



Voxels and Medical Applications

21st FLUKA Beginner's Course
ALBA – Barcelona, Spain
08 – 12 April 2019

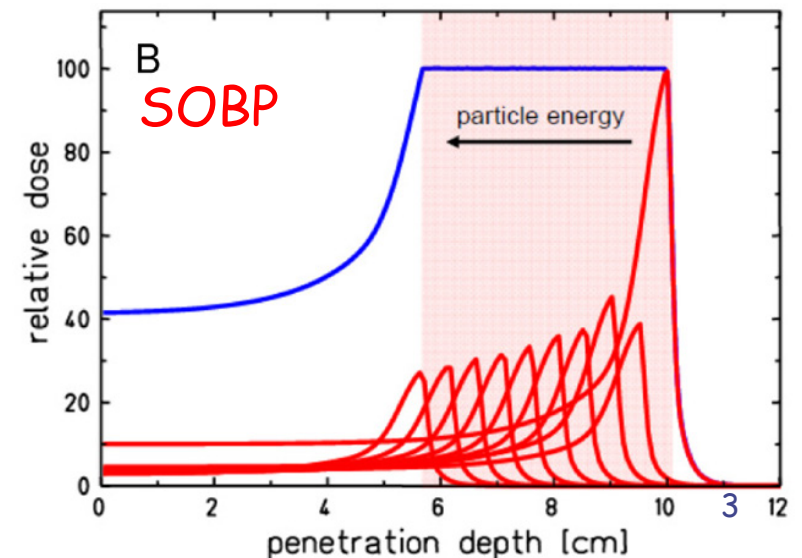
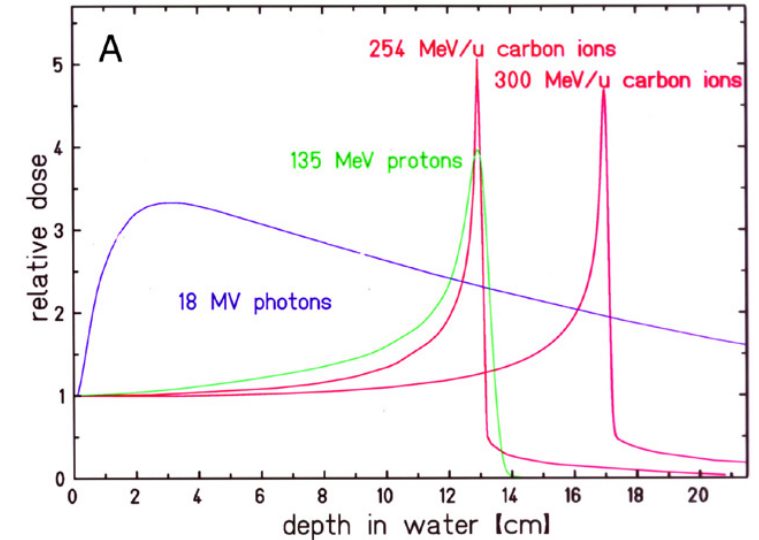
Medical Physics and related disciplines applications

- Nuclear Medicine
 - Dosimetry
- Radiotherapy
 - Simulation of therapy devices
 - Simulations of treatments / treatment assessment
- Particle Therapy
 - Shielding
 - Facility commissioning
 - Treatment planning and forward checks
 - Predictions and data processing for monitoring applications (imaging for hadrontherapy)
 - Design of instruments, dosimetry
 - Calculation for shielding and rad. protection in facilities

Medical applications: Particle Therapy

One of the powerful application of FLUKA & FLAIR is related to Particle Therapy.

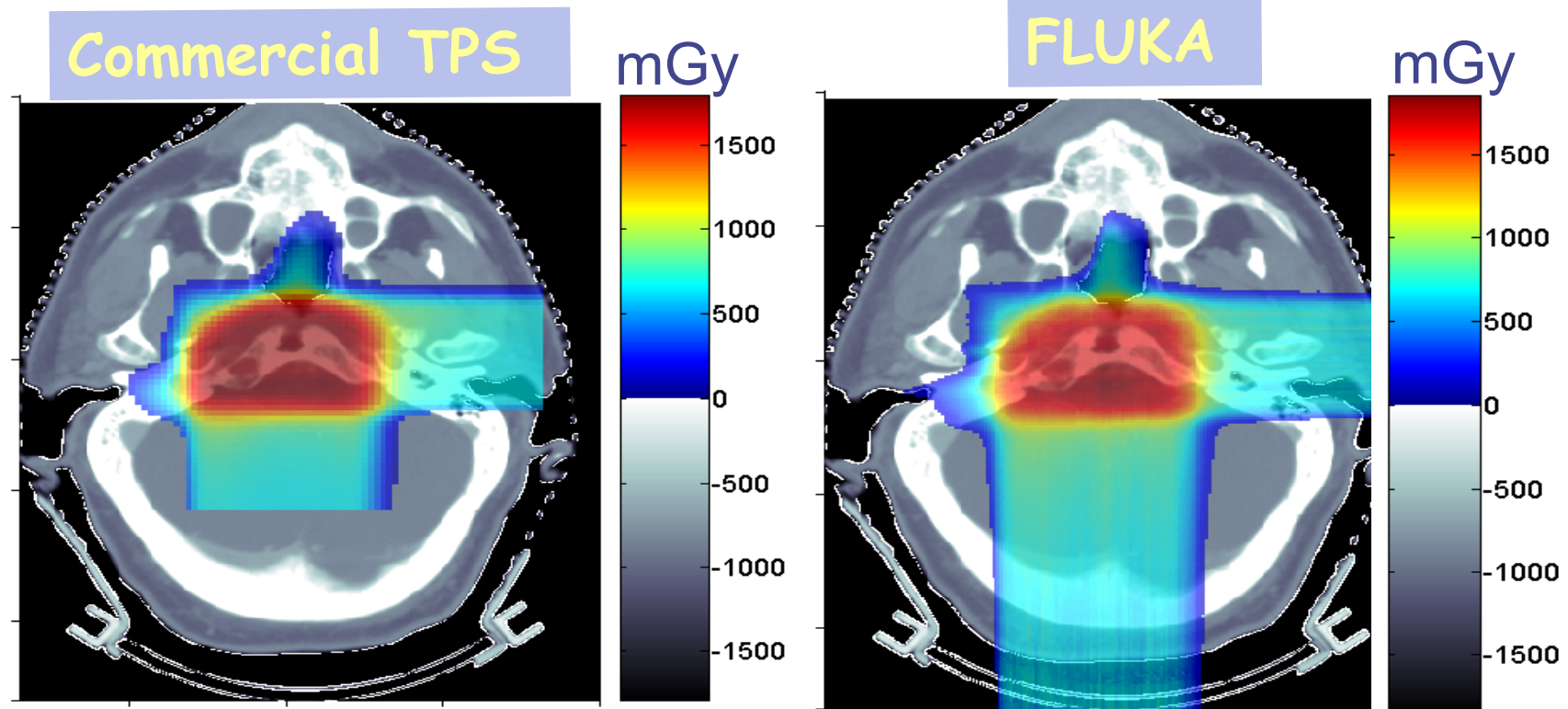
- **Particle Therapy** is a radiation therapy to treat tumors (deep seated, resistant to conventional RT with photons...)
- Exploits “heavy” **charged particle beams** (p, ^{12}C ...) typical energy loss in matter, characterized by the **Bragg peak** (BP)
- The more the beam kinetic energy the deeper the BP position
- Several BPs are summed up to cover the tumor volume (**SOBP**)



The issue of complex geometries: patient cases

In clinics, treatment plans are needed. The medical physicist have to decide in advance how to target the tumor based on patient CT.

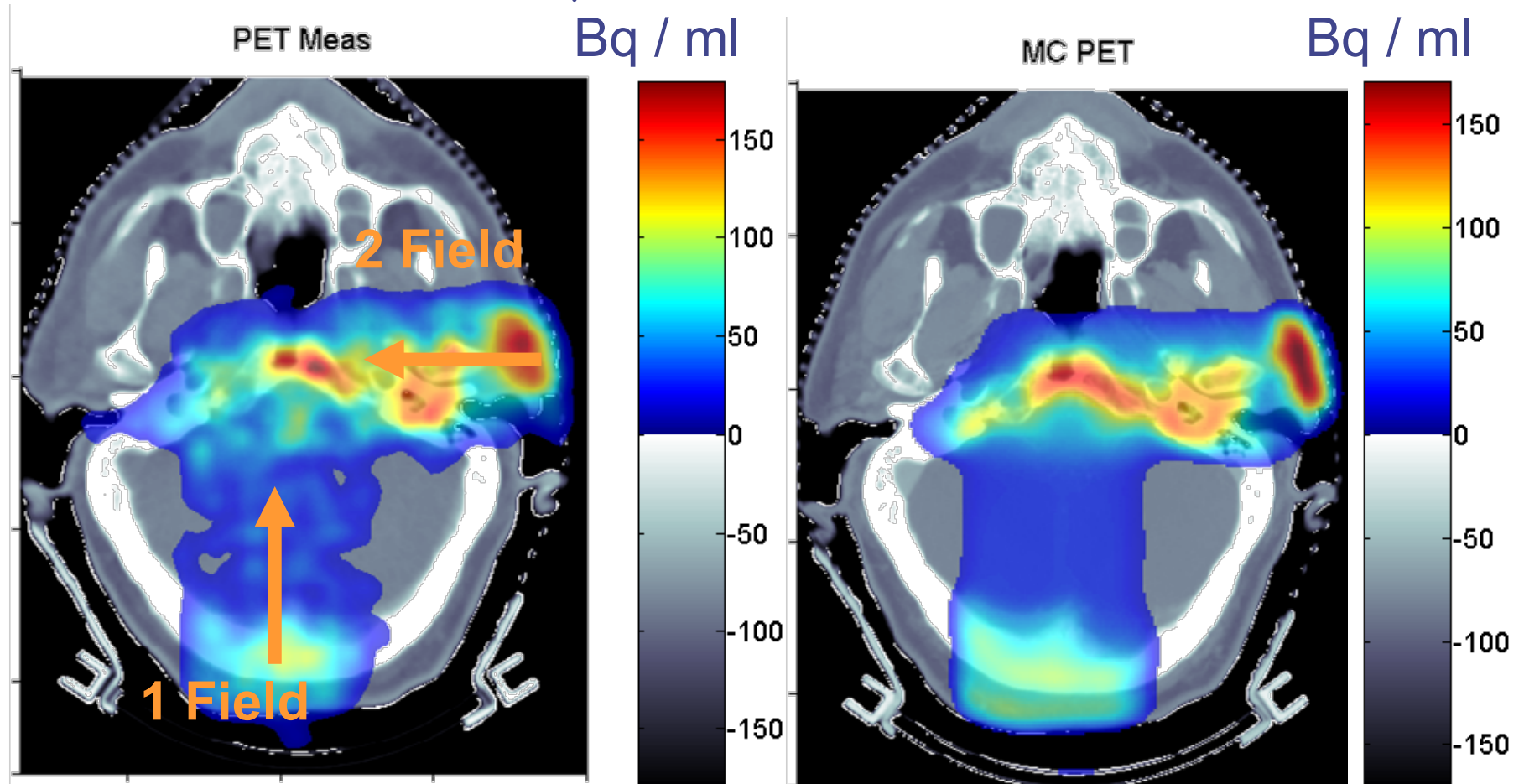
CT scans of a human body are important also for dosimetric calculations of the planned treatment in radiotherapy.



Post-radiation PET/CT @ MGH

Average Activity

Clival Chordoma, 0.96 GyE / field, $\Delta T1 \sim 26$ min, $\Delta T2 \sim 16$ min



K. Parodi et al, IJROBP 2007

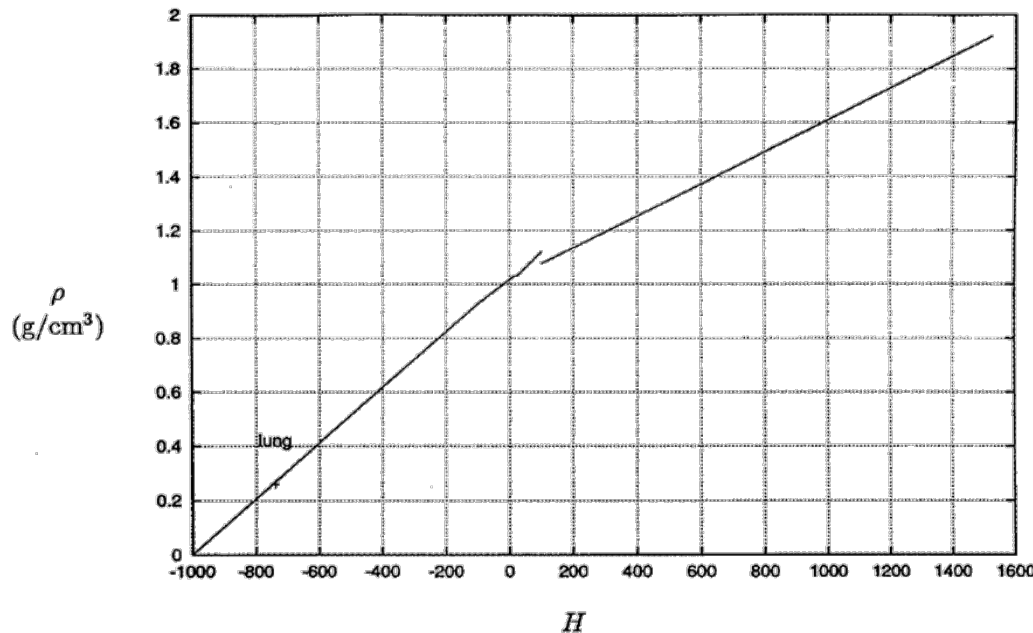
... and FLUKA-voxel functionalities
being also used at CNAO ...

CT stoichiometric calibration

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

$$HU_x = 1000 (\mu_x - \mu_{H2O}) / \mu_{H2O} , \quad \text{typically } -1000 \leq HU \leq 3500$$

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 !!!

Practical issues for Medical Applications: assigning a material to an *organ*

- 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 PT!!!)

