蘭州大學
LANZHOU UNIVERSITY

Medical applications (part I)

23rd FLUKA Beginner's Course
Lanzhou University
Lanzhou, China

June 2–7, 2024

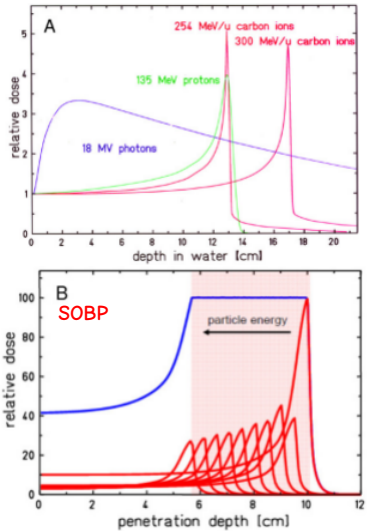
Medical Physics and related disciplines applications

- 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

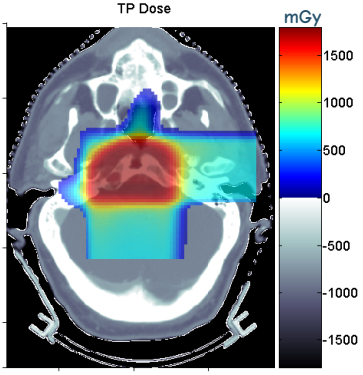
One of the powerful applications of FLUKA & FLAIR is related to Particle Therapy.

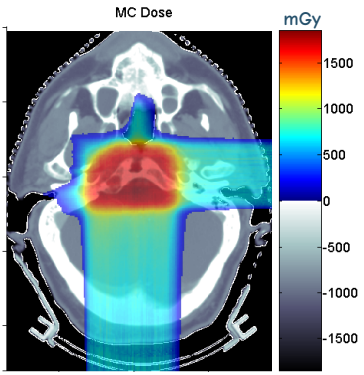
- Particle Therapy is a radiation therapy to treat tumors (deep seated, resistant to conventional RT with photons…)
- Exploits "heavy" charged particle beams (p, 12C,…); typical energy loss in matter characterized by the Bragg Peak (BP)
- With higher beam kinetic energy, particles will travel further and the BP will be situated deeper inside the target (the patient)
- Several Bragg Peaks with different energies can be summed up to cover the full tumor volume ("Spread-Out-Bragg-Peak (SPOB)"



The issue of complex geometries: patient cases

In clinics, treatment plans are needed. The medical physicists 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.

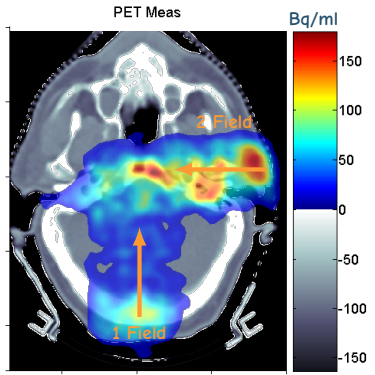


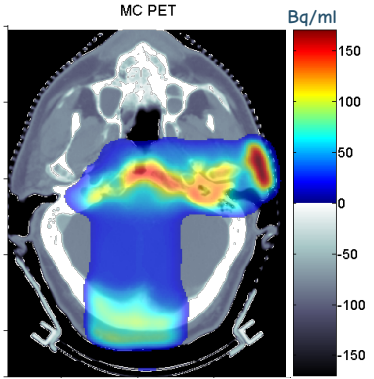


Example: Patient with clival chordoma receiving a posterior–anterior followed by a lateral field (0.96 GyE each), K. Parodi et al., Int J Radiat Oncol Biol Phys. 2007 July 1; 68(3): 920–934

Post irradiation PET/CT@MGH

Patient with clival chordoma receiving a posterior–anterior followed by a lateral field (0.96 GyE each). PET imaging 26 min and 16 min after field applications, respectively:

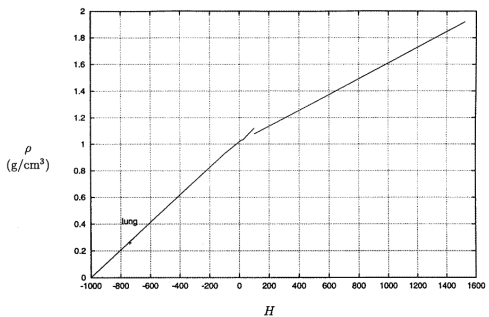




K. Parodi et al., Int J Radiat Oncol Biol Phys. 2007 July 1; 68(3): 920–934

CT stoichiometric calibration

- The CT scan contains integer values in units of "Hounsfield" reflecting the x-ray attenuation coefficient μ_X:
  $HU_X = 1000\ (\mu_X - \mu_{H_2O}) / \mu_{H_2O}$, 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)**



W. Schneider *et al* 2000 Phys. Med. Biol. 45 459

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

Practical issues: Assigning materials to organs

- How to assign realistic human tissue parameters (=materials) for MC calculations?
- How to find a good compromise between the number of different HU values ($\sim 3000 - 5000$) and the materials to be considered in the MC? (issues on memory and computation speed when attemtping to treat each HU number as a different material)
- How to preserve continuos, 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 24 materials of defined elemental composition (from analysis of 71 human CT scans)

Air, Lung

adipose tissue

Soft tissue

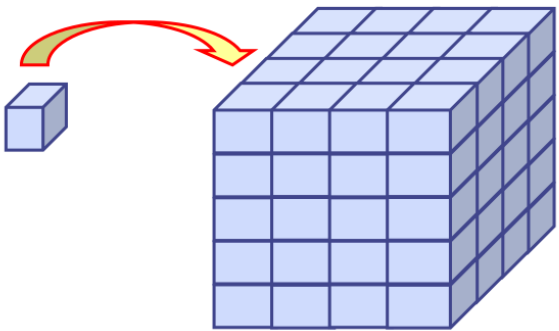
Skeletal tissue

	w_i (pp)											
H	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

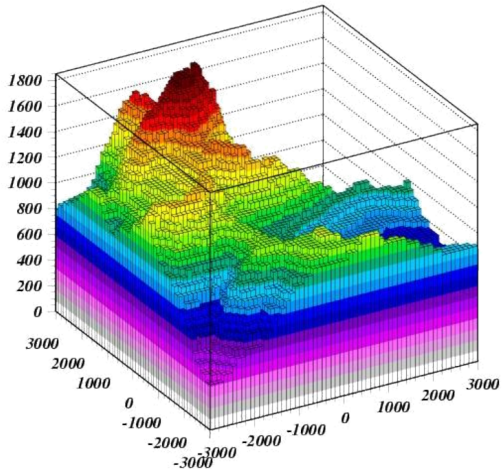
W. Schneider *et al* 2000 Phys. Med. Biol. 45 459

From CT to FLUKA voxel geometry

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

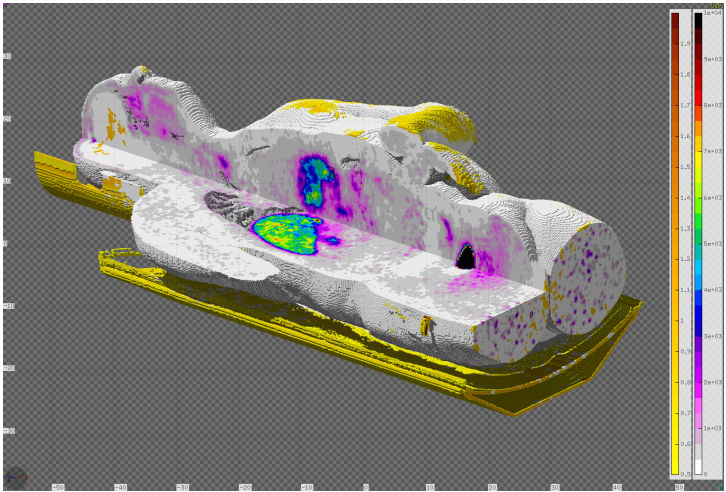


The Gran Sasso mountain (Italy) in FLUKA:



Voxel geometries: Examples

Voxel geometry with PET-CT:



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 $\leq$ 32 767. The organ numbering does not need to be contiguous, i.e. "holes" in the numbering sequence are allowed.
- One of the organs must have the number **0** and plays the role of the medium surrounding the voxels (usually vacuum or air).
- Assign to each non-zero 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.

