Comparison of FLUKA predictions to measured induced activities in shielding and environmental samples irradiated at the Pohang Light Source with 2.5 GeV electrons

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Outline

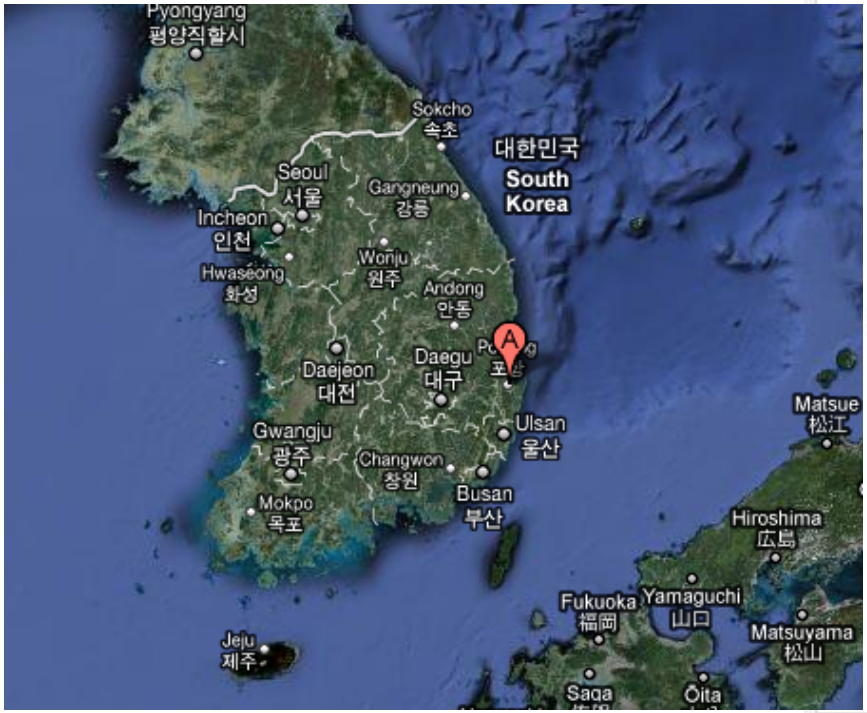
- Introduction and setup
- Irradiation and measurements
- Simulations and data analysis