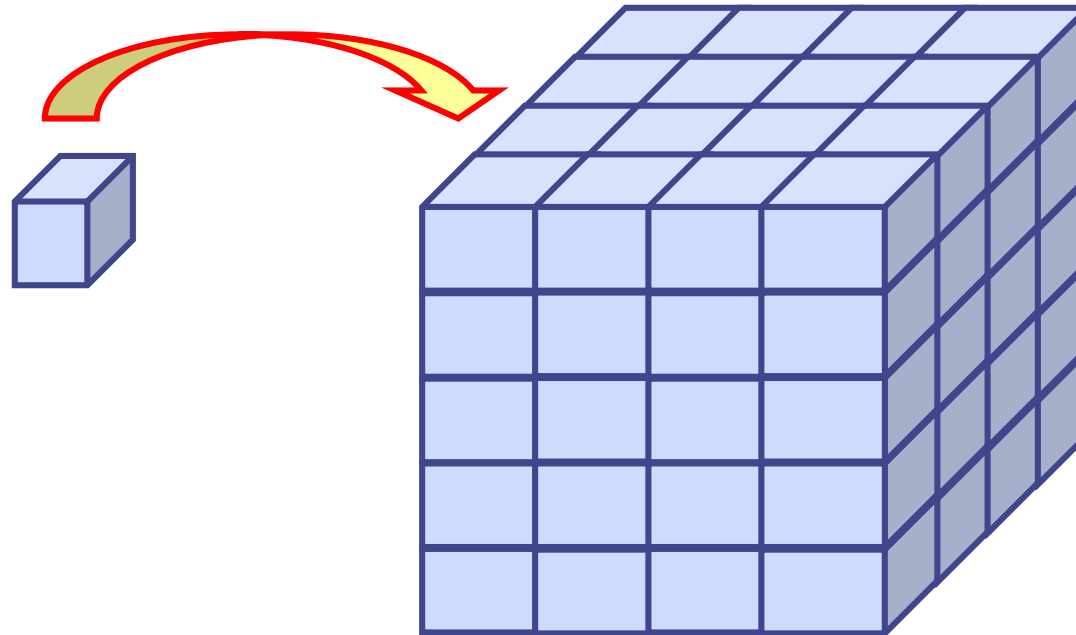
CT stoichiometric calibration

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

		$w_i(\text{pp})$												
H		H	C	N	O	Na	Mg	P	S	Cl	Ar	K	Ca	
Air, Lung, Adipose tissue	{	-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			
Soft tissue	{	-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
Skeletal tissue	{	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

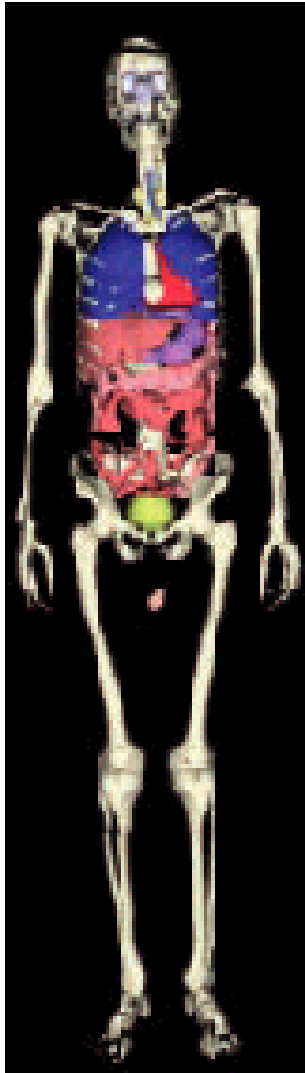
From CT to FLUKA voxel geometry

- The user must convert his CT scan or equivalent data to a format understood by FLUKA: **VOXEL geometry**. (Starting from DICOM images, this is performed directly by FLAIR - see next slides).
- It is possible to describe a geometry in terms of “**voxels**”, i.e., tiny parallelepipeds (all of equal size) forming a **3-dimensional grid**



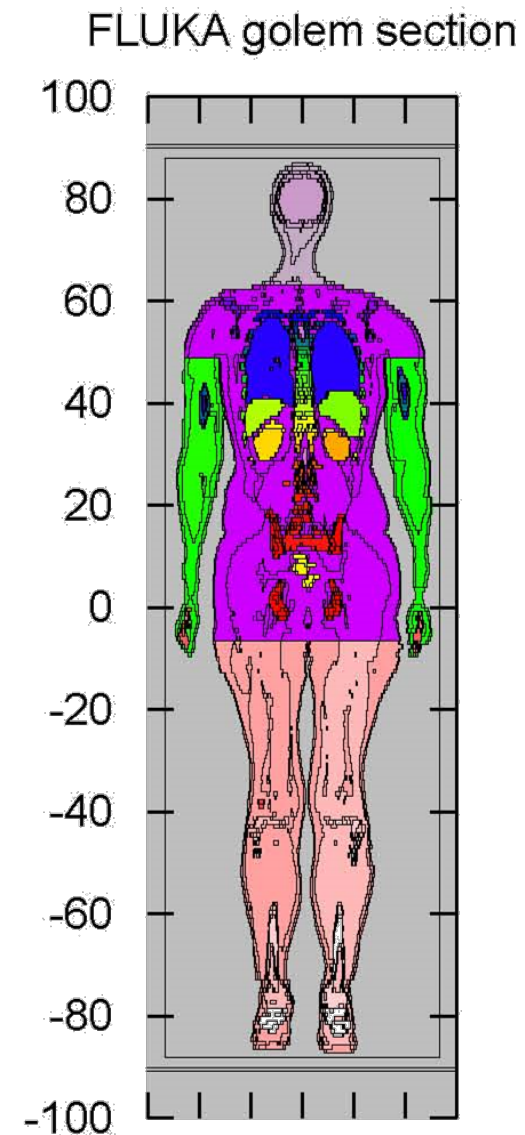
Voxel geometry - Example

The anthropomorphic
GOLEM phantom



Implementation in
FLUKA
(radioprotection
applications)

Petoussi-Henss
et al, 2002



From CT to FLUKA voxel geometry

- 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)
- Assign an organ index to each voxel. In many practical cases, the user will have a continuum of CT values (HU), 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).
- Assign to each NONZERO organ a voxel-region number. The voxel-region numbering has to be contiguous and starts from 1.

The FLUKA voxel geometry

- All CT information can be given as input to FLUKA through a special file *vxl containing:
 - The number of voxels in each coordinate
 - The number of voxel-regions, and the maximum organ number
 - The voxel dimension in each coordinate
 - A list of the organ corresponding to each voxel
 - A list of the voxel-region number corresponding to each organ
 - Definition of Regions of Interests (ROI)
 - ◆ A list of the ROIs for each voxel
- The code handles each organ as a Comb Geo 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.

Example – Medical application

FLAIR has a capability to process the DICOM* files using the pydicom module and convert them to FLUKA VOXELS, USRBIN compatible files as well as providing input for Treatment Plan simulations

Needed softwares: <http://www.fluka.org/flair/download.html>

- Flair and Flair-geoviewer
- Python2 and Python2-scipy
- Tkinter toolkit
- Python imaging library
- Pydicom
- Numpy

*DICOM=Digital Imaging and Communications in Medicine. It is a medical standard for distributing any kind of medical image

If some python package is missing, you will read a message like:

pydicom library is not installed

Website: <http://code.google.com/p/pydicom/>

Install:

```
Fedora # dnf install python2-pydicom
Ubuntu # apt-get install python-dicom python-scipy
all # easy_install pydicom
```

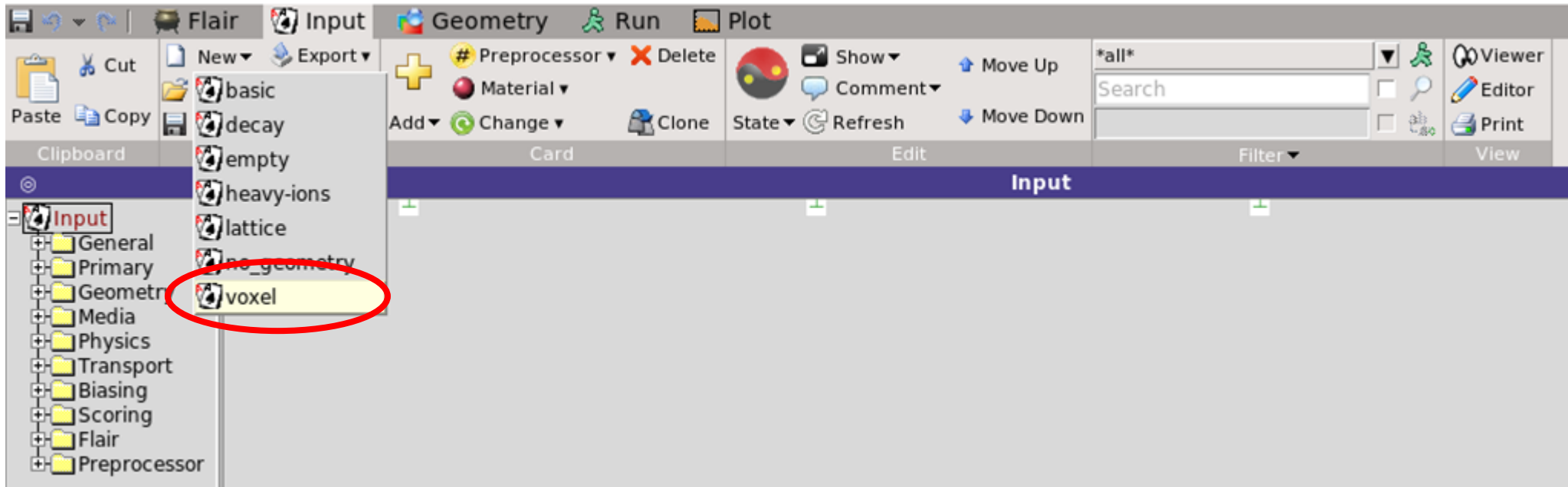
(Requires the python-setuptools),

Extra requirements:

```
python-numeric, python-imaging or python-pillow,
python-imaging-tk or python-pillow-tk
```

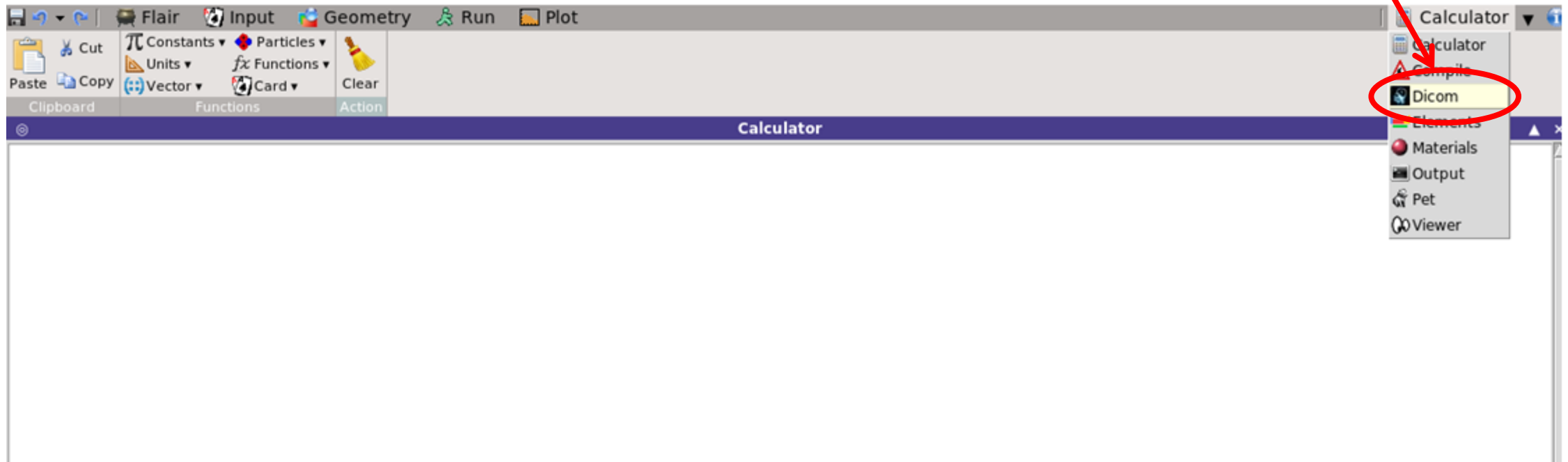
Prepare the input file:

- Create the default input file for voxel using Flair

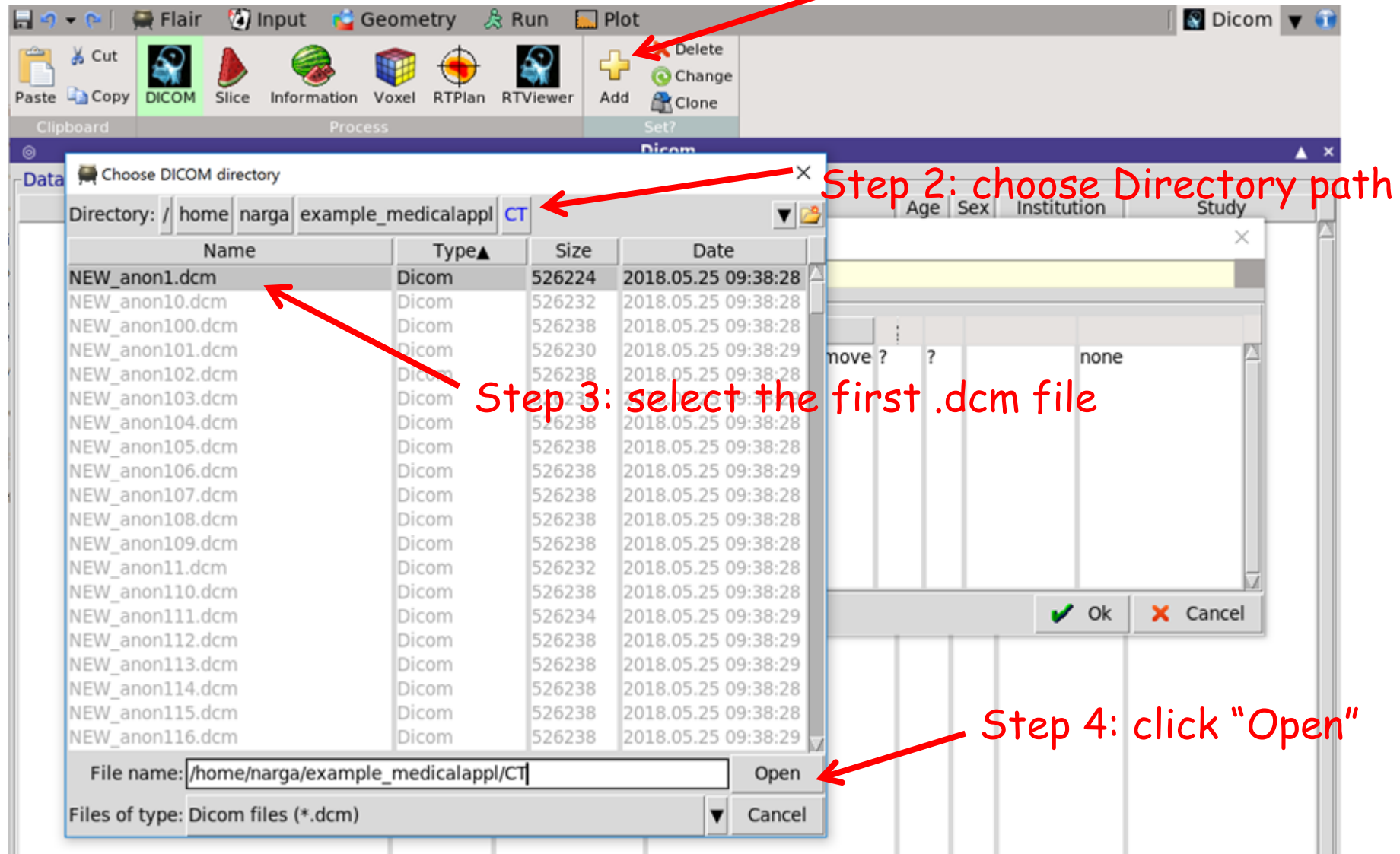


Import the DICOM

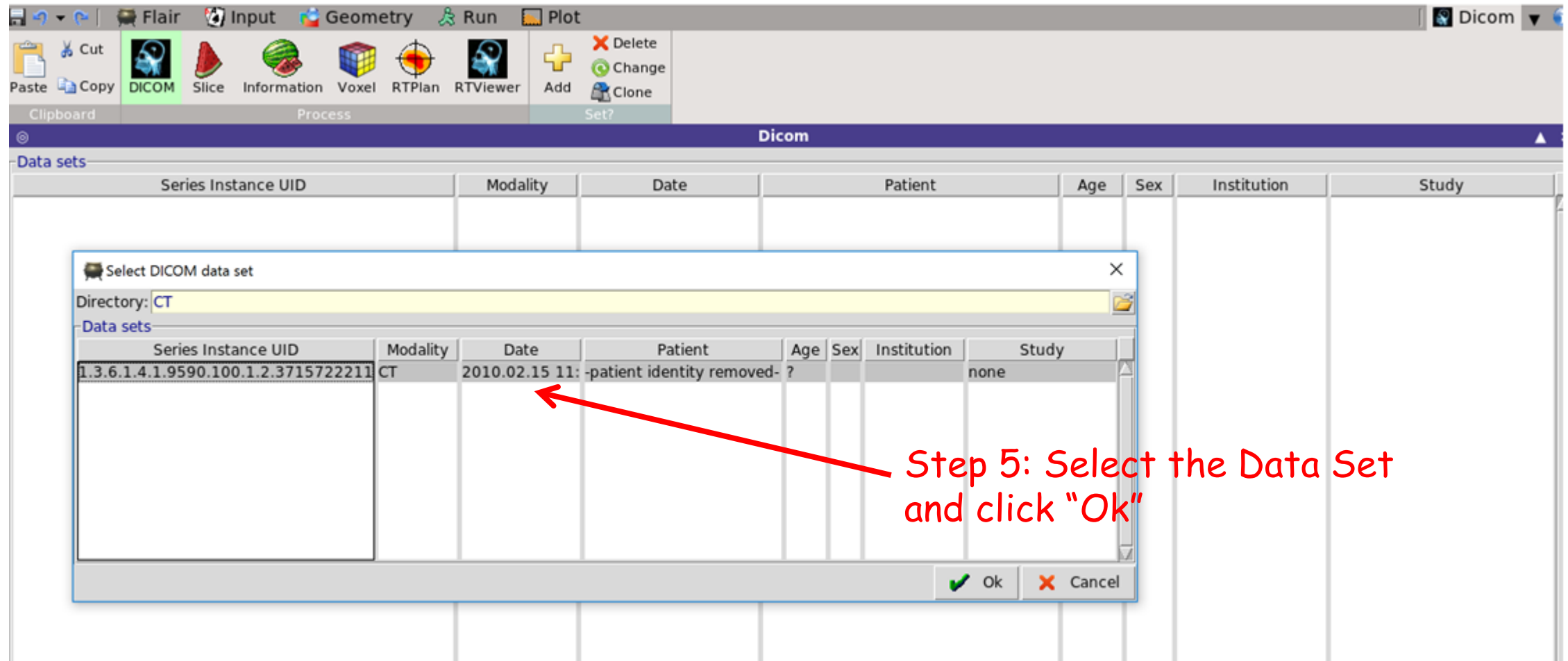
Step 0



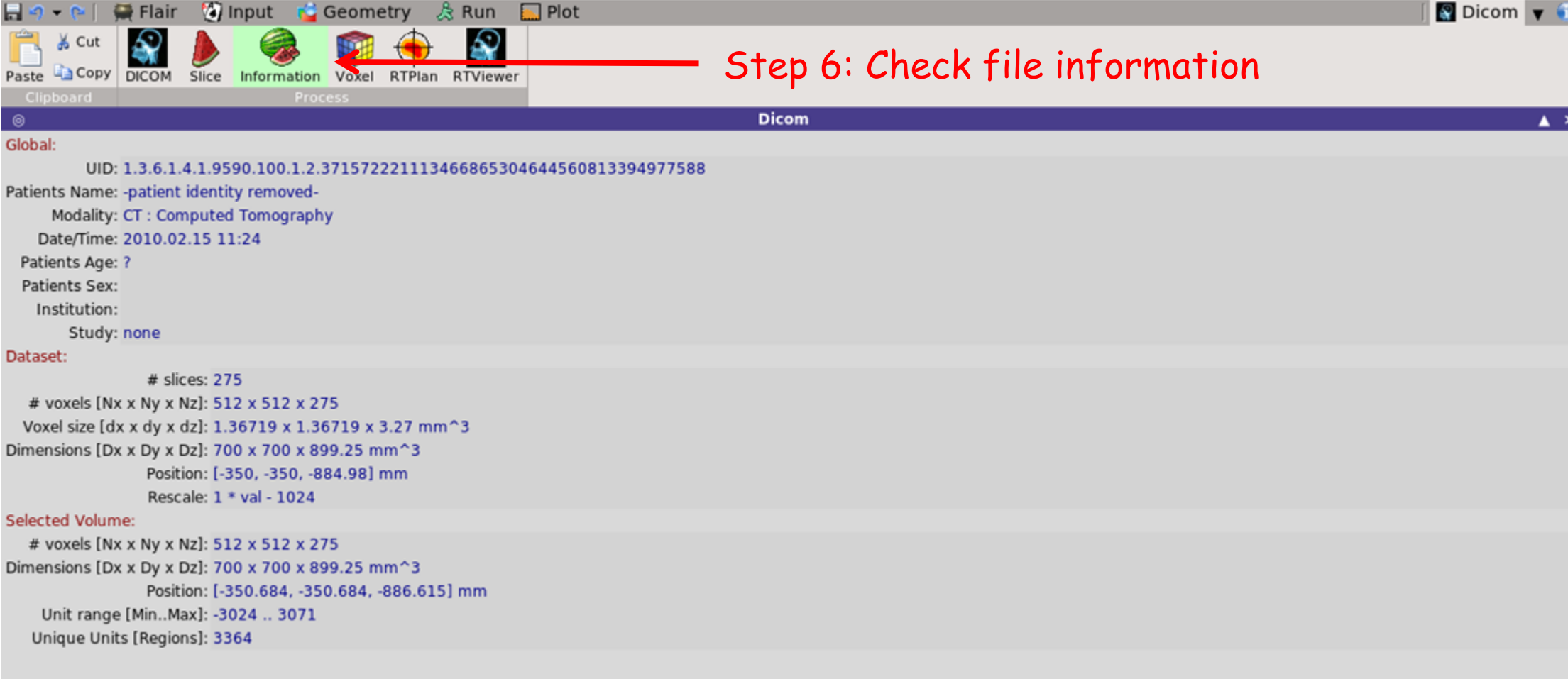
Choose DICOM



Open DICOM



Infos about CT just loaded



The screenshot shows the FLUKA graphical user interface. The top menu bar includes 'Flair', 'Input', 'Geometry', 'Run', and 'Plot'. Below it, a toolbar contains icons for 'DICOM', 'Slice', 'Information', 'Voxel', 'RTPlan', and 'RTViewer'. The 'Information' tab is currently selected, displaying patient and dataset details. A red arrow points from the text 'Step 6: Check file information' to the 'Information' tab icon in the toolbar.

Step 6: Check file information

Global:
UID: 1.3.6.1.4.1.9590.100.1.2.371572221113466865304644560813394977588
Patients Name: -patient identity removed-
Modality: CT : Computed Tomography
Date/Time: 2010.02.15 11:24
Patients Age: ?
Patients Sex:
Institution:
Study: none

Dataset:
slices: 275
voxels [Nx x Ny x Nz]: 512 x 512 x 275
Voxel size [dx x dy x dz]: 1.36719 x 1.36719 x 3.27 mm³
Dimensions [Dx x Dy x Dz]: 700 x 700 x 899.25 mm³
Position: [-350, -350, -884.98] mm
Rescale: 1 * val - 1024

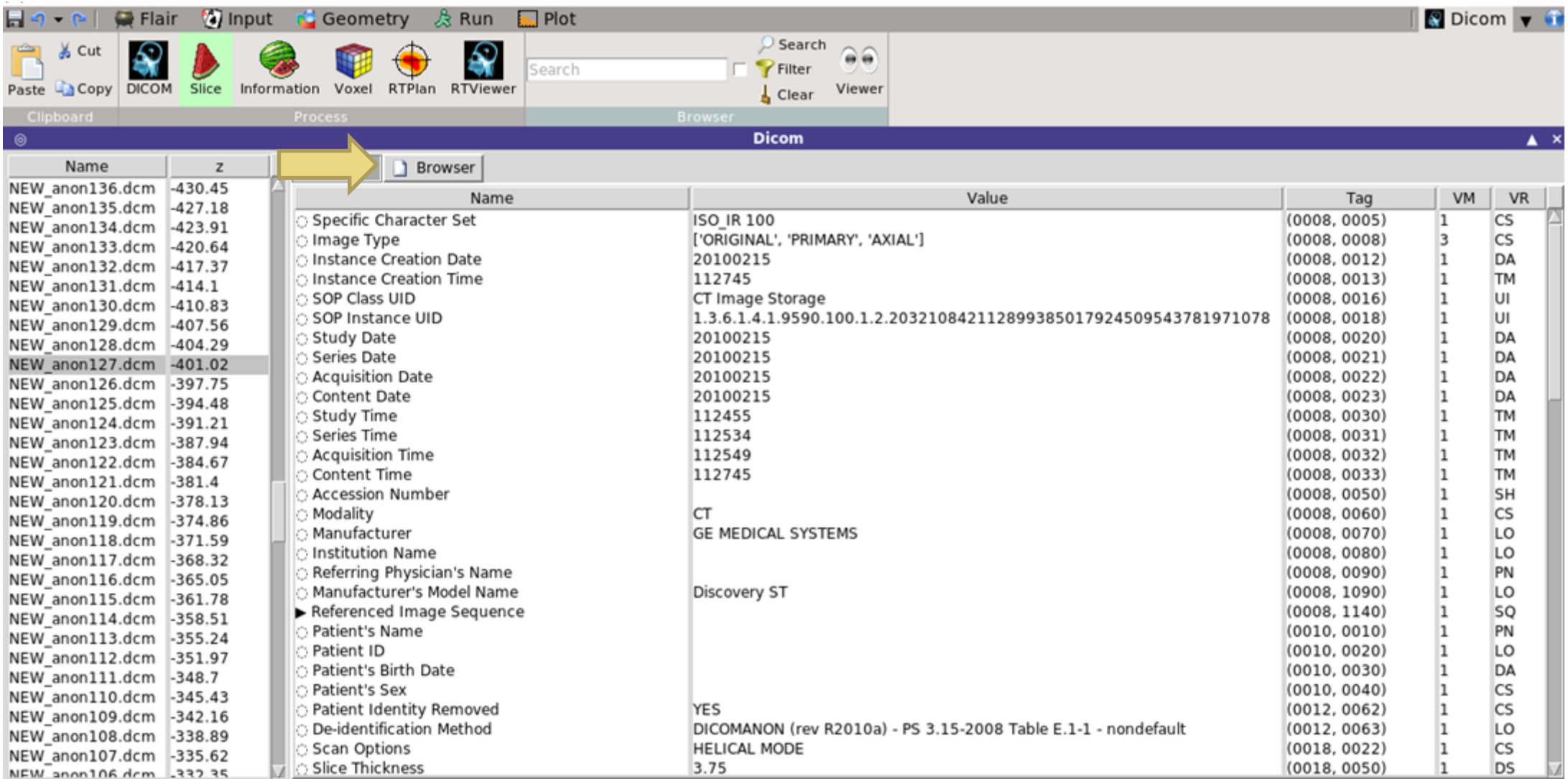
Selected Volume:
voxels [Nx x Ny x Nz]: 512 x 512 x 275
Dimensions [Dx x Dy x Dz]: 700 x 700 x 899.25 mm³
Position: [-350.684, -350.684, -886.615] mm
Unit range [Min..Max]: -3024 .. 3071
Unique Units [Regions]: 3364

Inspecting the Images (1/2)

Each .dcm file represents a CT slice.



