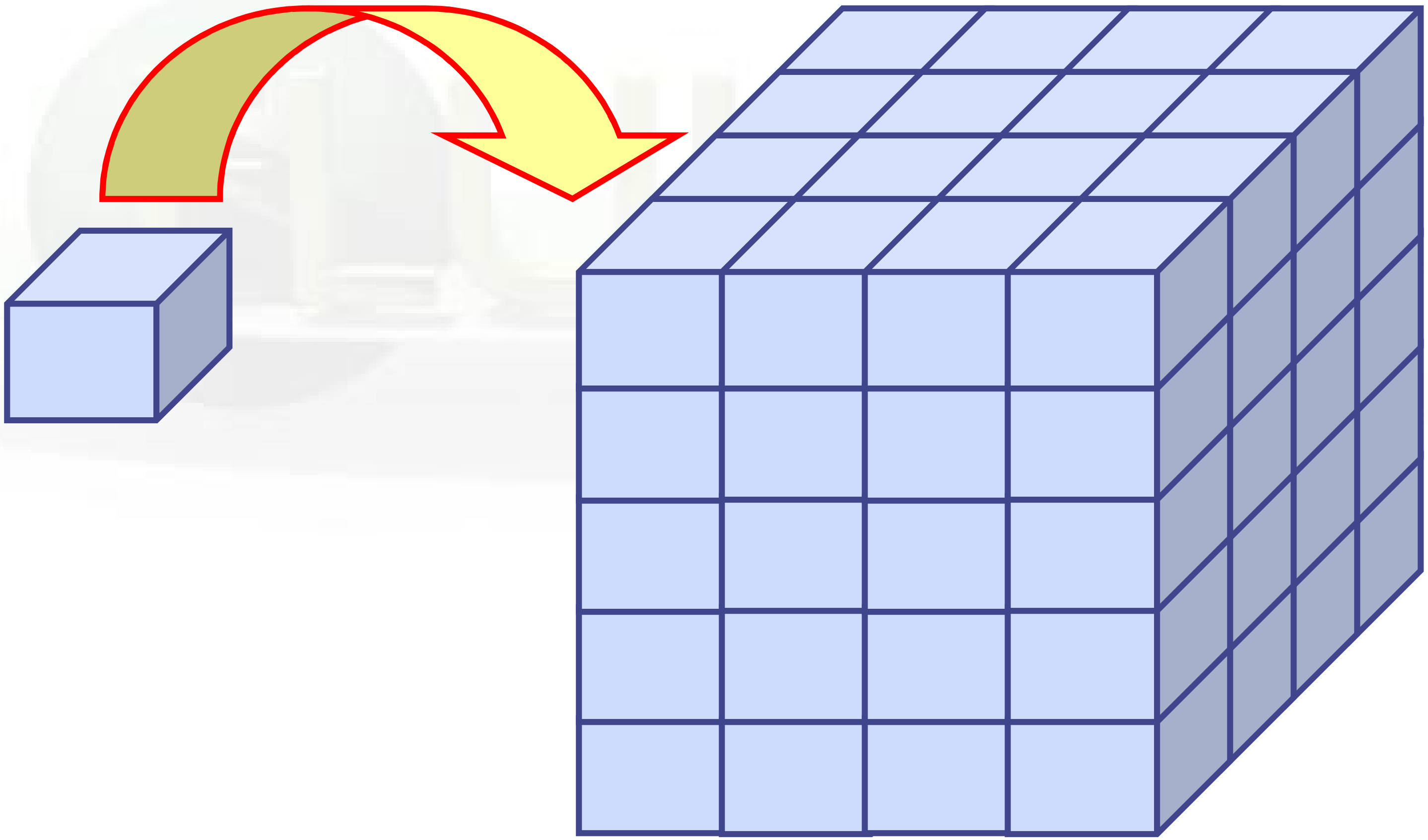
Voxels and Medical Applications

FLUKA Beginners course

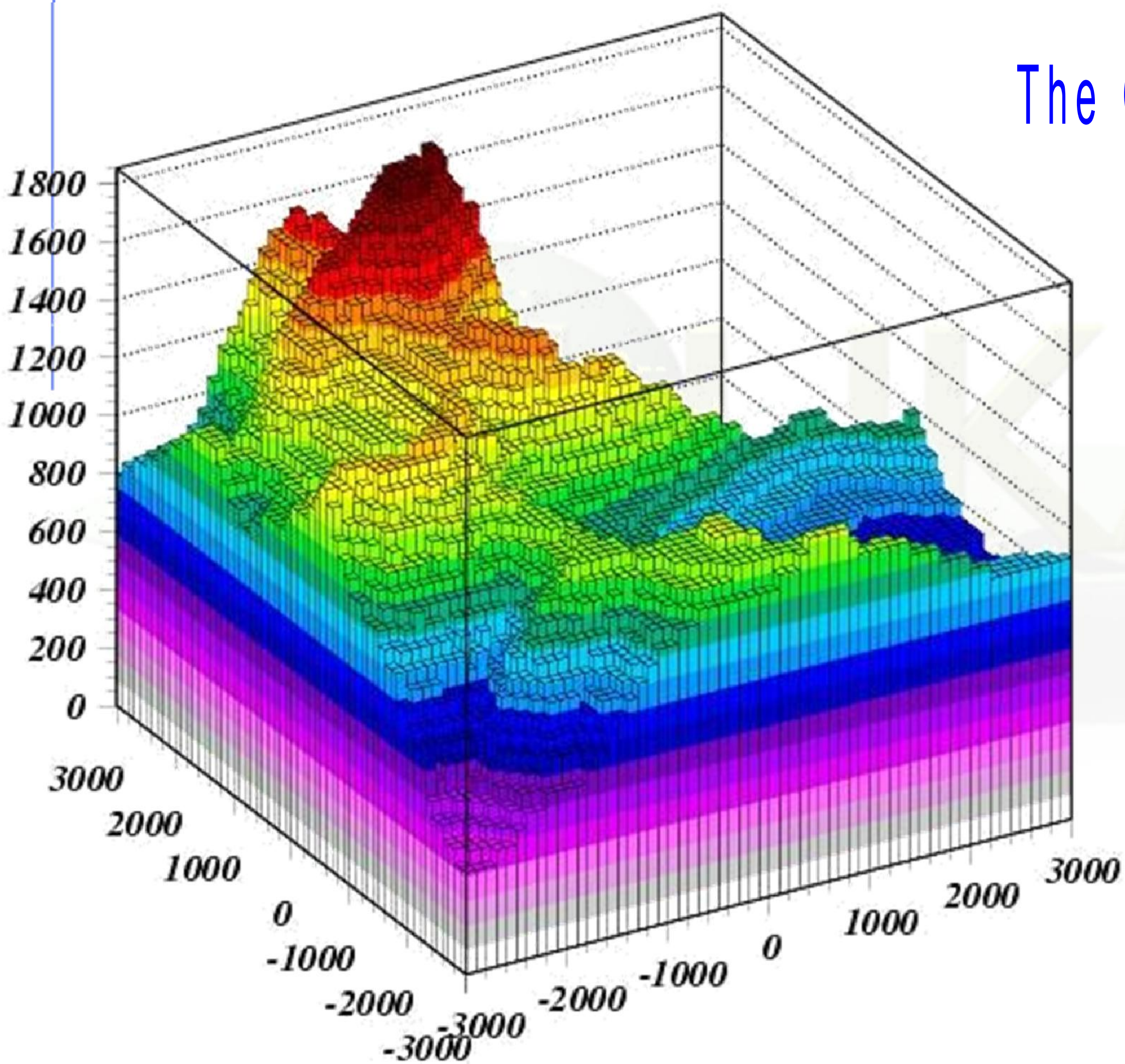
The FLUKA voxel geometry

- It is possible to describe a geometry in terms of "voxels", i.e., tiny parallelepipeds (all of equal size) forming a 3-dimensional grid