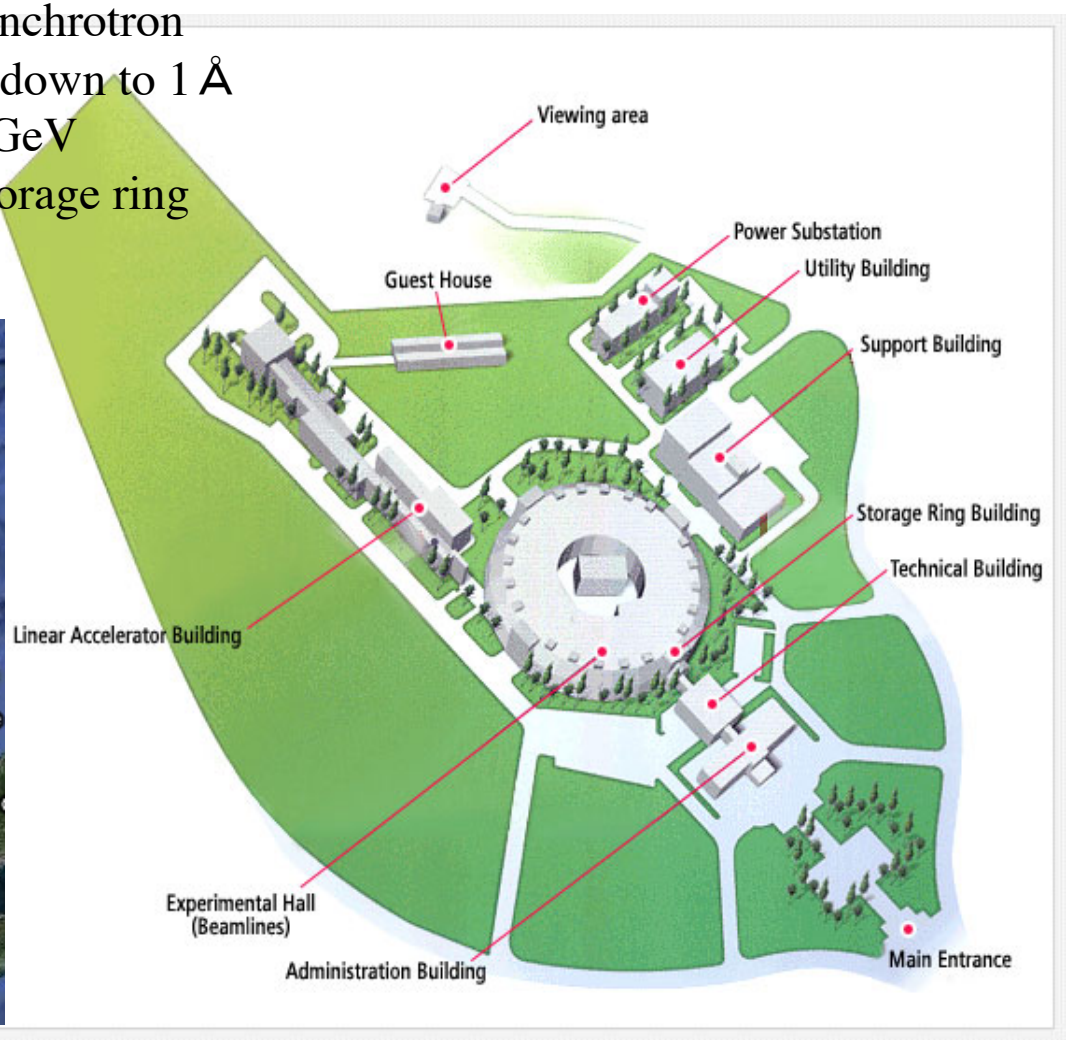
Experiment goals

- Monte Carlo is used in high energy accelerators to predict and minimize the dose to personnel, to the population and the production of waste (i.e, activation of beam components, detectors, and environment). **Benchmarking** those quantities for electron accelerators is needed to identify safety margins.
- **Support SLAC projects** like BaBar D&D, LCLS2 and the environmental-RP program.
- **Follow up on CERN-SLAC experiment T-489** (2007).
- Gain understanding on the activation of components used for **shielding of prompt and residual radiation**, e.g. marble, concrete.
- Identify **improvement opportunities in SLAC gamma-spectroscopy**, e.g. additional data libraries to use for certain samples, calibration with ISO-plus or FLUKA, etc.
- Compare predictions of several codes.
- Provide participants with a **training** opportunity in various fields: experiment planning, radioactive sample shipping, data analysis, experimental work.