Inspecting the Images (2/2)



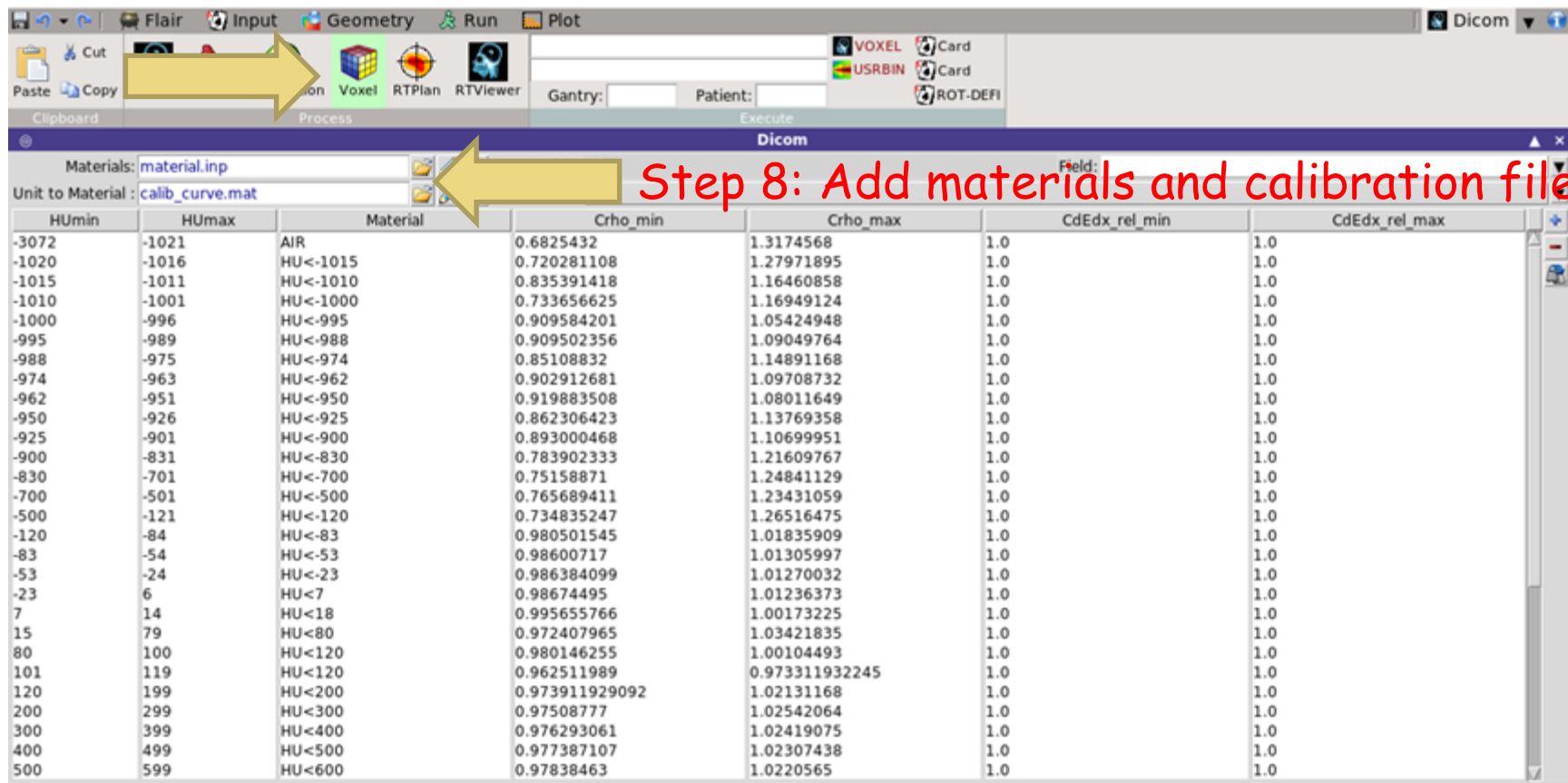
The screenshot shows the FLUKA DICOM browser interface. The top menu bar includes options like Flair, Input, Geometry, Run, and Plot. Below the menu is a toolbar with icons for Cut, Paste, Copy, DICOM, Slice, Information, Voxel, RTPlan, and RTViewer. A search bar and filter options are also present.

The main window displays a list of DICOM files on the left, with columns for Name and z. A yellow arrow points from the 'NEW_anon127.dcm' entry to the 'Browser' tab. The 'Browser' tab shows a detailed view of the DICOM file's metadata, organized into a table with columns for Name, Value, Tag, VM, and VR.

Name	Value	Tag	VM	VR
Specific Character Set	ISO_IR 100	(0008, 0005)	1	CS
Image Type	['ORIGINAL', 'PRIMARY', 'AXIAL']	(0008, 0008)	3	CS
Instance Creation Date	20100215	(0008, 0012)	1	DA
Instance Creation Time	112745	(0008, 0013)	1	TM
SOP Class UID	CT Image Storage	(0008, 0016)	1	UI
SOP Instance UID	1.3.6.1.4.1.9590.100.1.2.203210842112899385017924509543781971078	(0008, 0018)	1	UI
Study Date	20100215	(0008, 0020)	1	DA
Series Date	20100215	(0008, 0021)	1	DA
Acquisition Date	20100215	(0008, 0022)	1	DA
Content Date	20100215	(0008, 0023)	1	DA
Study Time	112455	(0008, 0030)	1	TM
Series Time	112534	(0008, 0031)	1	TM
Acquisition Time	112549	(0008, 0032)	1	TM
Content Time	112745	(0008, 0033)	1	TM
Accession Number		(0008, 0050)	1	SH
Modality	CT	(0008, 0060)	1	CS
Manufacturer	GE MEDICAL SYSTEMS	(0008, 0070)	1	LO
Institution Name		(0008, 0080)	1	LO
Referring Physician's Name		(0008, 0090)	1	PN
Manufacturer's Model Name	Discovery ST	(0008, 1090)	1	LO
Referenced Image Sequence		(0008, 1140)	1	SQ
Patient's Name		(0010, 0010)	1	PN
Patient ID		(0010, 0020)	1	LO
Patient's Birth Date		(0010, 0030)	1	DA
Patient's Sex		(0010, 0040)	1	CS
Patient Identity Removed	YES	(0012, 0062)	1	CS
De-identification Method	DICOMANON (rev R2010a) - PS 3.15-2008 Table E.1-1 - nondefault	(0012, 0063)	1	LO
Scan Options	HELICAL MODE	(0018, 0022)	1	CS
Slice Thickness	3.75	(0018, 0050)	1	DS

Creating the VOXEL file

The “Voxel” tab is used in order to convert the CT dataset to VOXELS. For the VOXEL geometry two additional files are needed (material.inp and calib_curve.mat).



The screenshot shows the Flair software interface with the 'Voxel' tab selected. A yellow arrow points to the 'Voxel' icon in the top toolbar. Another yellow arrow points to the 'Materials' field, which contains 'material.inp' and 'Unit to Material' field, which contains 'calib_curve.mat'. A red text overlay with a yellow arrow points to these fields, stating 'Step 8: Add materials and calibration files'.

HUmin	HUmax	Material	Crho_min	Crho_max	CdEdx_rel_min	CdEdx_rel_max
-3072	-1021	AIR	0.6825432	1.3174568	1.0	1.0
-1020	-1016	HU<-1015	0.720281108	1.27971895	1.0	1.0
-1015	-1011	HU<-1010	0.835391418	1.16460858	1.0	1.0
-1010	-1001	HU<-1000	0.733656625	1.16949124	1.0	1.0
-1000	-996	HU<-995	0.909584201	1.05424948	1.0	1.0
-995	-989	HU<-988	0.909502356	1.09049764	1.0	1.0
-988	-975	HU<-974	0.85108832	1.14891168	1.0	1.0
-974	-963	HU<-962	0.902912681	1.09708732	1.0	1.0
-962	-951	HU<-950	0.919883508	1.08011649	1.0	1.0
-950	-926	HU<-925	0.862306423	1.13769358	1.0	1.0
-925	-901	HU<-900	0.893000468	1.10699951	1.0	1.0
-900	-831	HU<-830	0.783902333	1.21609767	1.0	1.0
-830	-701	HU<-700	0.75158871	1.24841129	1.0	1.0
-700	-501	HU<-500	0.765689411	1.23431059	1.0	1.0
-500	-121	HU<-120	0.734835247	1.26516475	1.0	1.0
-120	-84	HU<-83	0.980501545	1.01835909	1.0	1.0
-83	-54	HU<-53	0.98600717	1.01305997	1.0	1.0
-53	-24	HU<-23	0.986384099	1.01270032	1.0	1.0
-23	6	HU<7	0.98674495	1.01236373	1.0	1.0
7	14	HU<18	0.995655766	1.00173225	1.0	1.0
15	79	HU<80	0.972407965	1.03421835	1.0	1.0
80	100	HU<120	0.980146255	1.00104493	1.0	1.0
101	119	HU<120	0.962511989	0.973311932245	1.0	1.0
120	199	HU<200	0.973911929092	1.02131168	1.0	1.0
200	299	HU<300	0.97508777	1.02542064	1.0	1.0
300	399	HU<400	0.976293061	1.02419075	1.0	1.0
400	499	HU<500	0.977387107	1.02307438	1.0	1.0
500	599	HU<600	0.97838463	1.0220565	1.0	1.0

- **material.inp**: file with conversion of HU to materials nominal density and composition
- **calib_curve.mat**: file with density correction factors to be applied to the lower/upper limit of the HU range

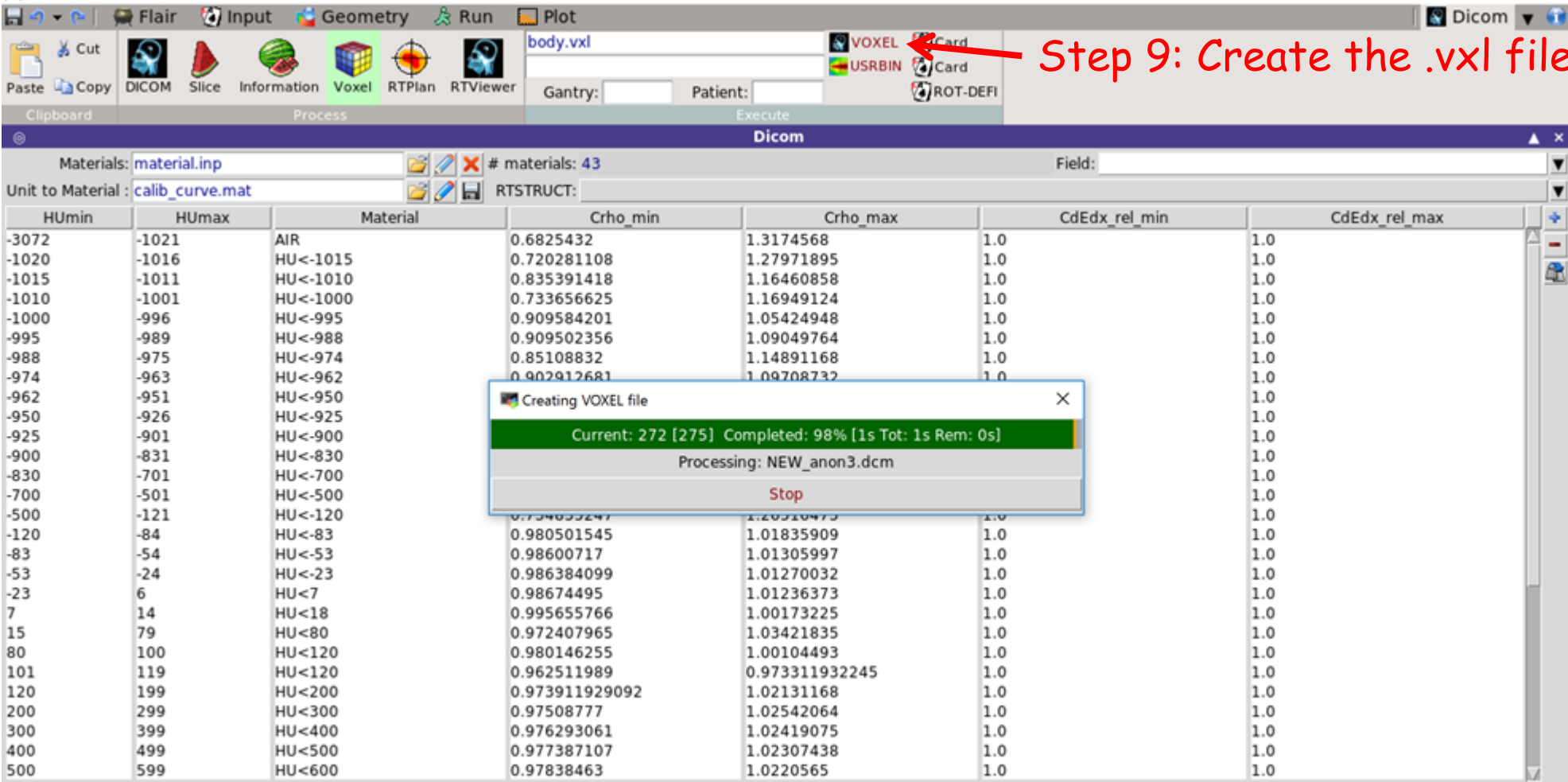
Creating the VOXEL file: the .mat file

- **<= 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.
- **CdEdx_rel_min/CdEdx_rel_max**: relative correction factors on dE/dx for minimum/maximum unit in the range.

HUmin	HUmax	Material	Crho_min	Crho_max	CdEdx_rel_min	CdEdx_rel_max
-3072	-1021	AIR	0.6825432	1.3174568	1.0	1.0
-1020	-1016	HU<-1015	0.720281108	1.27971895	1.0	1.0
-1015	-1011	HU<-1010	0.835391418	1.16460858	1.0	1.0
-1010	-1001	HU<-1000	0.733656625	1.16949124	1.0	1.0
-1000	-996	HU<-995	0.909584201	1.05424948	1.0	1.0
-995	-989	HU<-988	0.909502356	1.09049764	1.0	1.0
-988	-975	HU<-974	0.85108832	1.14891168	1.0	1.0
-974	-963	HU<-962	0.902912681	1.09708732	1.0	1.0
-962	-951	HU<-950	0.919883508	1.08011649	1.0	1.0
-950	-926	HU<-925	0.862306423	1.13769358	1.0	1.0
-925	-901	HU<-900	0.893000468	1.10699951	1.0	1.0
-900	-831	HU<-830	0.783902333	1.21609767	1.0	1.0
-830	-701	HU<-700	0.75158871	1.24841129	1.0	1.0
-700	-501	HU<-500	0.765689411	1.23431059	1.0	1.0
-500	-121	HU<-120	0.734835247	1.26516475	1.0	1.0
-120	-84	HU<-83	0.980501545	1.01835909	1.0	1.0
-83	-54	HU<-53	0.98600717	1.01305997	1.0	1.0
-53	-24	HU<-23	0.986384099	1.01270032	1.0	1.0
-23	6	HU<7	0.98674495	1.01236373	1.0	1.0
7	14	HU<18	0.995655766	1.00173225	1.0	1.0
15	79	HU<80	0.972407965	1.03421835	1.0	1.0
80	100	HU<120	0.980146255	1.00104493	1.0	1.0
101	119	HU<120	0.962511989	0.973311932245	1.0	1.0

Creating the VOXEL file

The "Voxel" tab is used in order to convert the CT dataset to VOXELS. For the VOXEL geometry two additional files are needed (material.inp and calib_curve.mat).