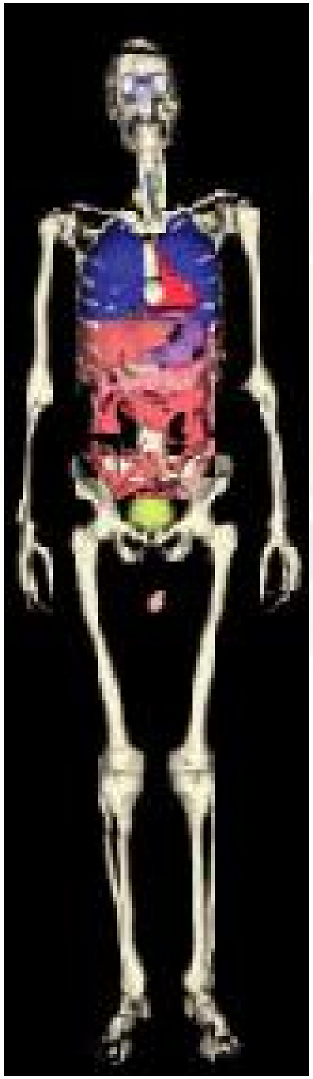
Voxel geometries: examples

The Gran Sasso in FLUKA



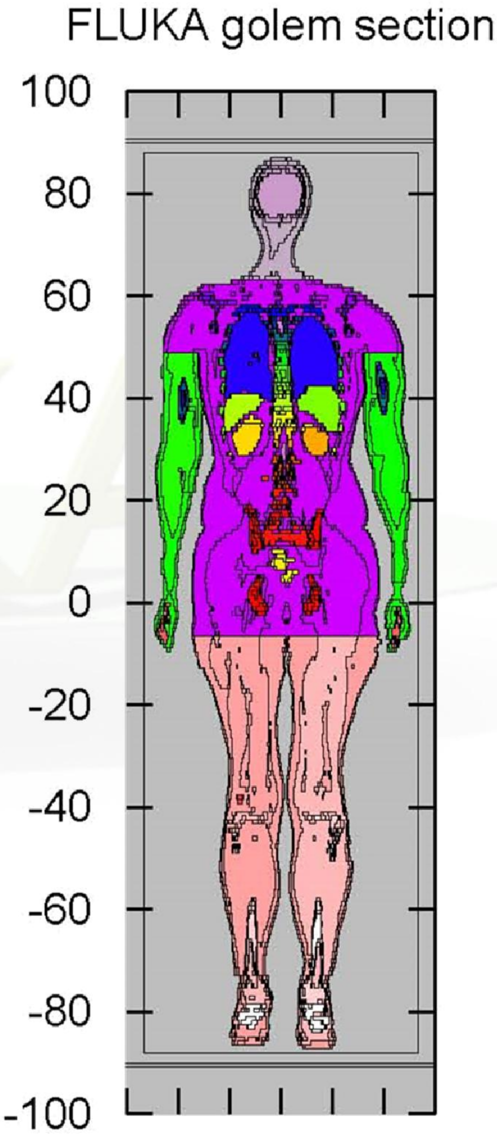
Voxel geometries: examples

The anthropomorphic
GOLEM phantom



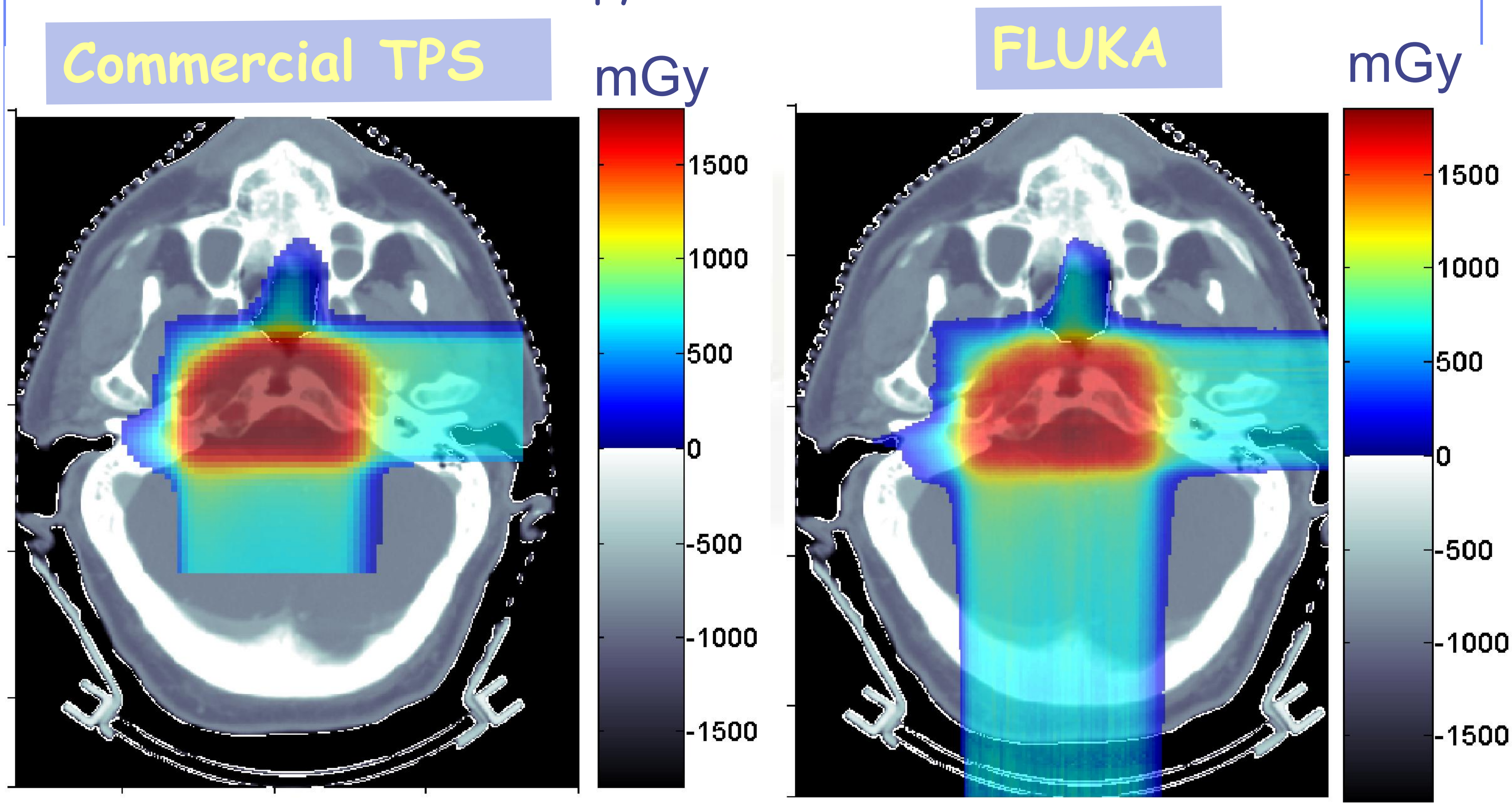
Implementation in FLUKA (radioprotection applications)

Petoussi-Henss
et al, 2002



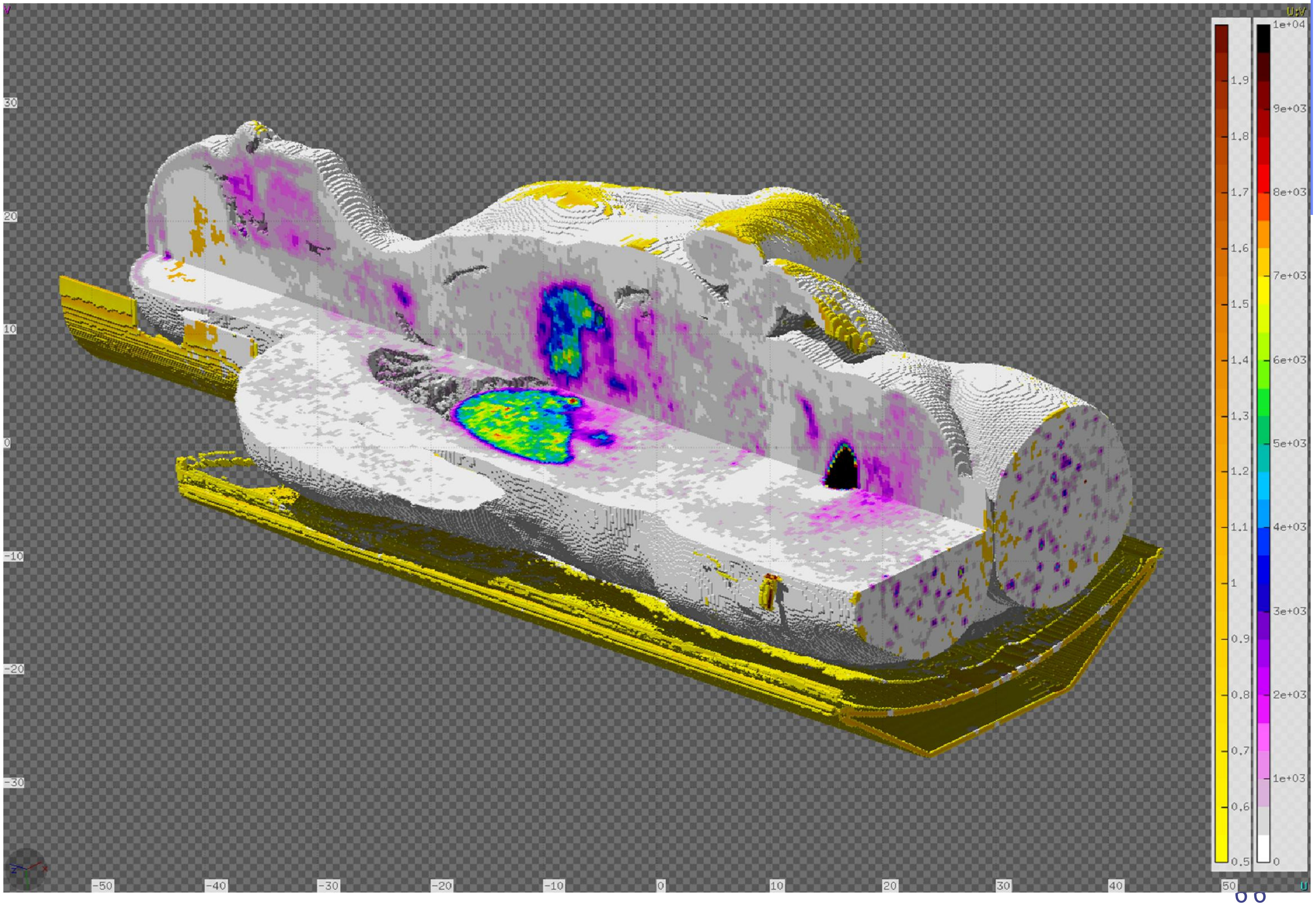
Voxel geometries in medical applications

- Voxel geometries are especially useful to import CT scan of a human body, e.g., for dosimetric calculations of the planned treatment in radiotherapy



Parodi et al., 2007

Voxel geometry with PET-CT



The FLUKA voxel geometry

- The CT scan contains integer values "Hounsfield Unit" reflecting the X-ray attenuation coefficient μ_x

  $HU_x = 1000\ (\mu_x - \mu_{H20})\ /\ \mu_{H20}$,   typically $-1000 \leq HU \leq 3500$

- We will use loosely the word "organ" to indicate a group of voxels (or even more than one group) made of the same "tissue" material (same HU value or in a given HU interval)
- The code handles each organ as a CG region, possibly in addition to other conventional "non-voxel" regions defined by the user
- The voxel structure can be complemented by parts written in the standard Combinatorial geometry
- The code assumes that the voxel structure is contained in a parallelepiped. This **RPP** is automatically generated from the voxel information.
- In the past conversion programs customized by the user were needed, **recently** for medical applications **FLAIR** takes care of the conversion.

