  0.00 Gy,
                          V0Gy = 100.00%, V0.385Gy =  16.17%,
V0.769Gy =   6.85%, V1.15Gy =   3.19%, V1.54Gy =   1.73%, V1.92Gy =
0.00%,

 1                Core - Mean dose =  0.60 Gy +/-  0.17 Gy (Max dose
=  0.90 Gy, Min dose =  0.21 Gy)
                          D2% =  0.89 Gy, D5% =  0.87 Gy, D98% =
0.24 Gy, D95% =  0.36 Gy,
                          V0Gy = 100.00%, V0.385Gy =  90.55%,
V0.769Gy =  20.31%, V1.15Gy =   0.00%, V1.54Gy =   0.00%, V1.92Gy =
0.00%,

 2         OuterTarget - Mean dose =  1.66 Gy +/-  0.02 Gy (Max dose
=  1.72 Gy, Min dose =  1.54 Gy)
                          D2% =  1.70 Gy, D5% =  1.70 Gy, D98% =
1.61 Gy, D95% =  1.63 Gy,
                          V0Gy = 100.00%, V0.385Gy = 100.00%,
V0.769Gy = 100.00%, V1.15Gy = 100.00%, V1.54Gy = 100.00%, V1.92Gy =
0.00%,
                          CI = 0.7568, HI =  3.76 for reference dose
of 1.7 Gy
```

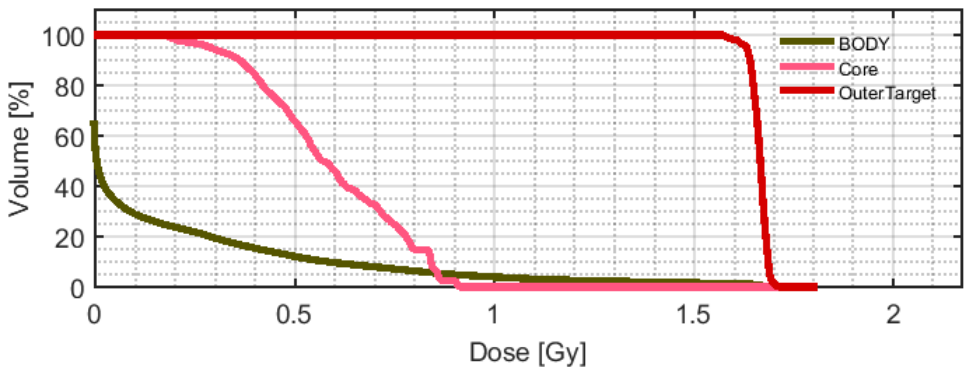
The treatment plan using more beams should in principle result in a better OAR sparing. Therefore lets have a look at the D95 of the OAR of both plans

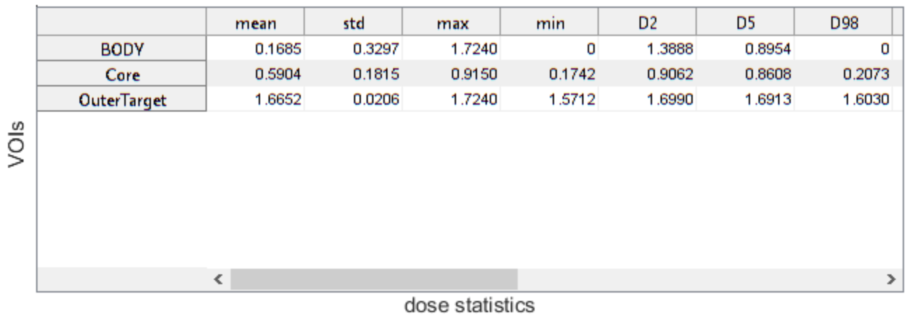
```
ixOAR = 2;
cst{ixOAR,9}{1}.D95
cst_coarse{ixOAR,9}{1}.D95
```

```
ans =

    0.2926


ans =

    0.3610
```

Indeed, the coarse beam plan yields a higher D95 in the OAR. Finally, lets plot the DVH

```
matRad_showDVH(cst,pln)
```





	mean	std	max	min	D2	D5	D98
BODY	0.1685	0.3297	1.7240	0	1.3888	0.8954	0
Core	0.5904	0.1815	0.9150	0.1742	0.9062	0.8608	0.2073
OuterTarget	1.6652	0.0206	1.7240	1.5712	1.6990	1.6913	1.6030

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