The screenshot shows the FLUKA GUI with the 'Voxel' tab selected. A red arrow points to the 'VOXEL' button in the top toolbar, with the text 'Step 9: Create the .vxl file' next to it. The main window displays a table of material properties. A dialog box titled 'Creating VOXEL file' is open in the foreground, showing progress: 'Current: 272 [275] Completed: 98% [1s Tot: 1s Rem: 0s]' and 'Processing: NEW_anon3.dcm'. The dialog has a 'Stop' button at the bottom.

HUmin	HUmax	Material	Crho_min	Crho_max	CdEdx_rel_min	CdEdx_rel_max
-3072	-1021	AIR	0.6825432	1.3174568	1.0	1.0
-1020	-1016	HU<-1015	0.720281108	1.27971895	1.0	1.0
-1015	-1011	HU<-1010	0.835391418	1.16460858	1.0	1.0
-1010	-1001	HU<-1000	0.733656625	1.16949124	1.0	1.0
-1000	-996	HU<-995	0.909584201	1.05424948	1.0	1.0
-995	-989	HU<-988	0.909502356	1.09049764	1.0	1.0
-988	-975	HU<-974	0.85108832	1.14891168	1.0	1.0
-974	-963	HU<-962	0.902912681	1.09708732	1.0	1.0
-962	-951	HU<-950			1.0	1.0
-950	-926	HU<-925			1.0	1.0
-925	-901	HU<-900			1.0	1.0
-900	-831	HU<-830			1.0	1.0
-830	-701	HU<-700			1.0	1.0
-700	-501	HU<-500			1.0	1.0
-500	-121	HU<-120			1.0	1.0
-120	-84	HU<-83	0.980501545	1.01835909	1.0	1.0
-83	-54	HU<-53	0.98600717	1.01305997	1.0	1.0
-53	-24	HU<-23	0.986384099	1.01270032	1.0	1.0
-23	6	HU<7	0.98674495	1.01236373	1.0	1.0
7	14	HU<18	0.995655766	1.00173225	1.0	1.0
15	79	HU<80	0.972407965	1.03421835	1.0	1.0
80	100	HU<120	0.980146255	1.00104493	1.0	1.0
101	119	HU<120	0.962511989	0.973311932245	1.0	1.0
120	199	HU<200	0.973911929092	1.02131168	1.0	1.0
200	299	HU<300	0.97508777	1.02542064	1.0	1.0
300	399	HU<400	0.976293061	1.02419075	1.0	1.0
400	499	HU<500	0.977387107	1.02307438	1.0	1.0
500	599	HU<600	0.97838463	1.0220565	1.0	1.0

Modifying the VOXEL card

The “Voxel” tab is used in order to convert the CT dataset to VOXELS. For the VOXEL geometry two additional files are needed (material.inp and calib_curve.mat).

The screenshot shows the Dicom software interface. At the top, there is a menu bar with options like 'Flair', 'Input', 'Geometry', 'Run', and 'Plot'. Below the menu bar is a toolbar with icons for 'Cut', 'Copy', 'Paste', 'DICOM', 'Slice', 'Information', 'Voxel', 'RTPlan', and 'RTViewer'. The 'Voxel' tab is currently selected. In the center, there is a panel with 'body.vxl' and 'Gantry:' and 'Patient:' fields. To the right of this panel, there are three buttons: 'VOXEL Card', 'USRBIN Card', and 'ROT-DEFI Card'. A red arrow points to the 'VOXEL Card' button, and the text 'Step 10: Modify VOXEL card' is written next to it. Below the toolbar, there is a 'Dicom' section with 'Materials: material.inp' and '# materials: 43'. Below this, there is a table with columns: 'HUmin', 'HUmax', 'Material', 'Crho_min', 'Crho_max', 'CdEdx_rel_min', and 'CdEdx_rel_max'. The table contains 43 rows of data, representing different materials and their properties.

HUmin	HUmax	Material	Crho_min	Crho_max	CdEdx_rel_min	CdEdx_rel_max
-3072	-1021	AIR	0.6825432	1.3174568	1.0	1.0
-1020	-1016	HU<-1015	0.720281108	1.27971895	1.0	1.0
-1015	-1011	HU<-1010	0.835391418	1.16460858	1.0	1.0
-1010	-1001	HU<-1000	0.733656625	1.16949124	1.0	1.0
-1000	-996	HU<-995	0.909584201	1.05424948	1.0	1.0
-995	-989	HU<-988	0.909502356	1.09049764	1.0	1.0
-988	-975	HU<-974	0.85108832	1.14891168	1.0	1.0
-974	-963	HU<-962	0.902912681	1.09708732	1.0	1.0
-962	-951	HU<-950	0.919883508	1.08011649	1.0	1.0
-950	-926	HU<-925	0.862306423	1.13769358	1.0	1.0
-925	-901	HU<-900	0.893000468	1.10699951	1.0	1.0
-900	-831	HU<-830	0.783902333	1.21609767	1.0	1.0
-830	-701	HU<-700	0.75158871	1.24841129	1.0	1.0
-700	-501	HU<-500	0.765689411	1.23431059	1.0	1.0
-500	-121	HU<-120	0.734835247	1.26516475	1.0	1.0
-120	-84	HU<-83	0.980501545	1.01835909	1.0	1.0
-83	-54	HU<-53	0.98600717	1.01305997	1.0	1.0
-53	-24	HU<-23	0.986384099	1.01270032	1.0	1.0
-23	6	HU<7	0.98674495	1.01236373	1.0	1.0
7	14	HU<18	0.995655766	1.00173225	1.0	1.0
15	79	HU<80	0.972407965	1.03421835	1.0	1.0
80	100	HU<120	0.980146255	1.00104493	1.0	1.0
101	119	HU<120	0.962511989	0.973311932245	1.0	1.0
120	199	HU<200	0.973911929092	1.02131168	1.0	1.0
200	299	HU<300	0.97508777	1.02542064	1.0	1.0
300	399	HU<400	0.976293061	1.02419075	1.0	1.0
400	499	HU<500	0.977387107	1.02307438	1.0	1.0
500	599	HU<600	0.97838463	1.0220565	1.0	1.0
600	699	HU<700	0.979297863	1.02112463	1.0	1.0

The voxels card

The geometry is written like a normal Combinatorial Geometry input, but in addition a **VOXELS** card is 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 the whole voxel
- **WHAT(5), WHAT(6)**: not used
- **SDUM** = name of the voxel file
extension will be assumed to be **.vxl**)












x: -35.068359
Trans: ▾

y: -35.068359
Filename: bodyCT ▾

z: -88.6855

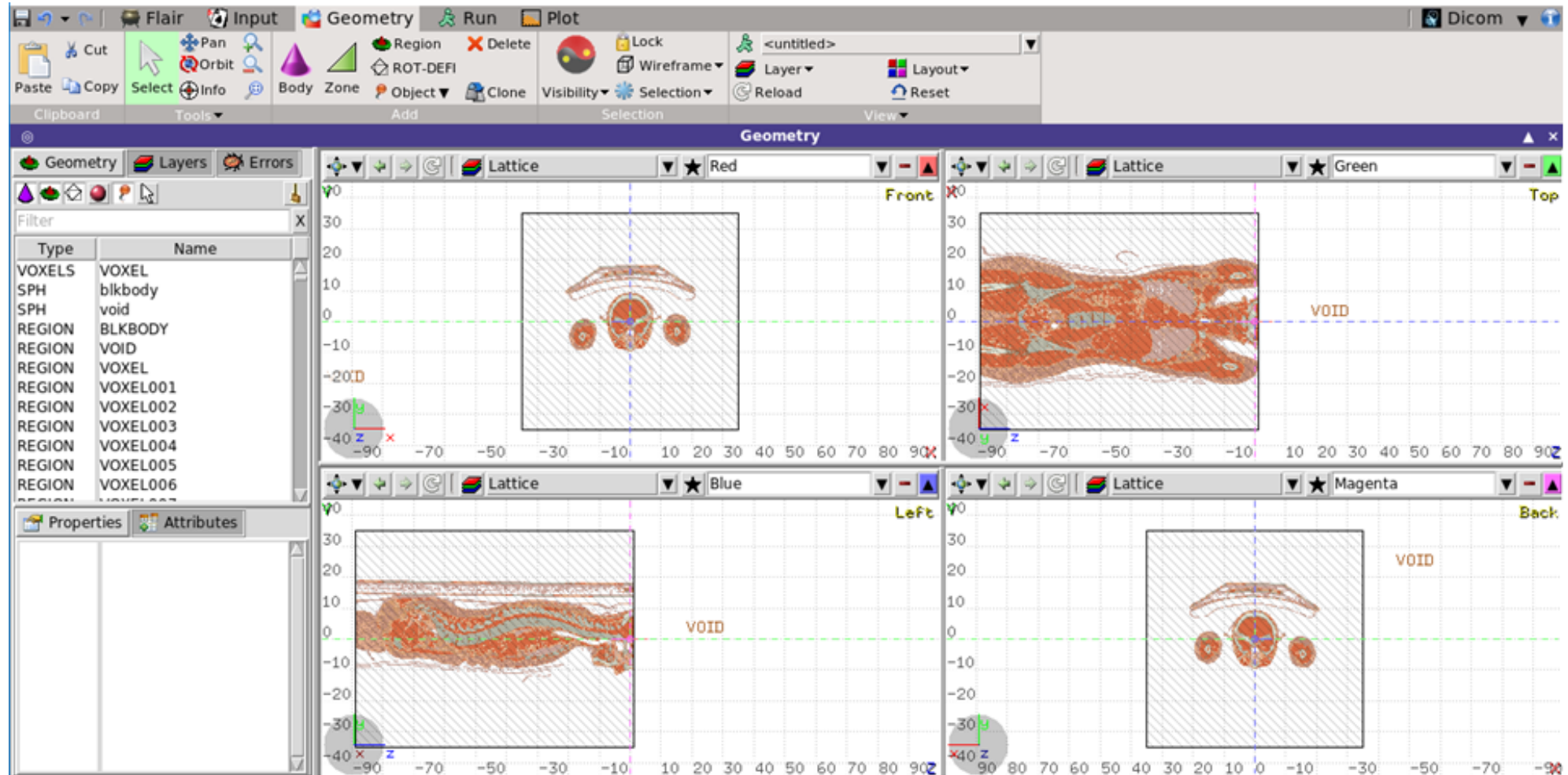
Voxel Body

- 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 $(\text{NB}+1)^{\text{th}}$ 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.

 GEOBEGIN		Log: ▼ Geometry: ▼	Acc: Out: ▼	Opt: ▼ Fmt: COMBNAME ▼
Title:				
 VOXELS		x: -35.0683594 Trans: ▼	y: -35.0683594 Filename: body ▼	z: -88.6615
Black body  SPH	blkbody	x: 0 R: 100000	y: 0	z: 0
Void sphere  SPH	void	x: 0 R: 10000	y: 0	z: 0
 END				
Black hole  REGION	BLKBODY expr: +blkbody -void		Neigh: 5	
Void around  REGION	VOID expr: +void -VOXEL		Neigh: 5	
 END				
 GEOEND				

Voxel Regions (1/2)

The code will automatically generate and add several regions



Voxel Regions

The code will automatically generate and add several regions.

- **NM** additional regions, where **NM** = 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+NM	corresponding to organ NM

Run the example and check the output

Run a simulation using 400 MeV/n primary carbon ions at (0.0, 0.0, -200.0) cm.

In the output file check:

- RPP bodies
- Voxel regions
- Range of HUs and corresponding density and dE/dx
- Composition of materials with HUs<-1015
- CORRFACtors

The region-dependent CORRFAC card

- “CORRFAC” card allows to alter material density for dE/dx and nuclear processes
- First two WHATs 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 WHAT(4-6) [cf. manual]
- Especially important in PT to force the MC to follow the same semi-empirical HU-range calibration curve as the Treatment Planning System (TPS) for dosimetric comparisons
- At the end of the .vxl file FLAIR automatically appends the CORRFAC cards, calculated taking into account the calibration curves provided by the user.

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 (\Rightarrow 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 25

CORRFACT 1.3 0.0 0.0 31

Region #25 corresponds
to "softer" bone than #31

Few remarks

- The assignment of materials to organ regions is made directly by FLAIR. The user has to assign the materials to the remaining regions defined by standard combinatorial geometry.
- The “calib_curve.mat” and “material.inp” files are examples, the users should update these files taking into account the calibration curves for their treatment planning systems (calibration curve depends on the calculation method, used phantom and (only slightly) scanner).



Additional Info

FLUKA PET TOOLS (1/2)

The FLUKA PET TOOLS package* consists of:

- **PET geometry tools:** to replicate the PET scanner existing commercial models or a customized model
- **Scoring routines:** to collect the relevant simulated data (e.g. coincidence γ)
- **Post-processing routines:** to generate both sinogram and coincidence lists output
- **Imaging tools:** by means of a filtered-back-projection algorithm, or an embedded maximum-likelihood-estimation-method**, the output is converted into images.