The FLUKA voxel geometry

- To describe a voxel geometry, the user must **convert** his **CT** scan or equivalent data to a format understood by FLUKA. Starting from DICOM images, this is performed directly by FLAIR.
- This stage should :
  - Assign an organ index to each voxel. In many practical cases, the user will have a continuum of HU (CT values), and may have to group these values in intervals.
  - Each organ is identified by a unique integer ≤32767. The organ numbering does not need to be contiguous i.e. “holes” in the numbering sequence are allowed.
  - One of the organs must have number **0** and plays the role of the medium surrounding the voxels (usually vacuum or air).
  - The user assigns to each NONZERO organ a voxel-region number. The voxel-region numbering has to be contiguous and starts from 1.

The FLUKA voxel geometry

- The information is input to FLUKA through a special file *.vxl containing:
  - The number of voxels in each coordinate axis
  - The voxel dimension in each coordinate axis
  - The number of voxel-regions, and the maximum organ number
  - A list of the organ corresponding to each voxel
  - A list of the voxel-region number corresponding to each organ

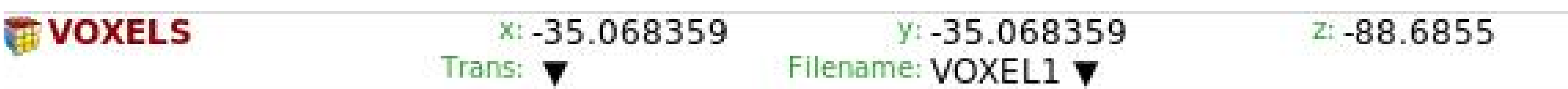
Input file

Prepare the usual FLUKA input file.

The geometry is written like a normal Combinatorial Geometry input, but in addition a VOXELS card must be inserted right after the GEOBEGIN card and before the Geometry title card

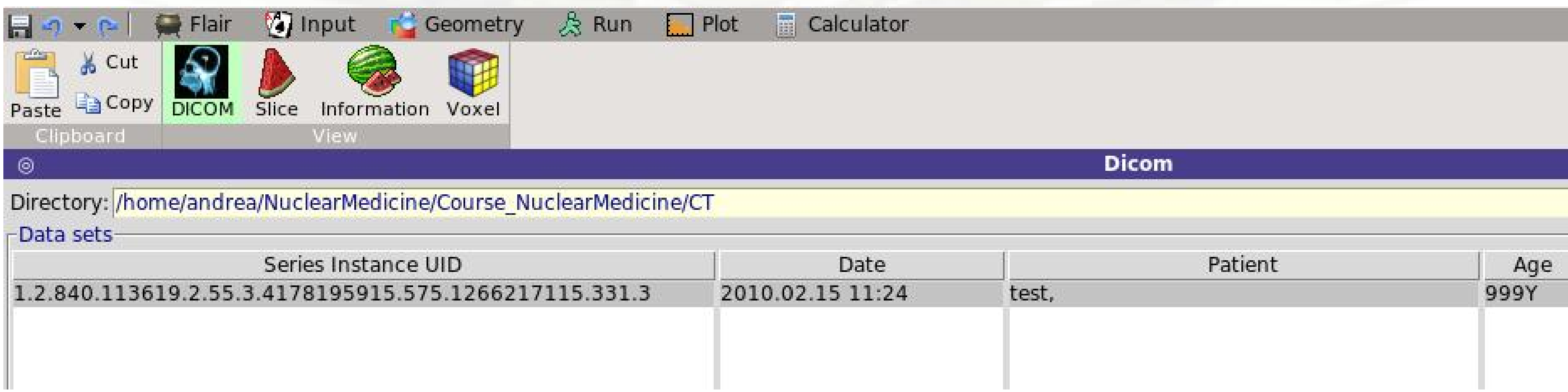
- WHAT(1), WHAT(2), WHAT(3) = x, y, z coordinates chosen as the origin of the “voxel volume”, (i.e. of a region made of a single RPP body extending from WHAT(1) to WHAT(1) + NX*DX, …) which contains all the voxels
- WHAT(4) ROT-DEFI transformation applied to whole voxel RPP
- WHAT(5), WHAT(6): not used
- SDUM = name of the voxel file

  extension will be assumed to be .vxl)



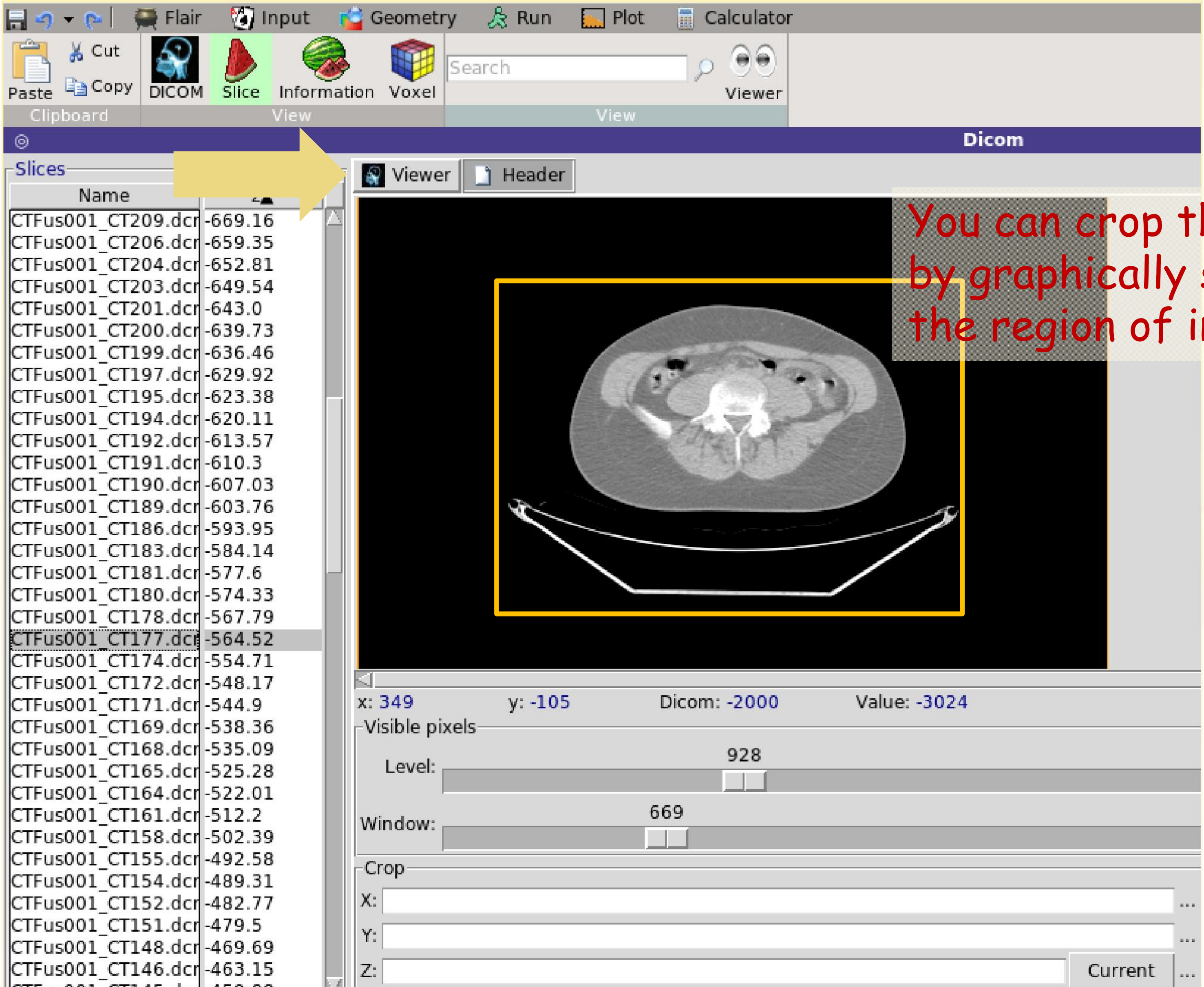
Processing the **DICOM** files with FLAIR I

- DICOM = Digital Imaging and Communications in Medicine is a medical standard for distributing any kind of medical image.
- FLAIR has a capability to process the DICOM files using the pydicom module and convert them to FLUKA VOXELS or USRBIN compatible files.
- First select the "Directory" where the DICOM data sets are located (if you have doubts press F1 and the flair manual will help you).