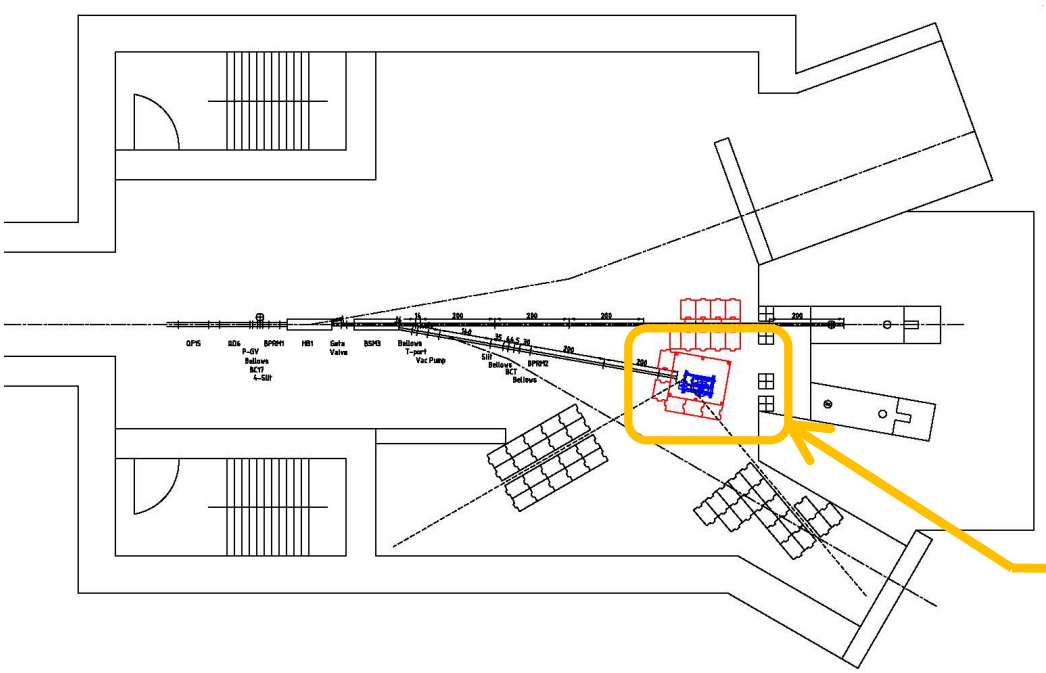
Pohang Accelerator Laboratory

- The Pohang Light Source provides synchrotron radiation with continuous wavelengths down to 1 Å
- Electron beam energy goes up to 2.5 GeV
- 205 m long linac + 134 m diameter storage ring
- Operation started in 1995