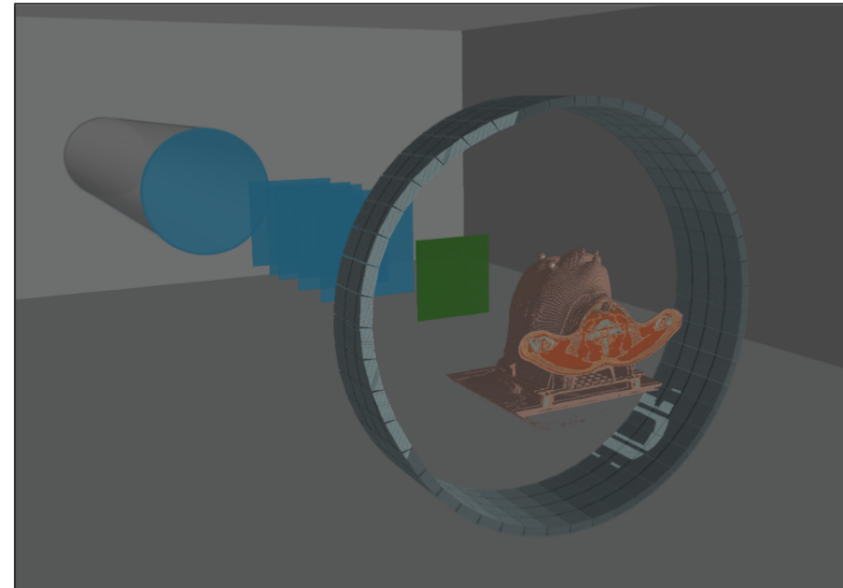
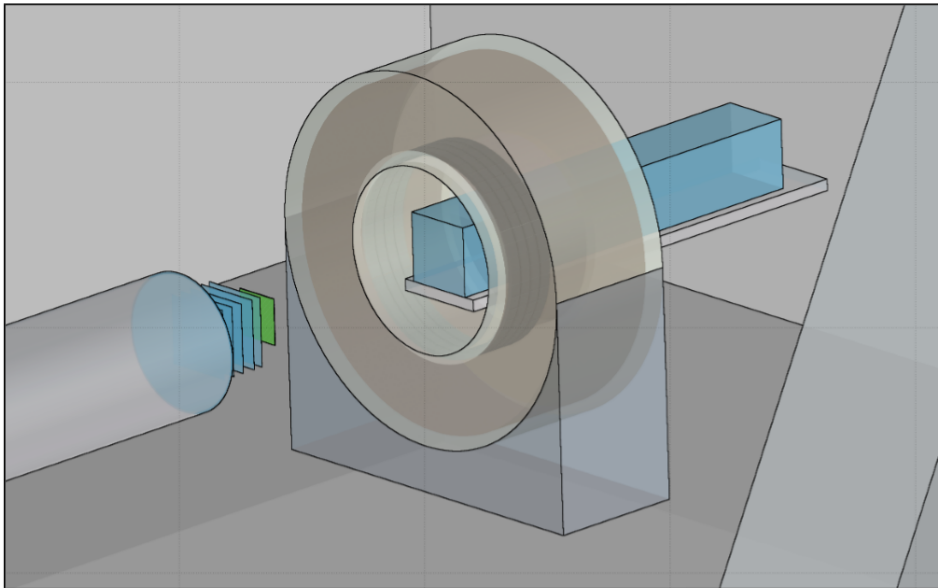
*Ortega P-PG *et al*/2014 Radiother Oncol, 110

**MLEM implementation code written by Toufique Y

FLUKA PET TOOLS (2/2)

The FLUKA PET TOOLS package allows:

- to model a realistic PET scanner in Flair
- image acquisition a in a patient VOXEL phantom
- integration of beam time structure and event filtering
- scanner design and image optimization



FLUKA PET TOOLS : Example of application

Mouse Geometry in
Flair



Radioisotope
density map
in Flair

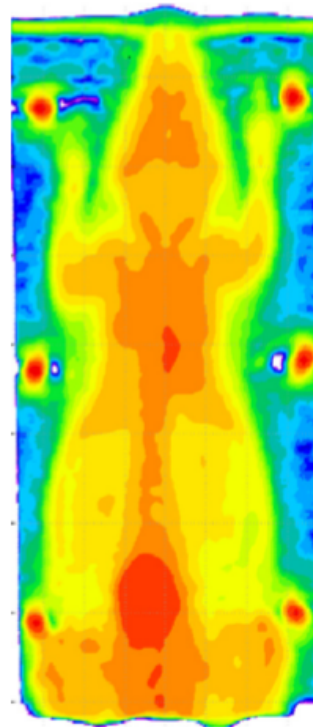


Image
reconstructed
with FBP

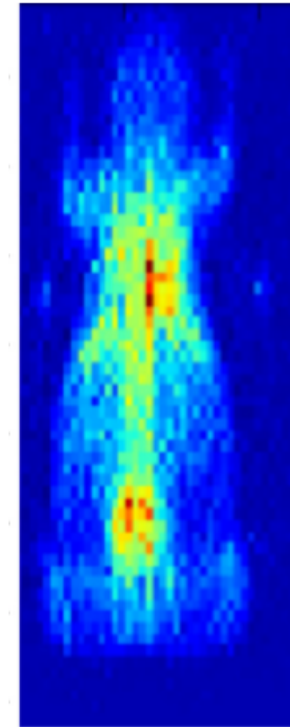
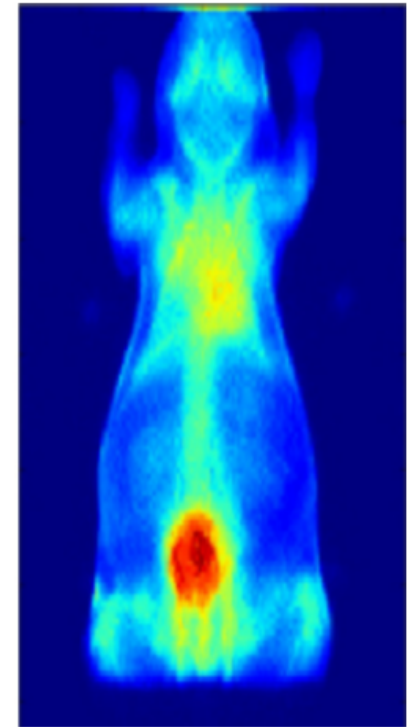
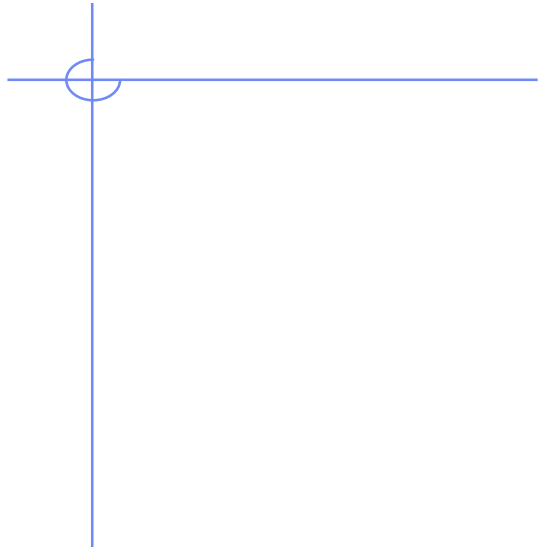


Image
reconstructed
with MLEM





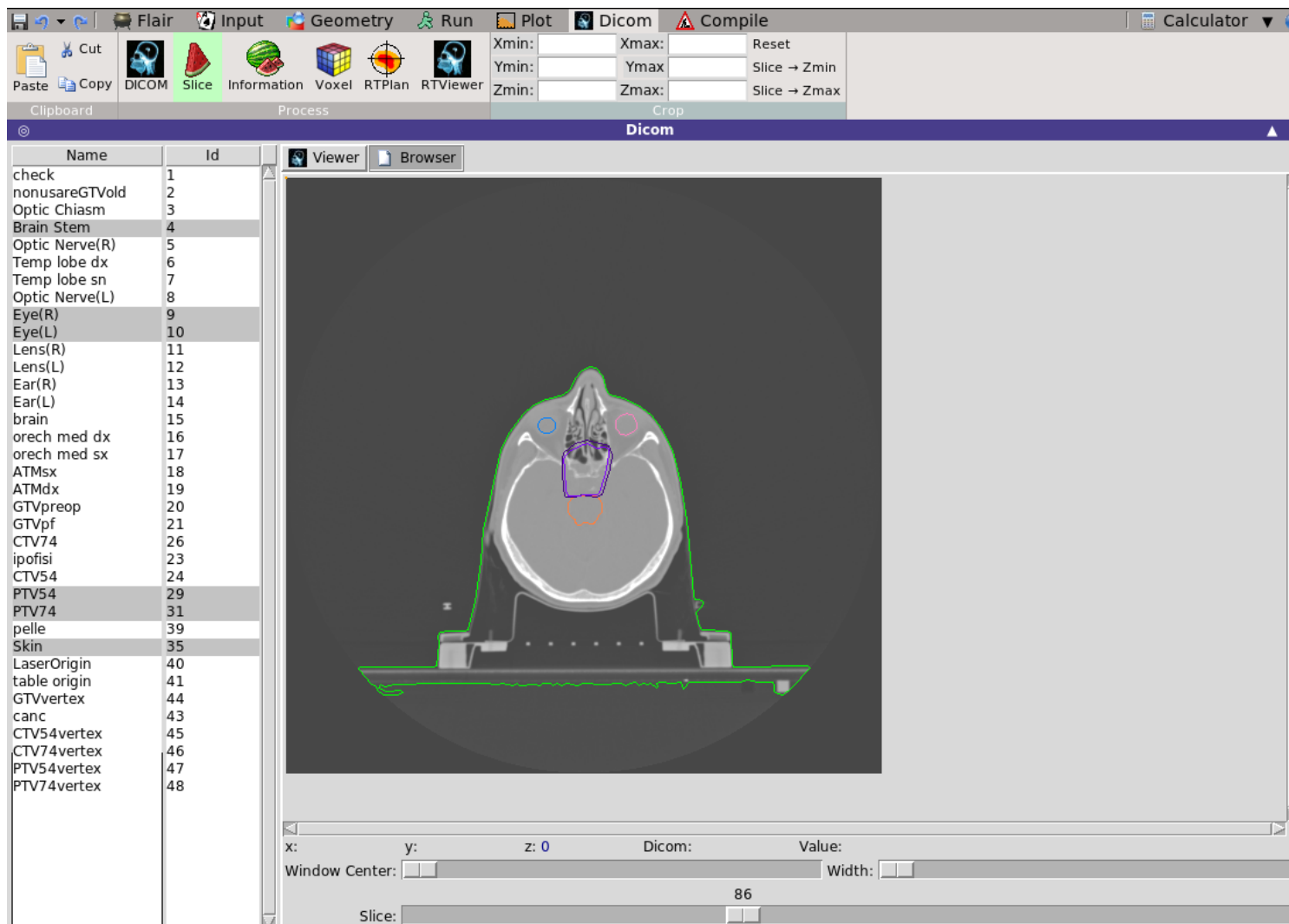
Spare

The FLUKA voxel with ROI

- The information for regions of interest (ROIs) and points of interests (eg. dose reference points) are included in RTSTRUCT file
- ROIs are represented as the points belonging to a closed polygon using 2D coordinates (not rounded to the pixel size of the corresponding CT image).
- User can embedded RTSTRUCT file into the VOXEL
 - For each voxel Flair identifies list of ROIs and creates ROI to voxel correspondence matrix
 - Voxel **with RT STRUCT** information can be currently used as an input for DVH calculations, however **simulations will be available with the next FLUKA release**
 - Flair provides some checks on the structures, like calculating volumes using the true polygonal information or the discretization to voxels. Differences up to few percent can be visible due to quantification process

Processing the **DICOM** files with FLAIR VII

Select RTSTRUCT “Data sets” and inspect the ROI’s



Processing the **DICOM** files with FLAIR VIII

User can include ROIs imported from RTSTRUCT. Selection of corresponding file is done in VoxelTab.

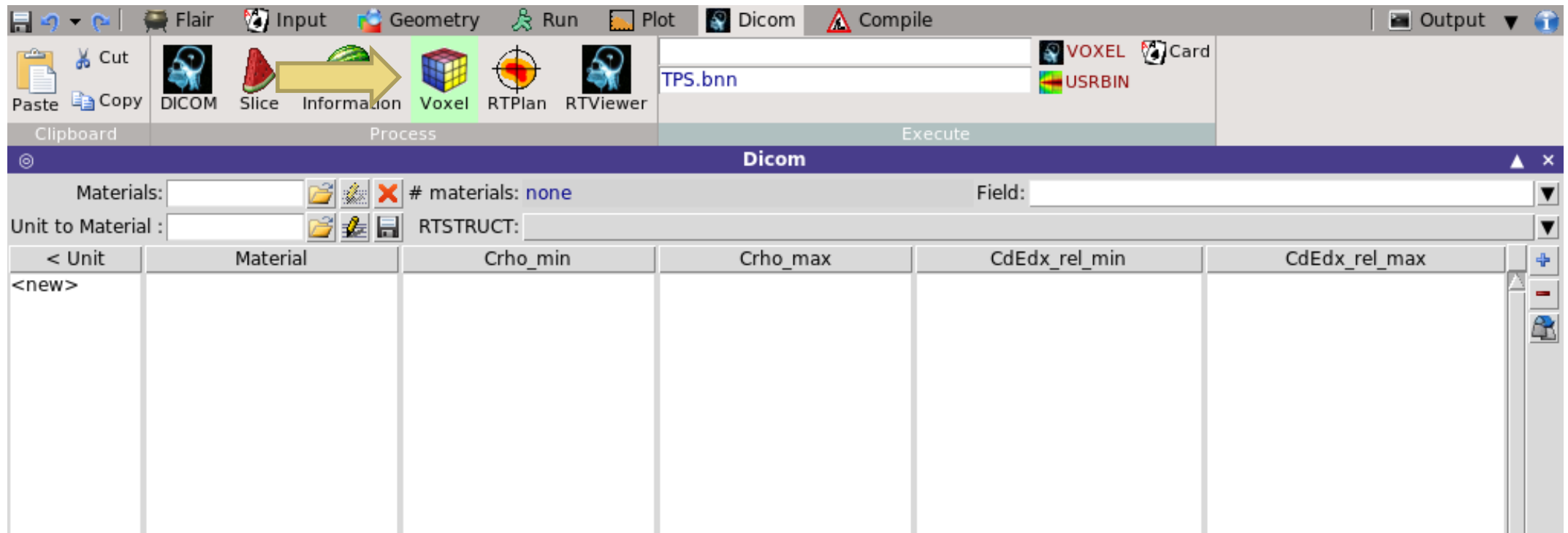
The screenshot displays the FLAIR VIII software interface. The main window is titled "Dicom" and contains a table with columns: "< Unit", "Material", "Crho_min", "Crho_max", "CdEdx_rel_min", and "CdEdx_rel_max". The table lists materials and their corresponding HU ranges and density values. A yellow arrow points to the "Unit to Material" field, which is set to ".../..flair/dicom/head.mat". A dialog box titled "Processing RTSTRUCTs" is overlaid on the table, showing a progress bar and the text "Current: 38 [230] Completed: 16% [0:00:10 | 0:01:00]". The dialog also displays the RTSTRUCT file path: "Processing: 1.3.12.2.1107.5.1.4.49597.30000012011114455237500000281".

< Unit	Material	Crho_min	Crho_max	CdEdx_rel_min	CdEdx_rel_max
-1020	AIR	0.000432	1.3174568	1.0	1.0
-1015	HU<-1015	0.721281108	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				1.0
-700	HU<-700				1.0
-500	HU<-500				1.0
-120	HU<-120				1.0
-83	HU<-83				1.0
-53	HU<-53				1.0
-23	HU<-23				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

Processing the **DICOM** files with FLAIR IX

The “VoxelTab” is also for converting the RTDOSE dataset to FLUKA understandable format – USRBIN.

This can be further used for postprocessing and plotting purposes.