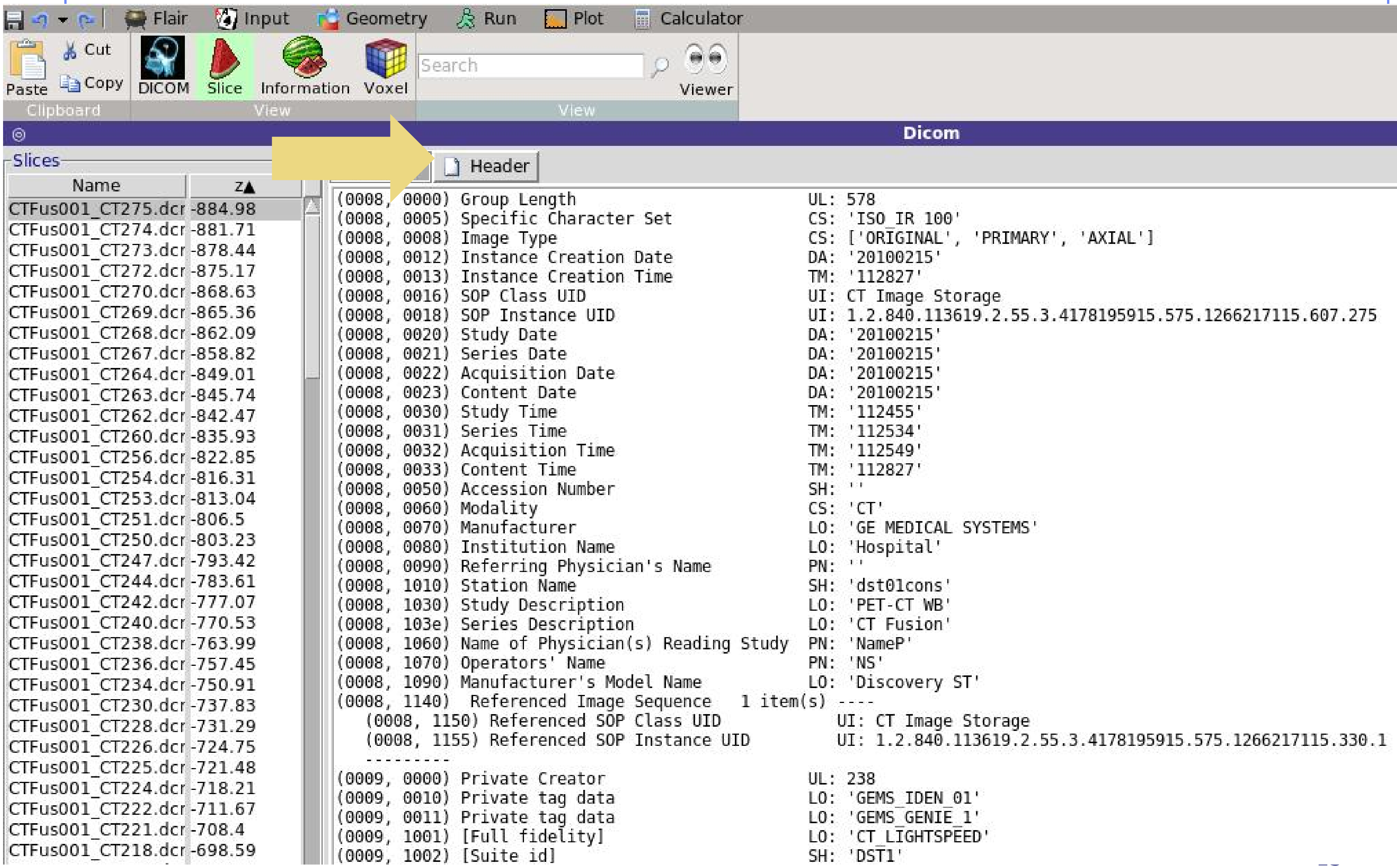
- Select one "Data sets" and inspect the images.

Processing the **DICOM** files with FLAIR II

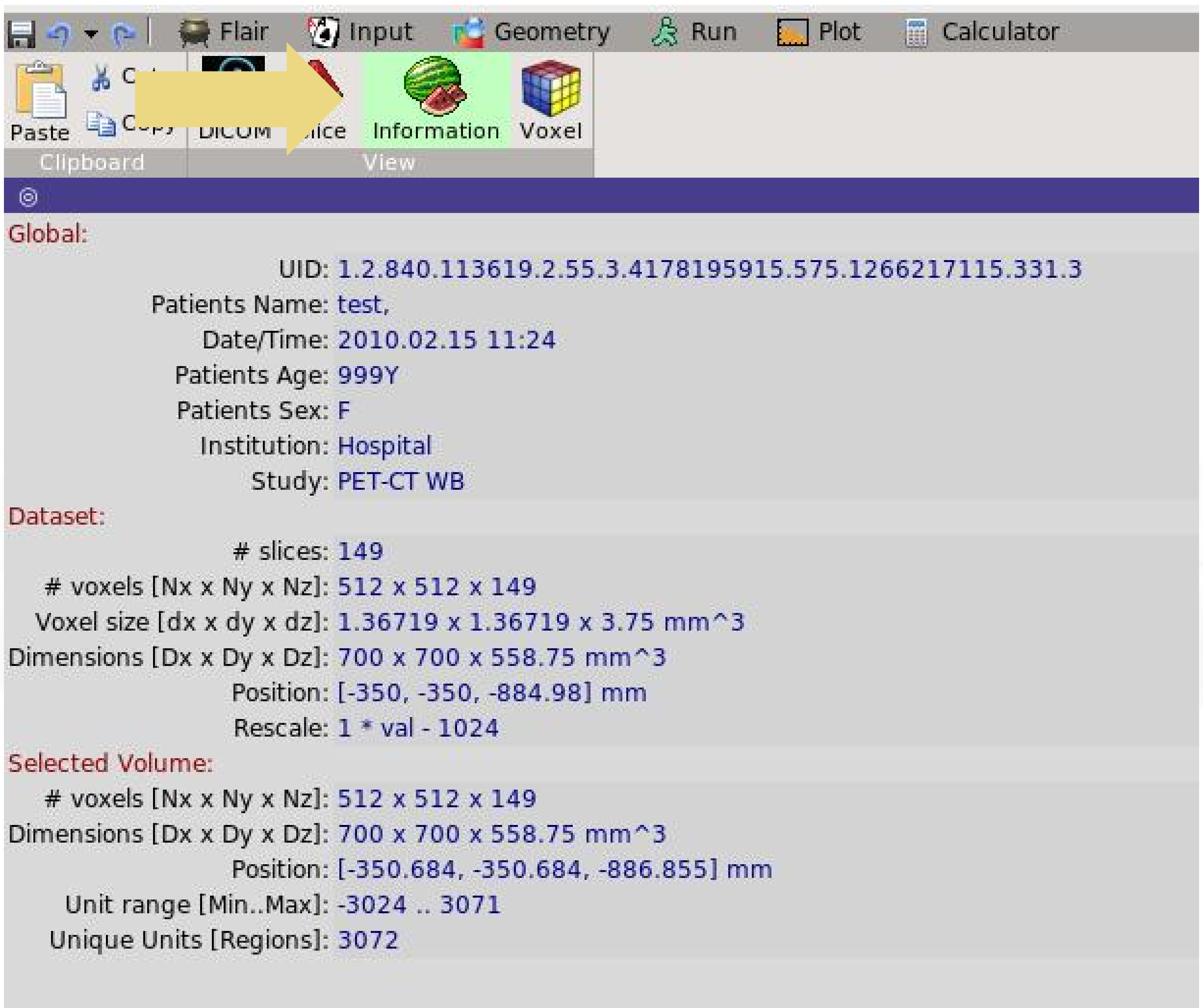


You can crop the voxel by graphically selecting the region of interest

Processing the **DICOM** files with FLAIR III



Processing the **DICOM** files with FLAIR IV



Processing the **DICOM** files with FLAIR V

- The “Voxel” tab is used in order to convert the dataset to VOXELS or USRBIN format. For the VOXEL geometry two additional files are needed (example: material.inp and head.mat in the flair/dicom dir).

≤ Unit	Material	Crho_min	Crho_max	CdEdx_rel_min	CdEdx_rel_max
-1020	AIR	0.6825432	1.3174568	1.0	1.0
-1015	HU<-1015	0.720281108	1.27971895	1.0	1.0
-1010	HU<-1010	0.869629081	1.16460858	1.0	1.0
-1000	HU<-1000	0.773675179	1.16949124	1.0	1.0
-995	HU<-995	0.969155491	1.05424948	1.0	1.0
-988	HU<-988	0.969432473	1.09049764	1.0	1.0
-974	HU<-974	0.91139082	1.14891168	1.0	1.0
-962	HU<-962	0.969659741	1.09708732	1.0	1.0
-950	HU<-950	0.989308216	1.08011649	1.0	1.0
-925	HU<-925	0.862306423	1.13769358	1.0	1.0
-900	HU<-900	0.893000468	1.10699951	1.0	1.0
-830	HU<-830	0.783902333	1.21609767	1.0	1.0
-700	HU<-700	0.75158871	1.24841129	1.0	1.0
-500	HU<-500	0.765689411	1.23431059	1.0	1.0
-120	HU<-120	0.734835247	1.26516475	1.0	1.0
-83	HU<-83	0.980501545	1.01835909	1.0	1.0
-53	HU<-53	0.98600717	1.01305997	1.0	1.0
-23	HU<-23	0.986384099	1.01270032	1.0	1.0
7	HU<7	0.98674495	1.01236373	1.0	1.0
15	HU<18	0.995655766	1.00173225	1.0	1.0
80	HU<80	0.972407965	1.03421835	1.0	1.0
101	HU<120	0.980146255	1.00104493	1.0	1.0
120	HU<120	0.962511989	0.973311932245	1.0	1.0
200	HU<200	0.973911929092	1.02131168	1.0	1.0
300	HU<300	0.97508777	1.02542064	1.0	1.0
400	HU<400	0.976293061	1.02419075	1.0	1.0
500	HU<500	0.977387107	1.02307438	1.0	1.0
600	HU<600	0.97838463	1.0220565	1.0	1.0
700	HU<700	0.979297863	1.02112463	1.0	1.0
800	HU<800	0.980137058	1.02026831	1.0	1.0
900	HU<900	0.980910866	1.01947871	1.0	1.0
1000	HU<1000	0.981626645	1.01874832	1.0	1.0

Processing the **DICOM** files with FLAIR VI

- ≤ Unit: specify the upper limit of the range. Every entry will correspond to a range from the previous upper limit+1 until the current upper limit.
- Material: select any of the predefined FLUKA materials defined previously.

Optionally you can specify correction factors for the density and dE/dx

- Crho_min/Chro_max: density correction factors to be applied on the lower/upper limit of the unit range (see next slides).
- CdEdx_rel_min/CdEdx_rel_max: relative correction factors on dE/dx for minimum/maximum unit in the range (see next slides).