How to convert a patient's CT to a VOXEL geometry

What is needed:

☐ Patient's CT: Directory with DICOM files (.dcm)

☐ FLUKA input file (example.inp) with VOXEL card (and CORRFACT card)

☐ Process DICOM files to transform the patient's CT in a VOXEL geometry:

- 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

(examples for the files material.inp and calib_curve.mat can be found in the `Medical_exercise/`-folder, see the following lecture).

The material.inp-file


```
*
* Schneider parametrisation of HU to materials
* This file should be used together with the dicom/material.inp
*
* Based on the work of Andrea Mairani
*
MATERIAL         16.    32.066       2.0                              SULFUR
MATERIAL         15. 30.973761       2.2                              PHOSPHO
MATERIAL         17.   35.4527 0.0029947                              CHLORINE
MATERIAL         19.   39.0983     0.862                              POTASSIU
* MIXTURE : HU<-1020
MATERIAL                        .00315972                          0.HU<-1020
COMPOUND      -0.755  NITROGEN    -0.232    OXYGEN    -0.013     ARGONHU<-1020
STERNHEI     10.5961    1.7418    4.2759   0.10914    3.3994          HU<-1020
MAT-PROP                            85.7  HU<-1020
* MIXTURE : HU<-1015
MATERIAL                        .00717201                          0.HU<-1015
COMPOUND      -0.755  NITROGEN    -0.232    OXYGEN    -0.013     ARGONHU<-1015
* MIXTURE : HU<-1010
MATERIAL                         .0121874                          0.HU<-1010
COMPOUND      -0.755  NITROGEN    -0.232    OXYGEN    -0.013     ARGONHU<-1010
* MIXTURE : HU<-1000
MATERIAL                         .0207135                          0.HU<-1000
COMPOUND      -0.755  NITROGEN    -0.232    OXYGEN    -0.013     ARGONHU<-1000
* MIXTURE : HU<-995
MATERIAL                          .027735                          0.HU<-995
COMPOUND      -0.755  NITROGEN    -0.232    OXYGEN    -0.013     ARGONHU<-995
* MIXTURE : HU<-988
MATERIAL                         .0333252                          0.HU<-988
COMPOUND      -0.755  NITROGEN    -0.232    OXYGEN    -0.013     ARGONHU<-988
```

The calib_curve.mat-file


```
#
# Schneider parametrisation of HU to materials
# This file should be used together with the dicom/material.inp
#
# Based on the work of Andrea Mairani
#
-1020 AIR 0.6825432 1.3174568
-1015 HU<-1015 0.720281108 1.27971895
-1010 HU<-1010 0.835391418 1.16460858
-1000 HU<-1000 0.733656625 1.16949124
-995 HU<-995 0.909584201 1.05424948
-988 HU<-988 0.909502356 1.09049764
-974 HU<-974 0.85108832 1.14891168
-962 HU<-962 0.902912681 1.09708732
-950 HU<-950 0.919883508 1.08011649
-925 HU<-925 0.862306423 1.13769358
-900 HU<-900 0.893000468 1.10699951
-830 HU<-830 0.783902333 1.21609767
-700 HU<-700 0.75158871 1.24841129
-500 HU<-500 0.765689411 1.23431059
-120 HU<-120 0.734835247 1.26516475
-83 HU<-83 0.980501545 1.01835909
-53 HU<-53 0.98600717 1.01305997
-23 HU<-23 0.986384099 1.01270032
7 HU<7 0.98674495 1.01236373
15 HU<18 0.995655766 1.00173225
80 HU<80 0.972407965 1.03421835
101 HU<120 0.980146255 1.00104493
120 HU<120 0.962511989 0.973311932245
200 HU<200 0.973911929092 1.02131168
```

The input file

Prepare the usual 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)

```
VOXELS      -35.068359-35.068359   -88.6855                          bodyCT
```

The region-dependent CORRFACT card

- Materials are defined from groups of HU, but "real densities" varies continuously with HU
- The "CORRFACT" card allows to alter material density for dE/dx and nuclear processes
- The 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 ($\Rightarrow$ ion range!) in the regions corresponding to different organs IO (i.e., different HU values) sharing the same MATERIAL assignment

```
CORRFACT   0.85   0.0   0.0    VOXEL005
CORRFACT   1.30   0.0   0.0    VOXEL016
```

(region 25 corresponds to "softer" bone than region 31)

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