Processing the **DICOM** files with FLAIR X

The "RTPlan" tab is used to modify input file for Treatment Plan Simulations using data from RTPLAN and RTDOSE

The screenshot displays the FLUKA FLAIR X software interface. The top menu bar includes options like Flair, Input, Geometry, Run, Plot, Dicom, and Compile. Below the menu is a toolbar with icons for various functions. The main window is divided into several panels. The 'Dicom' panel is active, showing a table of RTPlan files and a list of beams. The 'Information' panel on the right displays patient and beam details. Two yellow arrows point to specific fields: one to the 'RTDOSE' dropdown menu and another to the 'Beam Weight' field.

RTPlan Table:

RTPlan	Date
RTPlan74GyE.dcm	2012.01.20

Choose Beam Number Table:

Beam	# points	Gantry Ang	Patient Ang
1	98	90.0	0
2	92	90.0	180.0
3	48	90.0	270.0

Information Panel:

Patient Info:

- Patient's Name: S, F
- Patient's Age: 100Y
- Patient's Sex: F

RT Plan Info:

- RT Plan Name: 2Beam54
- Dose Type: EFFECTIVE
- Plan Intent: CURATIVE
- Approval Status: APPROVED
- Review Date: 2012.01.20 130922.64:89
- Reviewer Name:

General Beam Info:

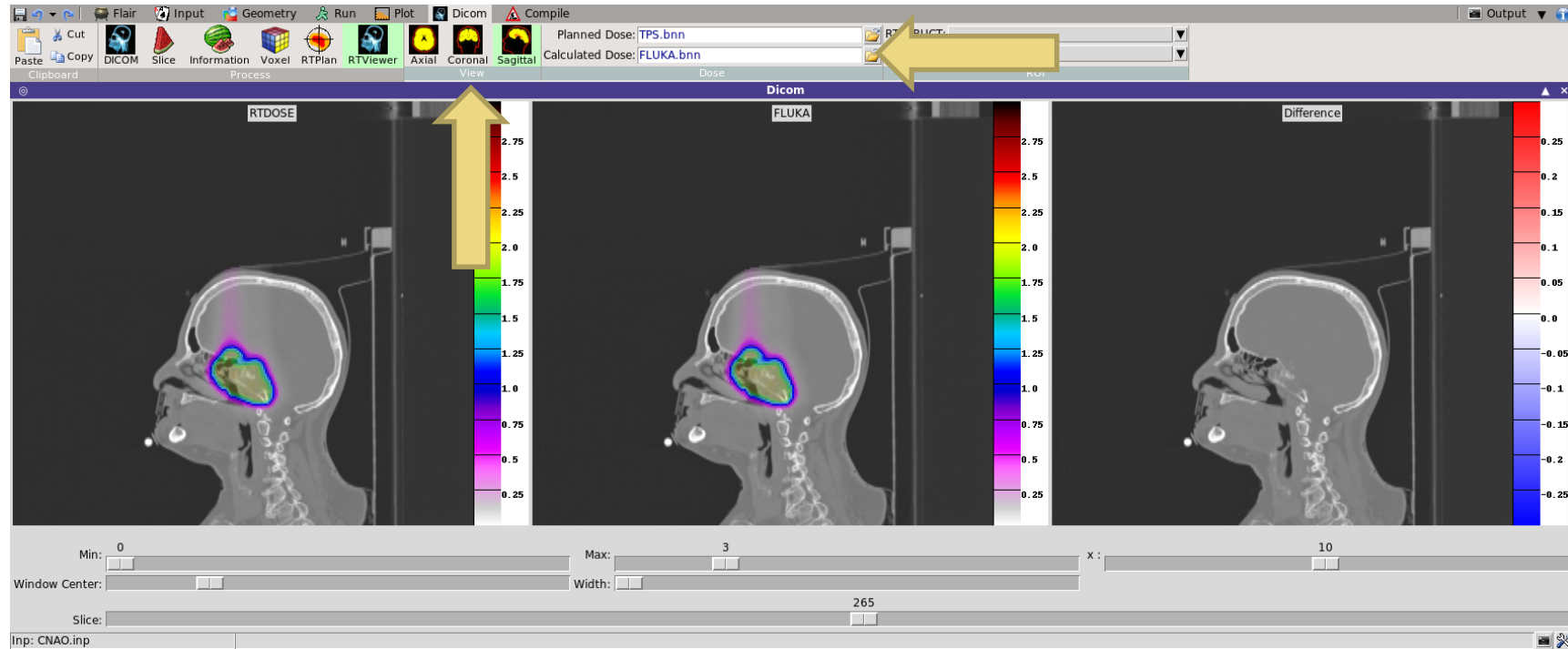
- Beam Name: B1
- Beam Weight: 15331795521.4688
- Beam Type: STATIC
- Radiation Type: PROTON
- Scan Mode: MODULATED
- # Control Points: 98

Rotations Info:

- Gantry Angle: 90.0
- Gantry Pitch Angle: 0
- Patient Support Angle: 0
- Table Top Pitch Angle: 0
- Table Roll Angle: 0

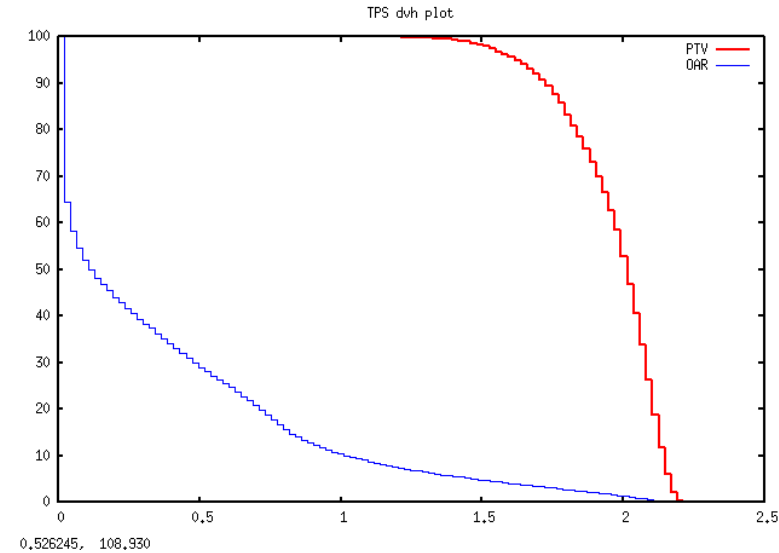
Processing the **DICOM** files with FLAIR XI

- The “RTViewer” tab provides graphical comparison of TPS and FLUKA calculations using USRBIN files
- Available views for Axial, Coronal and Sagittal planes



Processing the **DICOM** files with FLAIR XII

FLAIR postprocessing routine allows to create data for Dose-Volume Histograms (DVH) plots



The screenshot displays the FLAIR software interface. The 'Run' tab is active, showing a table of commands and outputs. The 'Input' tab is also visible, showing a table of input parameters.

Run	Command	Output	Unit
TPS	usrbin	TPS_22.bnn	22
TPS	usrbin	TPS_23.bnn	23
TPS	usrbin	TPS_24.bnn	24
TPS	usrbin2dvh	TPS_dvh_tab.lis	0

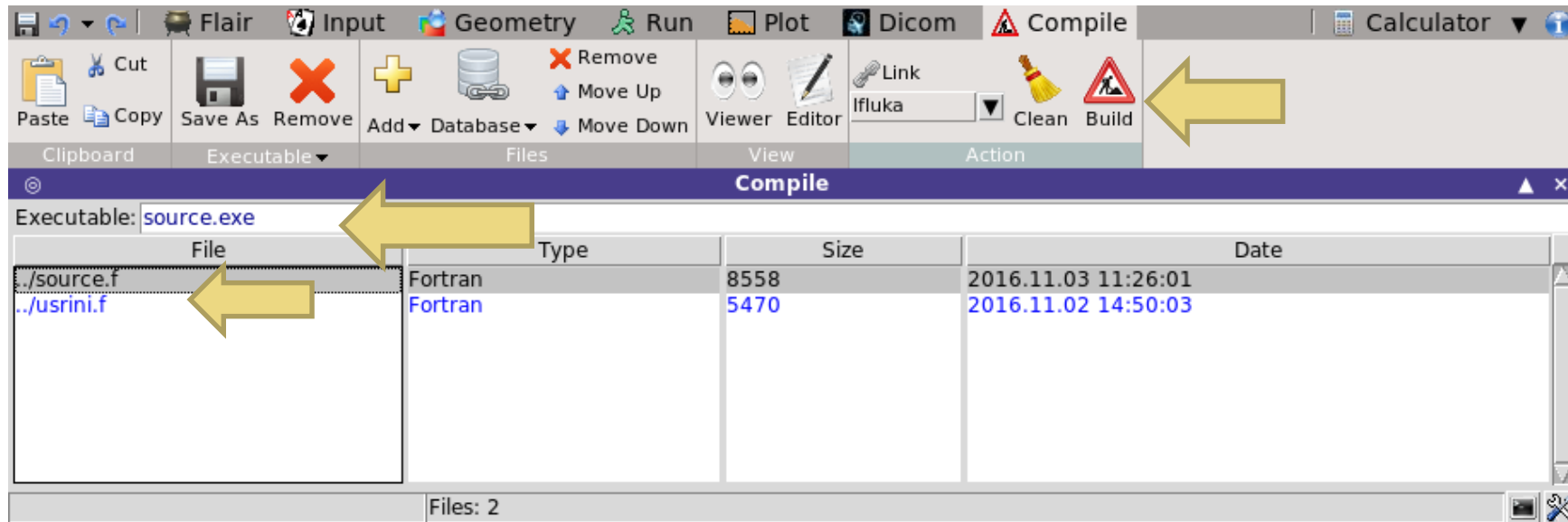
Name	Tag	Value	Type	Default
Output file	-o	TPS_dvh_tab.lis	output	V:\U_dvh_tab.lis
Usrbin file	-u	TPS.bnn	file	V:\U.bnn
Detector index	-d	1	int	1
Voxel file	-v	test_struct.vxl	file	=C(VOXELS,0,0)+".vxl"
Relative dose (Gray)	-r	0.0	float	0.0
Voxel x	-x	-25	float	=C(VOXELS,0,1)
Voxel y	-y	-49.2	float	=C(VOXELS,0,2)
Voxel z	-z	-14.9	float	=C(VOXELS,0,3)

Few remarks

- Updated input file from RTPlan Tab uses `#include` cards in order to import pencil beam parameters. Due to typical vast number of described beams user needs to **activate/deactivate** these cards.
- Simulated and processed FLUKA files have to be **weighted** according to the information from RTPlan – `usrwei` routine available in FLAIR.
- DVH plots requires `*.vxl` file **with RTSTRUCT** information.
- In RTViewer graphical comparison is available only for the `*.bnn` files with the **same binnings and positions**. Editing input file by RTPlan Tab allows to provide correct parameters – user chooses corresponding RTDOSE file.

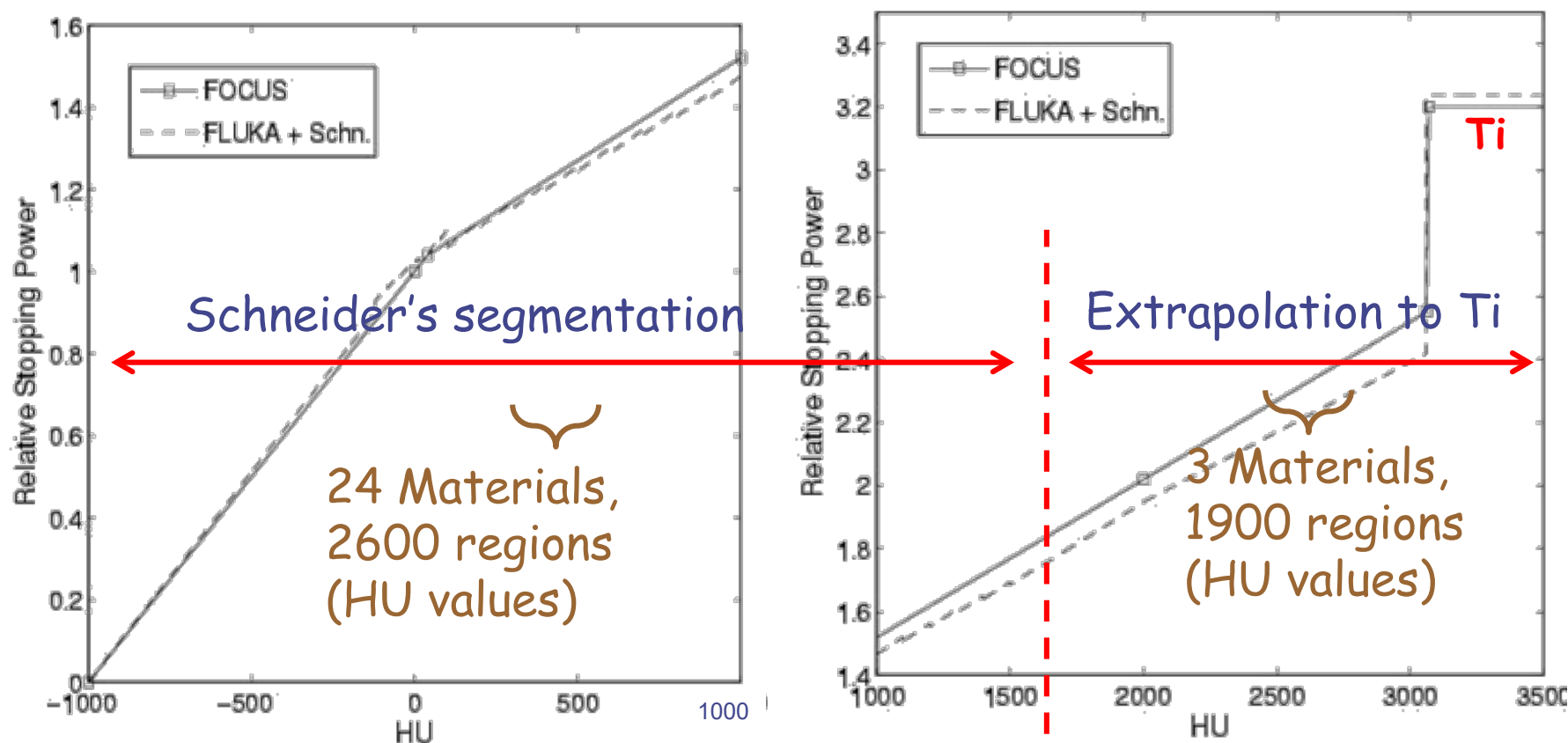
Additional material – user routine

- In current version user needs to compile special routine for defining pencil beam source parameters.
- In the next FLUKA release new cards will allow user to simulate RTPLAN without external routines.