≤ Unit	Material	Crho_min	Crho_max	CdEdx_rel_min	CdEdx_rel_max
-1020	AIR	0.6825432	1.3174568	1.0	1.0
-1015	HU<-1015	0.720281108	1.27971895	1.0	1.0
-1010	HU<-1010	0.869629081	1.16460858	1.0	1.0
-1000	HU<-1000	0.773675179	1.16949124	1.0	1.0
-995	HU<-995	0.969155491	1.05424948	1.0	1.0
-988	HU<-988	0.969432473	1.09049764	1.0	1.0
-974	HU<-974	0.91139082	1.14891168	1.0	1.0
-962	HU<-962	0.969659741	1.09708732	1.0	1.0
-950	HU<-950	0.989308216	1.08011649	1.0	1.0
-925	HU<-925	0.862306423	1.13769358	1.0	1.0
-900	HU<-900	0.893000468	1.10699951	1.0	1.0
-830	HU<-830	0.783902333	1.21609767	1.0	1.0
-700	HU<-700	0.75158871	1.24841129	1.0	1.0
-500	HU<-500	0.765689411	1.23431059	1.0	1.0
-120	HU<-120	0.734835247	1.26516475	1.0	1.0
-83	HU<-83	0.980501545	1.01835909	1.0	1.0
-53	HU<-53	0.98600717	1.01305997	1.0	1.0

Voxel Body

- The usual list of NB bodies, not including the RPP corresponding to the "voxel volume" (see VOXELS card above). This RPP will be generated and added automatically by the code as the (NB+1) th body, with one corner in the point indicated in the VOXELS card, and dimensions NX*DX, NY*DY and NZ*DZ as read from the voxel file.
- The usual region list of NR regions, with the space occupied by body named VOXEL or numbered NB+1 (the "voxel volume") subtracted. In other words, the NR regions listed must cover the whole available space, excepted the space corresponding to the "voxel volume". This is easily obtained by subtracting body VOXEL or NB+1 in the relevant region definitions, even though this body is not explicitly input at the end of the body list.

VOXELS		x: -35.068359 Trans: ▼	y: -35.068359 Filename: VOXEL1 ▼	z: -88.6855
SPH	BODY1	x: 0. R: 10000.	y: 0.	z: 0.
SPH	BODY2	x: 0. R: 1000.	y: 0.	z: 0.
END				
REGION	REG1 expr: BODY1-BODY2		Neigh: 5	Volume:
REGION	REG2 expr: BODY2-VOXEL		Neigh: 5	Volume:
END				
GEOEND		▼		

Voxel Regions

The code will automatically generate and add several regions:

- NO additional regions, where NO = number of non-zero organs:

Name	Number	Description
VOXEL	NR+1	sort of a "cage" for all voxels. Nothing should ever be deposited in it. The user shall assign vacuum to it.
VOXEL001	NR+2	containing all voxels belonging to organ number 0. There must be at least 2 of such voxels, but in general they should be many more. Typical material assignment to this region is air
VOXEL002	NR+3	corresponding to organ 1
VOXEL003	NR+4	corresponding to organ 2
VOXEL###	NR+2+NO	corresponding to organ NO

Few remarks

- The assignment of materials is made directly by FLAIR. The user has to assign the materials to the regions defined by combinatorial geometry.
- The “head.mat” and “material.inp” files are examples, the user should update these files taking into account his calibration curves.

Practical issues for Medical Applications

General problems for MC calculations on CT scans

- How to assign realistic human tissue parameters (= materials) for MC Calculation?
- How to find a good compromise between the number of different HU values (~ 3000-5000) and the materials to be considered in the MC?

  (issues on memory and computation speed when attempting to treat each HU number as a different material !!!)
- How to preserve continuous, HU-dependent information when segmenting the HU numbers into intervals sharing the same "tissue" material ?

  (critical for ion range calculation in hadron therapy !!!)

CT stoichiometric calibration (I)

CT segmentation into 27 materials of defined elemental composition (from analysis of 71 human CT scans)

Air, Lung, Adipose tissue

Soft tissue

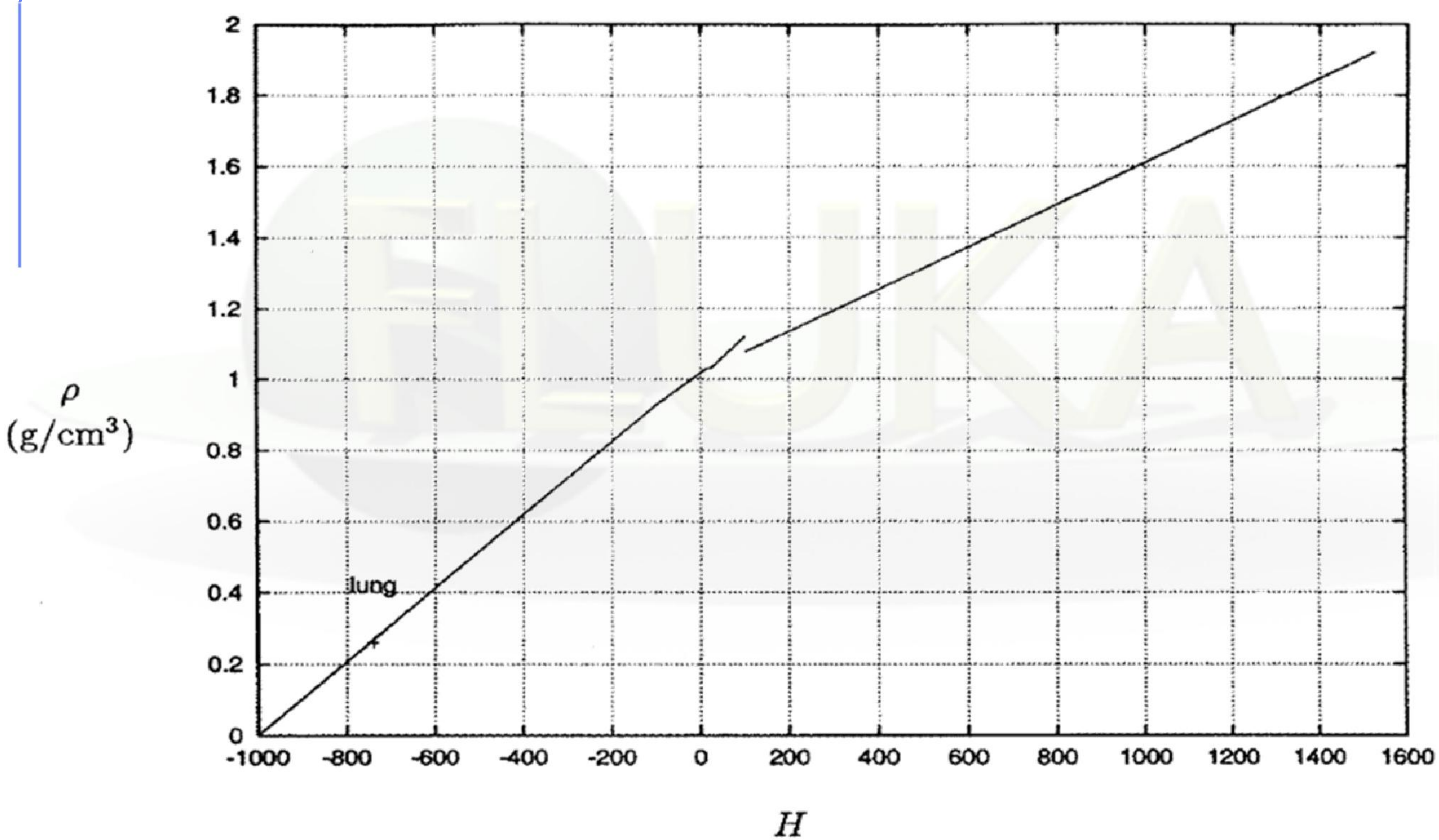
Skeletal tissue

H	w_i (pp)											
	H	C	N	O	Na	Mg	P	S	Cl	Ar	K	Ca
−1000−−950			75.5	23.2						1.3		
−950−−120	10.3	10.5	3.1	74.9	0.2		0.2	0.3	0.3		0.2	
−120−−83	11.6	68.1	0.2	19.8	0.1			0.1	0.1			
−82−−53	11.3	56.7	0.9	30.8	0.1			0.1	0.1			
−52−−23	11.0	45.8	1.5	41.1	0.1		0.1	0.2	0.2			
−22–7	10.8	35.6	2.2	50.9			0.1	0.2	0.2			
8–18	10.6	28.4	2.6	57.8			0.1	0.2	0.2		0.1	
19–80	10.3	13.4	3.0	72.3	0.2		0.2	0.2	0.2		0.2	
80–120	9.4	20.7	6.2	62.2	0.6			0.6	0.3			
120–200	9.5	45.5	2.5	35.5	0.1		2.1	0.1	0.1		0.1	4.5
200–300	8.9	42.3	2.7	36.3	0.1		3.0	0.1	0.1		0.1	6.4
300–400	8.2	39.1	2.9	37.2	0.1		3.9	0.1	0.1		0.1	8.3
400–500	7.6	36.1	3.0	38.0	0.1	0.1	4.7	0.2	0.1			10.1
500–600	7.1	33.5	3.2	38.7	0.1	0.1	5.4	0.2				11.7
600–700	6.6	31.0	3.3	39.4	0.1	0.1	6.1	0.2				13.2
700–800	6.1	28.7	3.5	40.0	0.1	0.1	6.7	0.2				14.6
800–900	5.6	26.5	3.6	40.5	0.1	0.2	7.3	0.3				15.9
900–1000	5.2	24.6	3.7	41.1	0.1	0.2	7.8	0.3				17.0
1000–1100	4.9	22.7	3.8	41.6	0.1	0.2	8.3	0.3				18.1
1100–1200	4.5	21.0	3.9	42.0	0.1	0.2	8.8	0.3				19.2
1200–1300	4.2	19.4	4.0	42.5	0.1	0.2	9.2	0.3				20.1
1300–1400	3.9	17.9	4.1	42.9	0.1	0.2	9.6	0.3				21.0
1400–1500	3.6	16.5	4.2	43.2	0.1	0.2	10.0	0.3				21.9
1500–1600	3.4	15.5	4.2	43.5	0.1	0.2	10.3	0.3				22.5

Schneider et al PMB 45, 2000

CT stoichiometric calibration (II)

Assign to each material a "nominal mean density", e.g. using the density at the center of each HU interval **(Jiang et al, MP 2004)**



Schneider et al PMB 45, 2000

But "real density" (and related physical quantities) varies continuously with HU value !!!