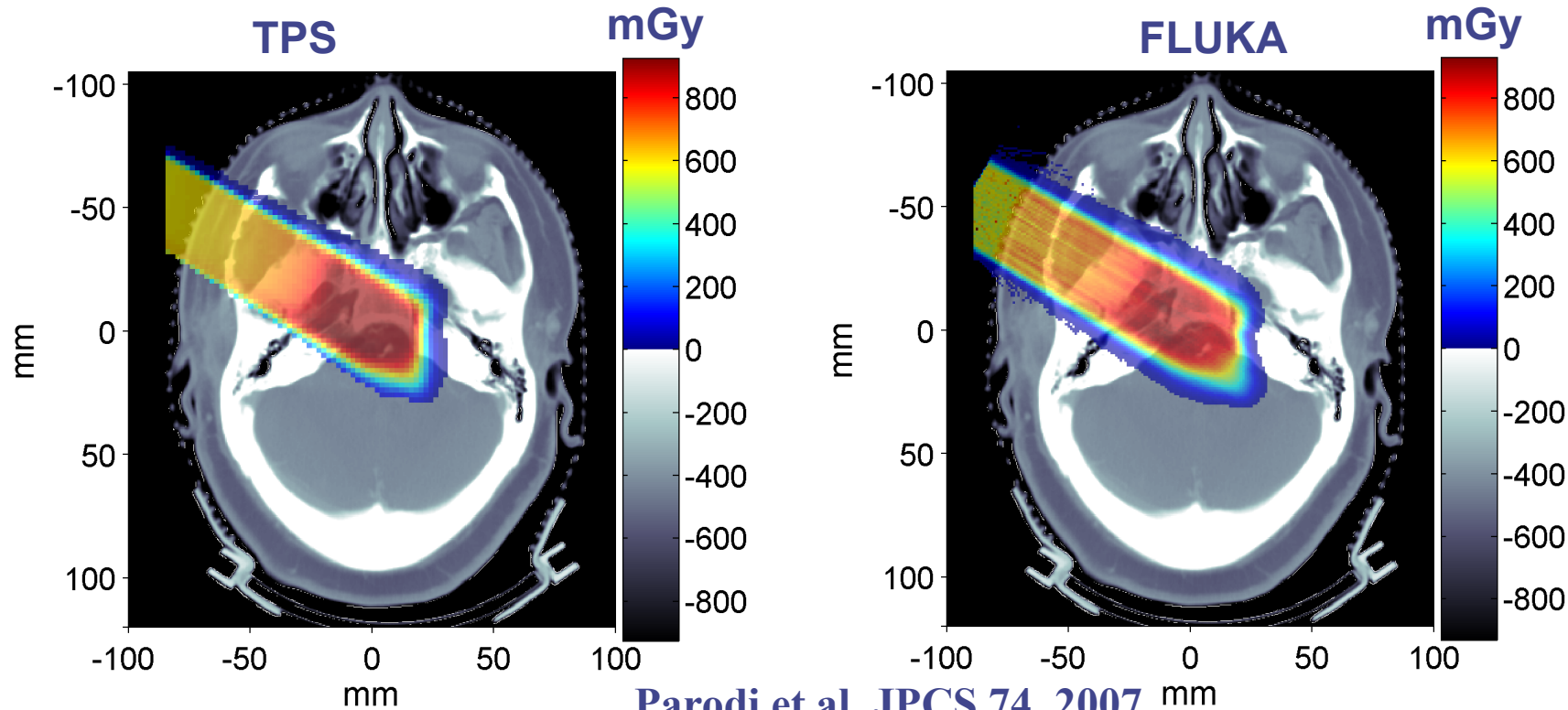
Forcing FLUKA to follow the same range calibration curve as TPS for p @ MGH Boston

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



Applications of FLUKA to p therapy @ MGH

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



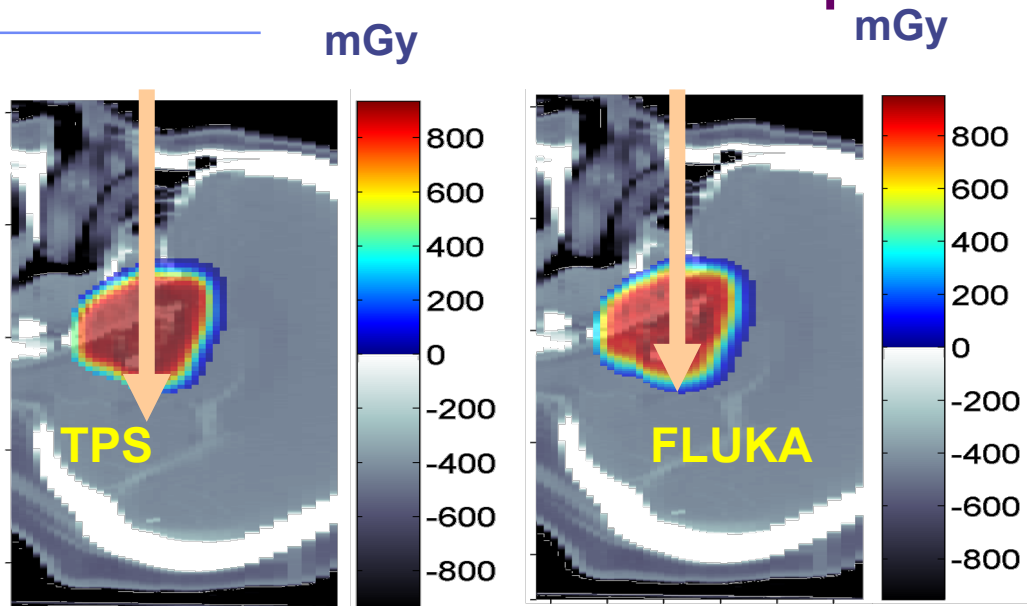
Parodi et al, JPCS 74, 2007

Prescribed dose: 1 GyE

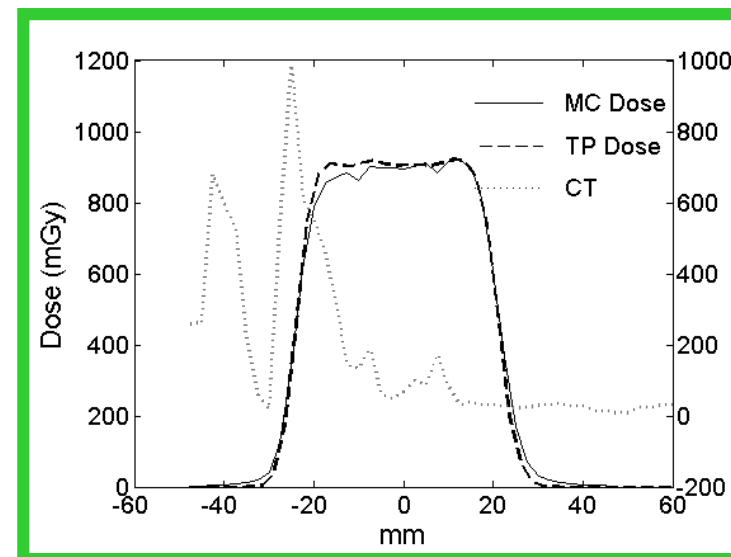
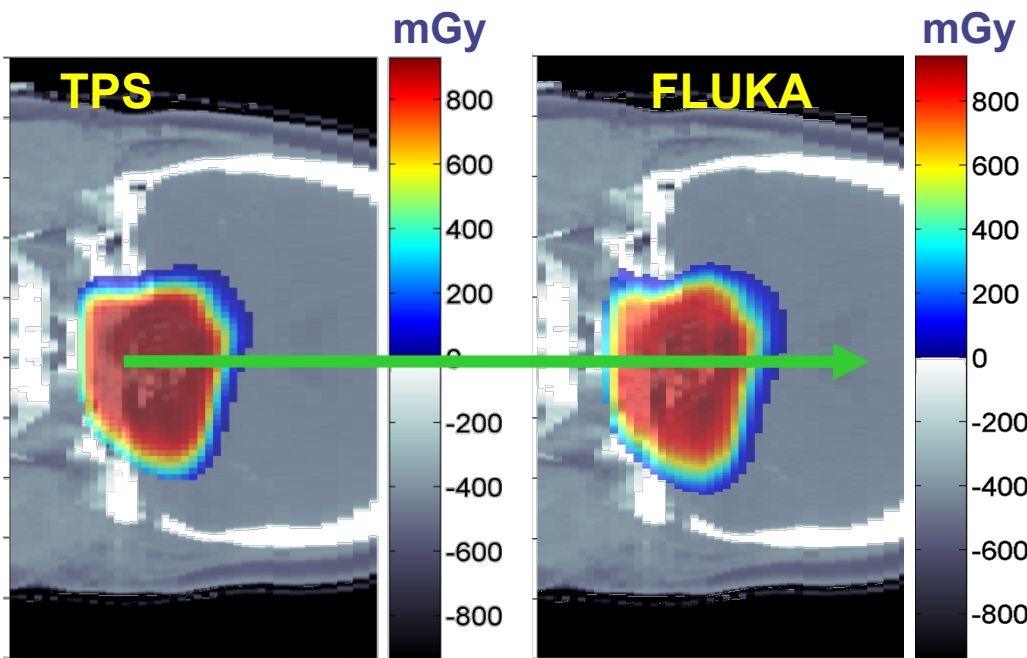
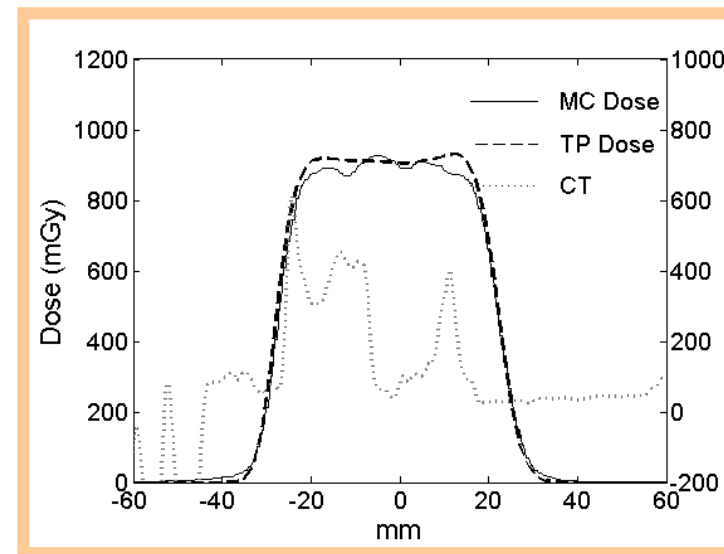
MC : $\sim 5.5 \cdot 10^6$ protons in 10 independent runs

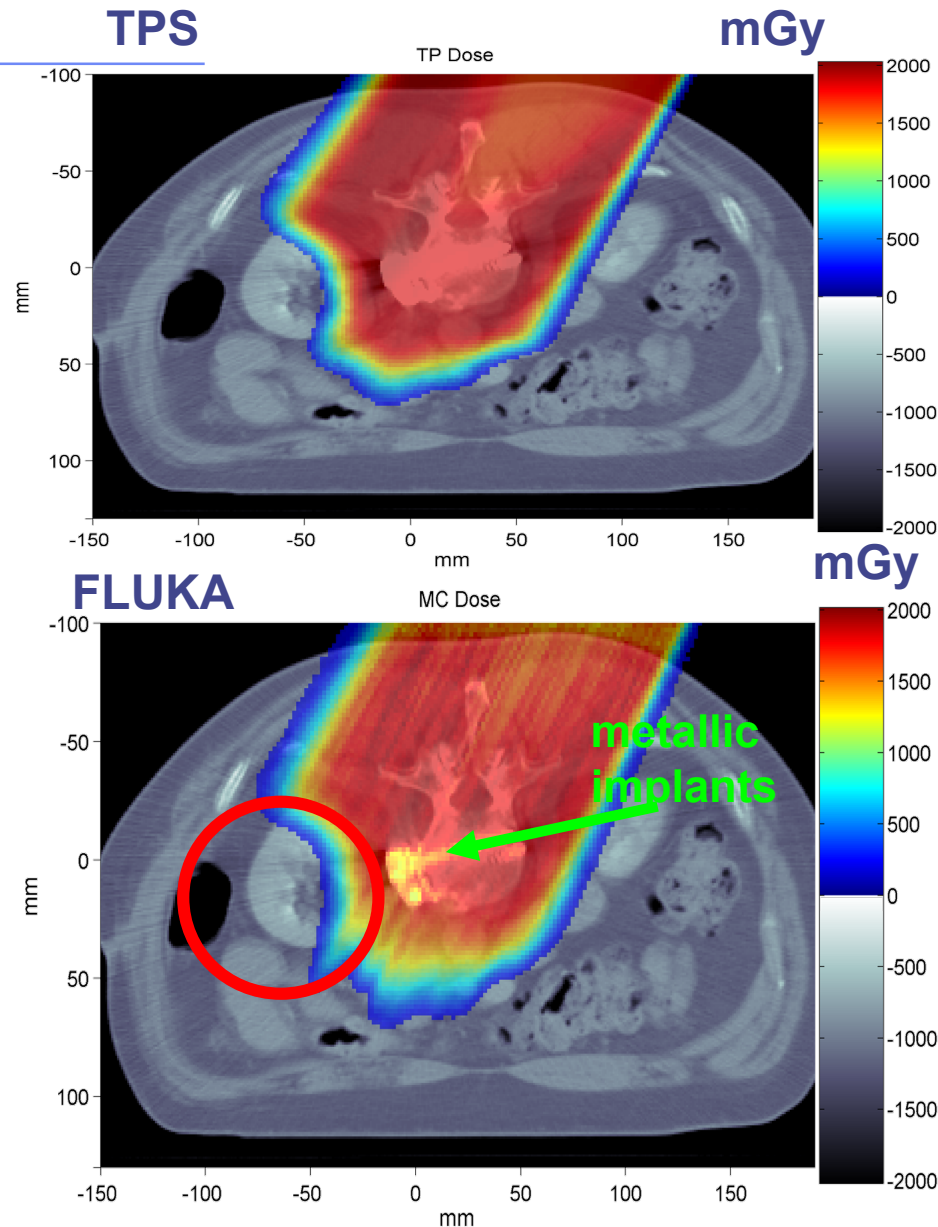
(11h each on Linux Cluster mostly using 2.2GHz Athlon processors)

Applications of FLUKA to p therapy @ MGH



Parodi et PMB 52, 2007





Applications of FLUKA to p therapy @ MGH

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

Applications of FLUKA to p therapy @ MGH

Clival Chordoma, 0.96 GyE / field

Planned dose