The region-dependent CORRFACT card

- "CORRFACT" card allows to alter material density for dE/dx and nuclear processes

- First two inputs specify a density scaling factor (restricted to the interval [2/3,3/2]) for charged particle ionization processes (WHAT(1)) and for all other processes (WHAT(2)) to the region(s) specified by the inputs WHAT(4-6) *[cf. manual]*

- This is especially important in ion beam therapy to force the MC to follow the same semi-empirical HU-range calibration curve as the Treatment Planning System (TPS) for dosimetric comparisons

- FLAIR automatically appends the CORRFACT cards calculated taking into account the calibration curves provided by the user at the end of the .vxl file.

How to account for HU-dependent dEdx

- In the INPUT
  - Let several regions share the same material composition and mean density according to CT segmentation (reduced number of materials to save memory / initialization time)

    ASSIGNMA BONE VOXEL005 (region number 25)

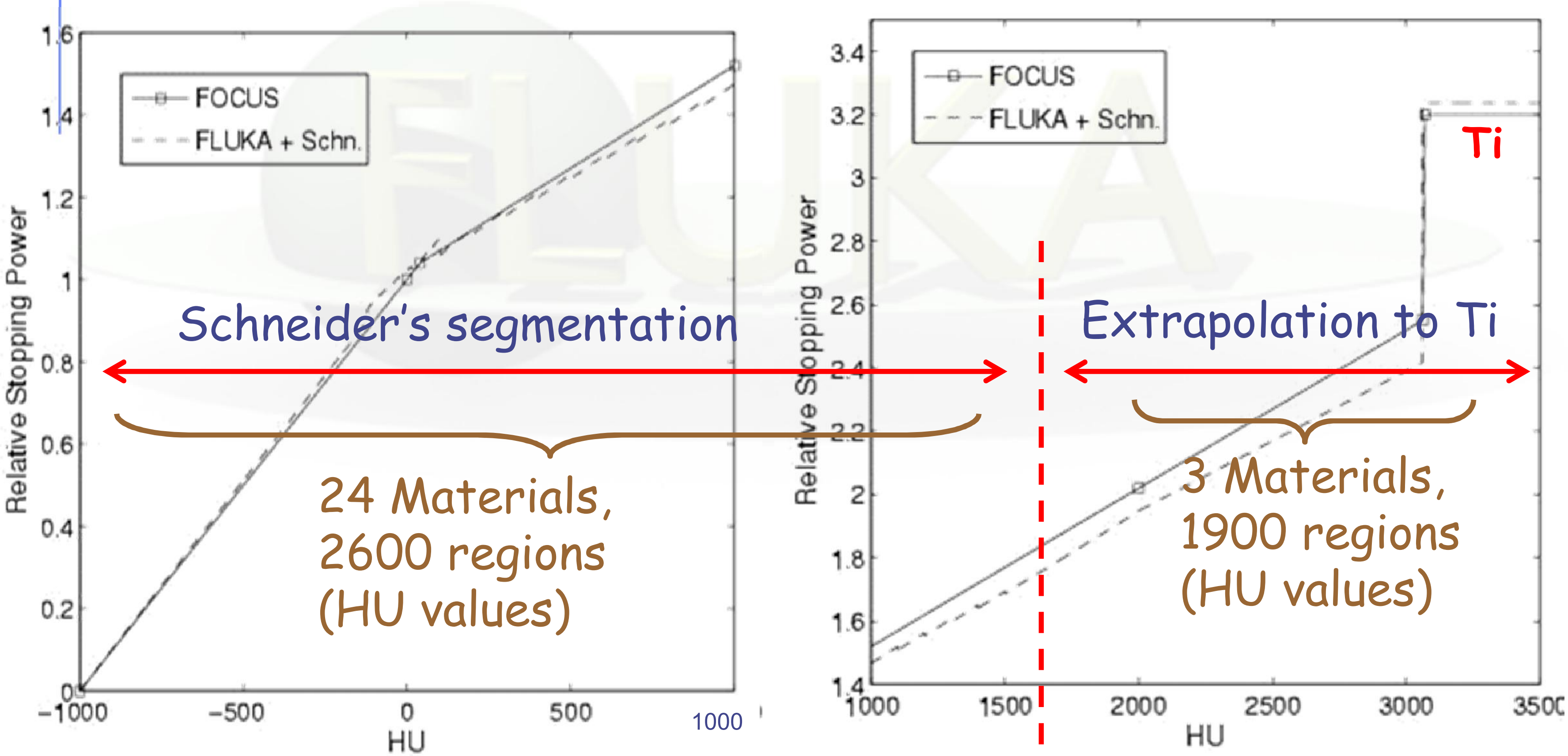
    ASSIGNMA BONE VOXEL016 (region number 31)

  - Use CORRFACT to impose the desired correction for stopping power (⇒ ion range!) in the regions KREG corresponding to different organs IO (i.e., different HU values) sharing the same MATERIAL assignment

CORRFACT	0.85	0.0	0.0	VOXEL005	Region #25 corresponds
CORRFACT	1.3	0.0	0.0	VOXEL016	to "softer" bone than #31

Forcing FLUKA to follow the same range calibration curve as TPS for p @ MGH Boston

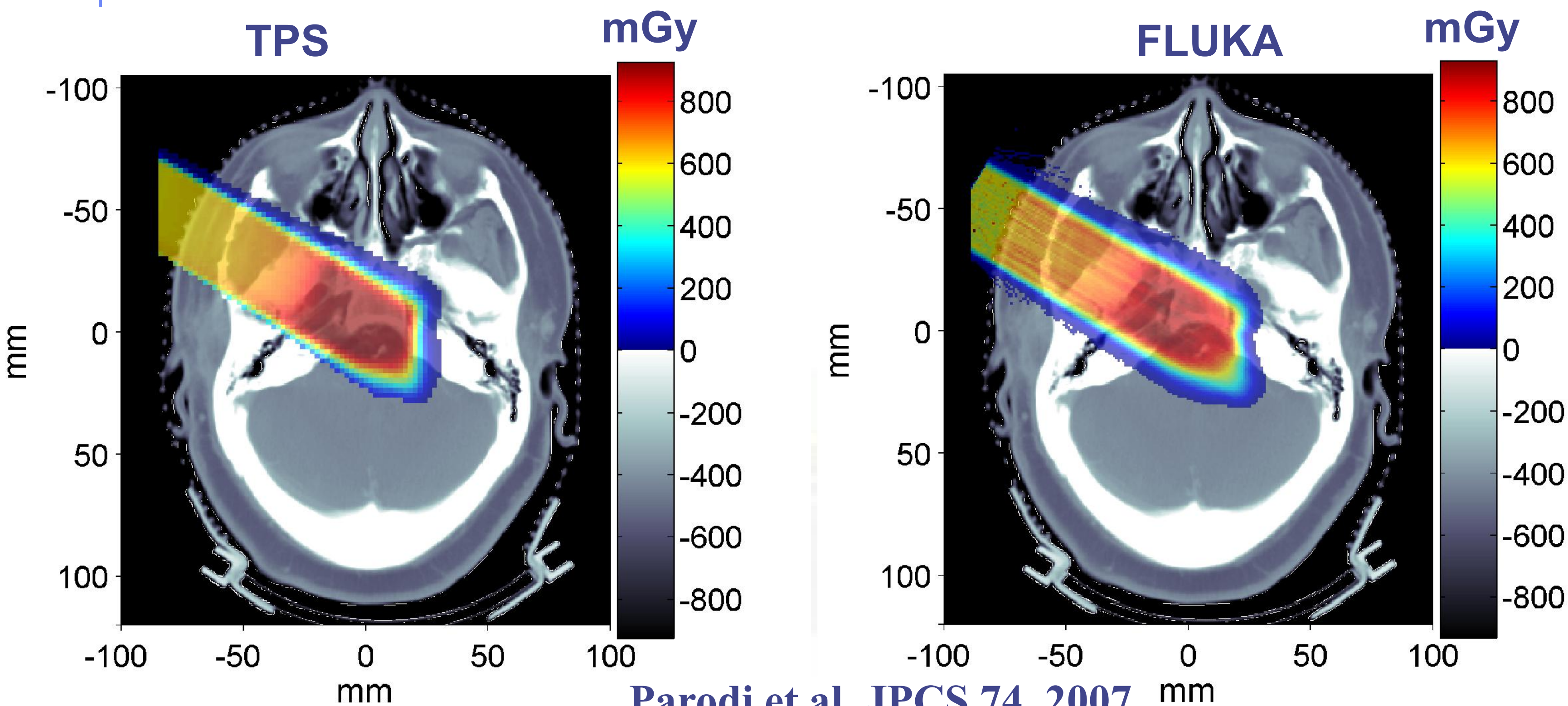
The CORRFACT ionization scaling factors were obtained from the dEdx ratio between TPS and FLUKA (+ Schneider "mass density") -> The user should update the "head.mat" file with his own calibration for CdEdX_rel taking into account his TPS.



Parodi et al MP 34, 2007, Parodi et PMB 52, 2007

Applications of FLUKA to p therapy @ MGH

Input phase-space provided by H. Paganetti, MGH Boston

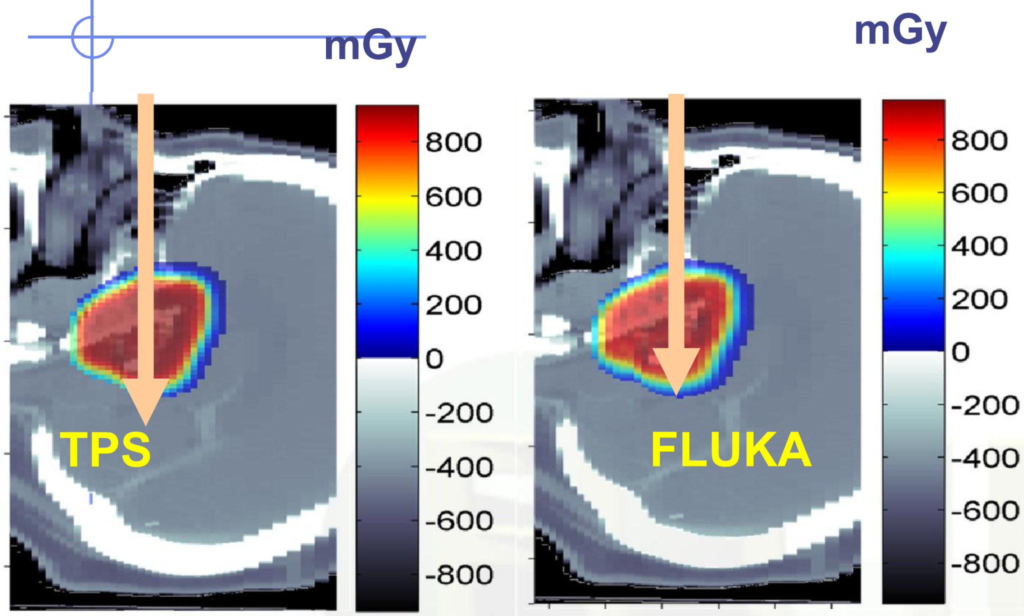


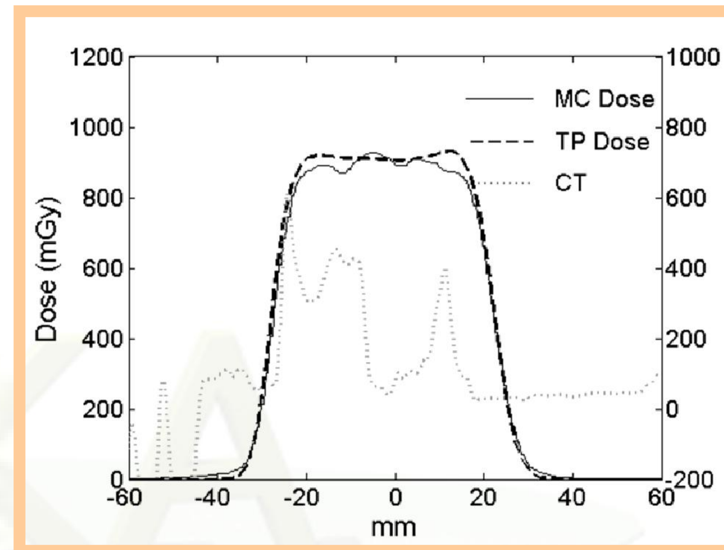
Parodi et al, JPCS 74, 2007

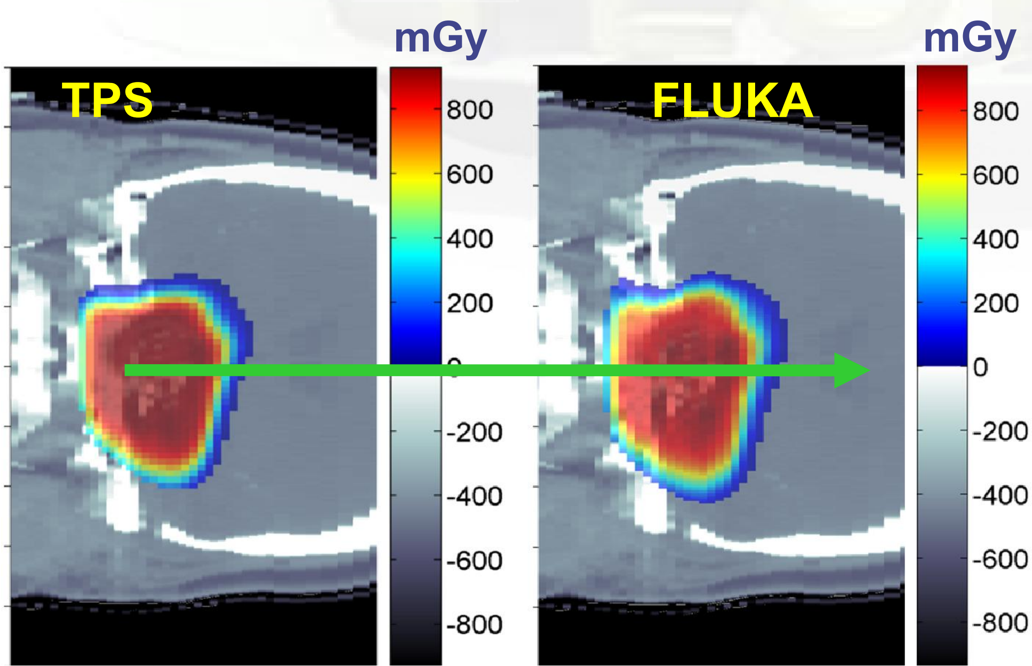
Prescribed dose: 1 GyE
MC : ~ 5.5 10^6 protons in 10 independent runs
(11h each on Linux Cluster mostly using 2.2GHz Athlon processors)

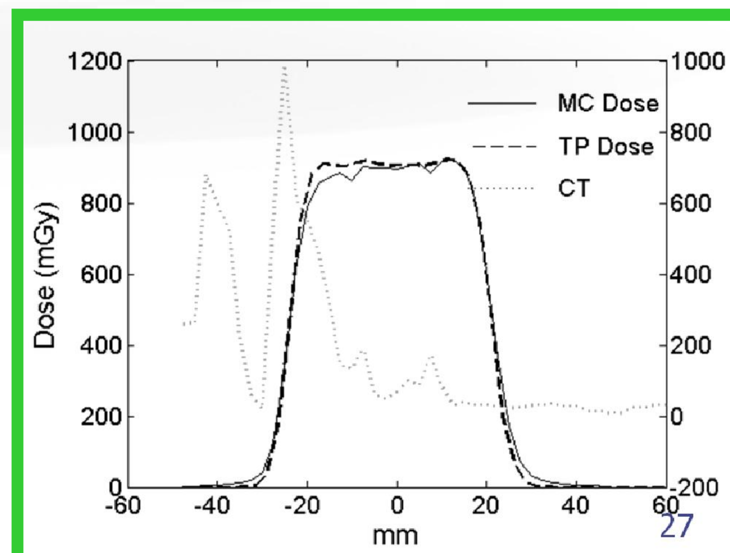
Applications of FLUKA to p therapy @ MGH

Parodi et PMB 52, 2007

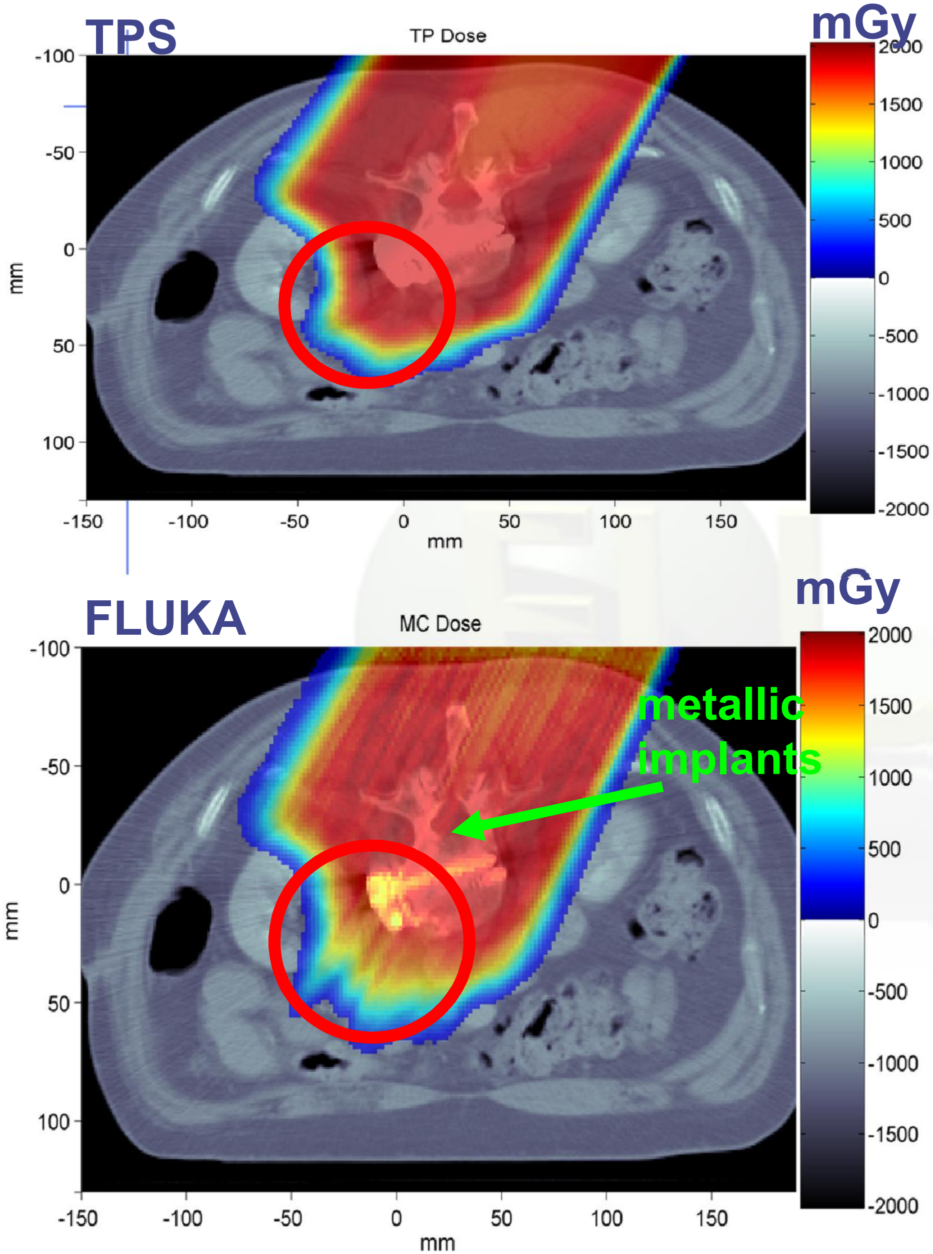








Applications of FLUKA to p therapy @ MGH



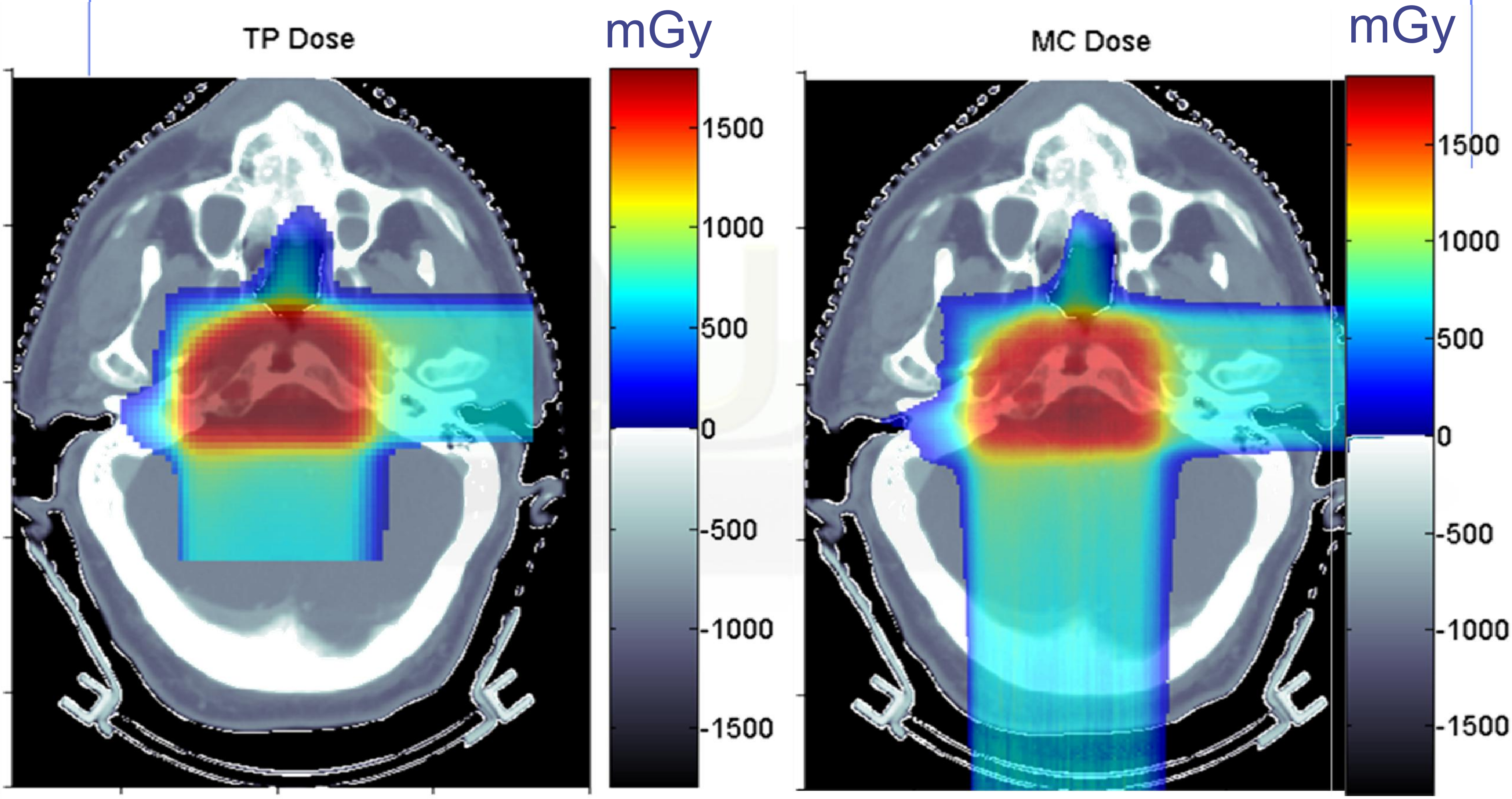
Prescribed dose: 2 GyE
MC : ~ 7.4 10^7p in 12 independent runs (~ 130h each on 2.2 GHz Linux cluster)

K. Parodi et al, IJROBP 2007

Applications of FLUKA to p therapy @ MGH

Clival Chordoma, 0.96 GyE / field

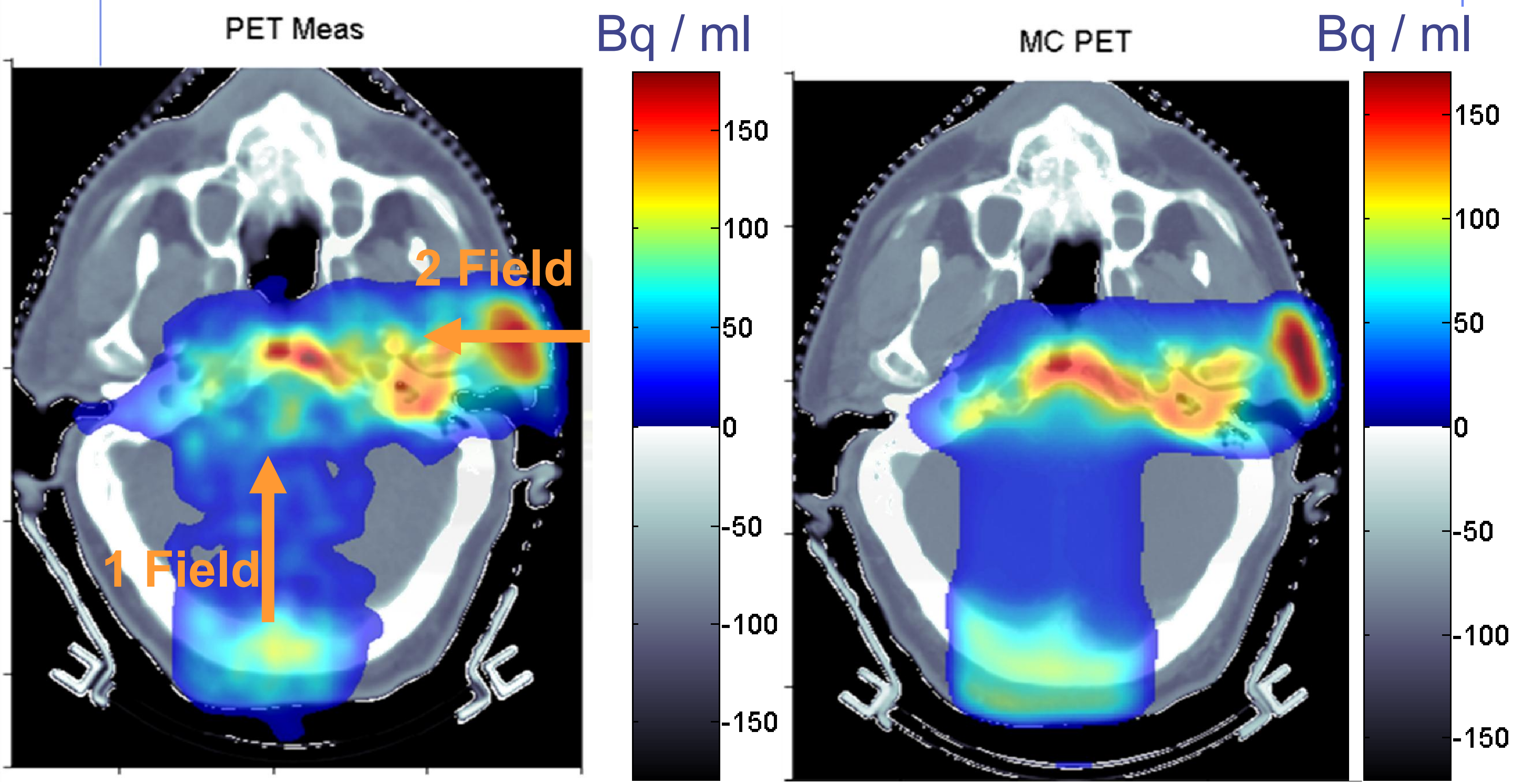
Planned dose



Post-radiation PET/CT @ MGH

Average Activity

Clival Chordoma, 0.96 GyE / field, ΔT1 ~ 26 min, ΔT2 ~ 16 min



K. Parodi et al, IJROBP 2007

… and FLUKA-voxel functionalities being also used at HIT and CNAO …