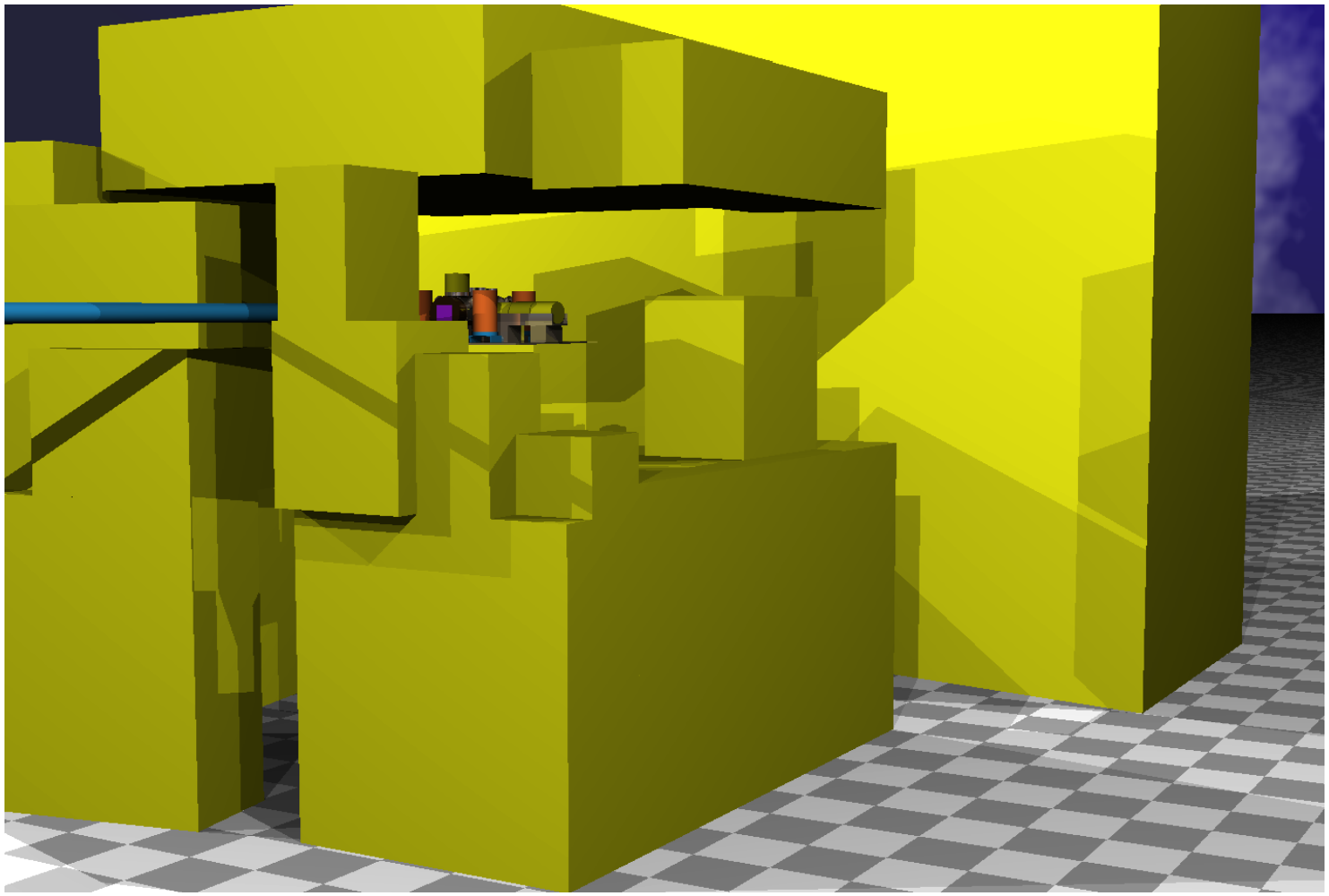




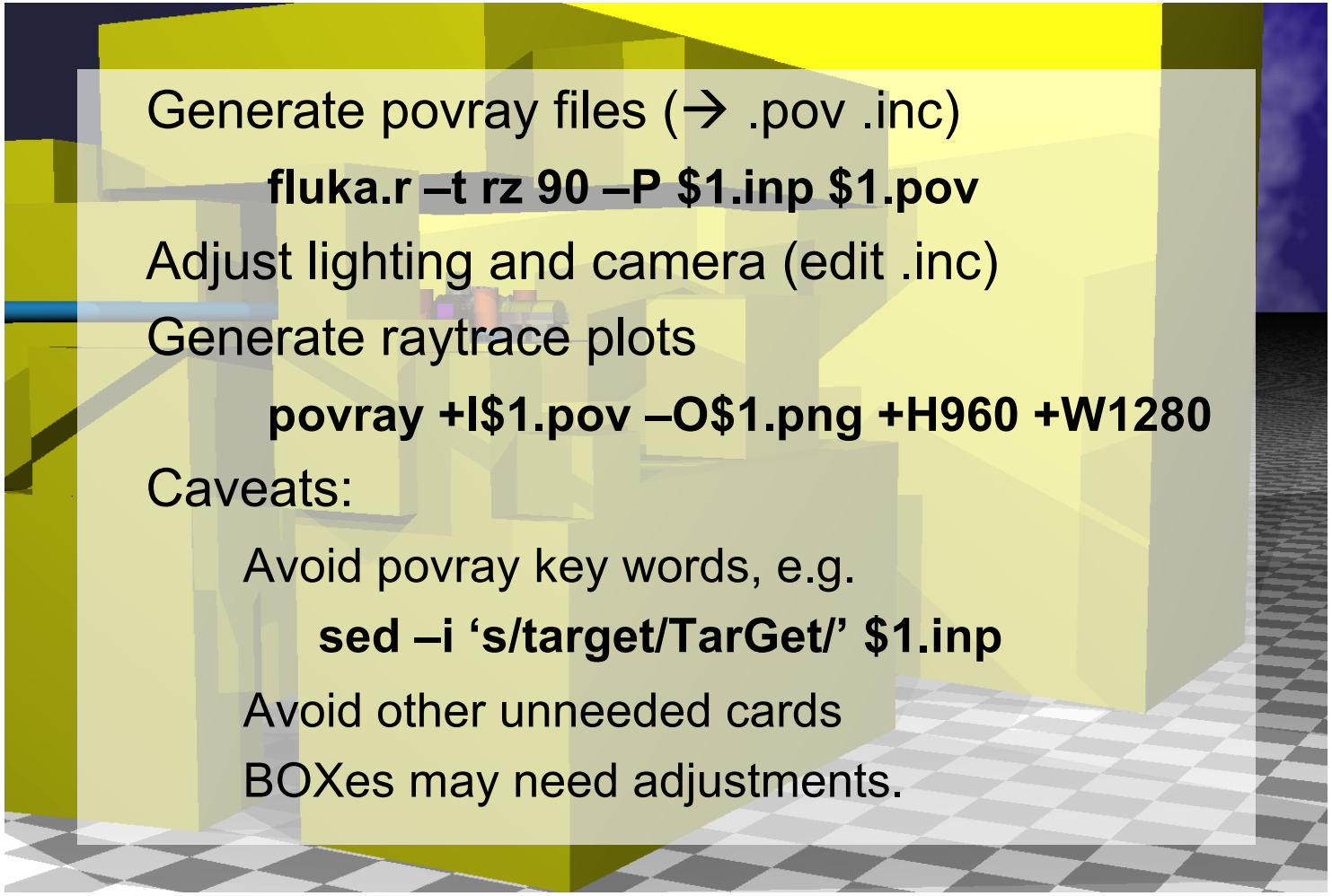
PHERF Beam Switch Yard



PHERF Bunker



PHERF Bunker. 3D rendering



Generate povray files (→ .pov .inc)

fluka.r –t rz 90 –P $1.inp $1.pov

Adjust lighting and camera (edit .inc)

Generate raytrace plots

povray +I$1.pov –O$1.png +H960 +W1280

Caveats:

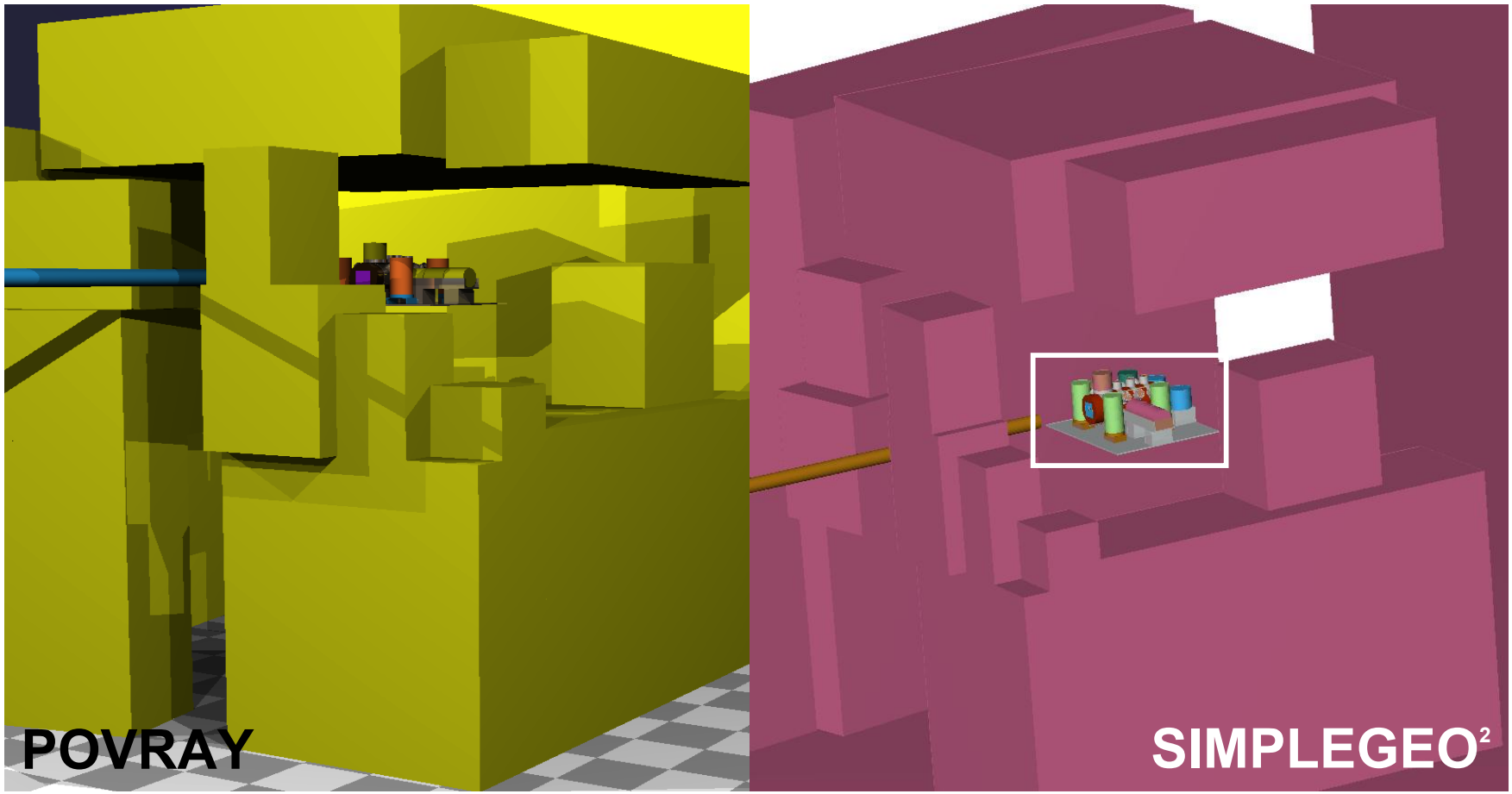
Avoid povray key words, e.g.

sed –i 's/target/TarGet/' $1.inp

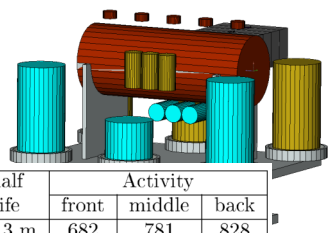
Avoid other unneeded cards

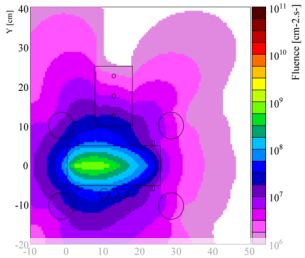
BOXes may need adjustments.

PHERF bunker. 3D rendering



Setup flowchart



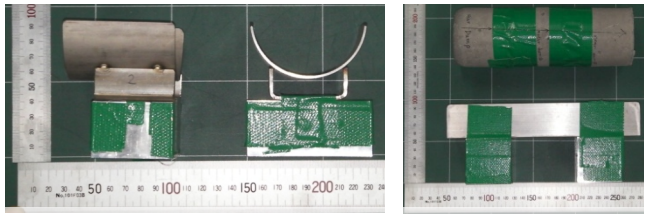


	half life	Activity front	middle	back
^{11}C	20.3 m	682	781	828
^{7}Be	53.2 d	912	107	120
^{3}H	12.3 y			

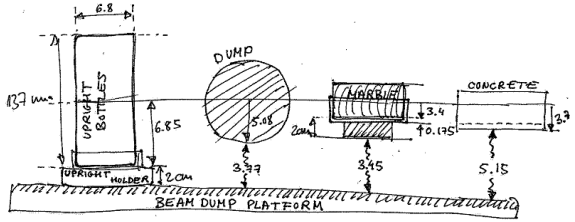
Preliminary design, expected radiation fields and activation

Preparation of samples.

Chemical analysis.



Measurements and verification

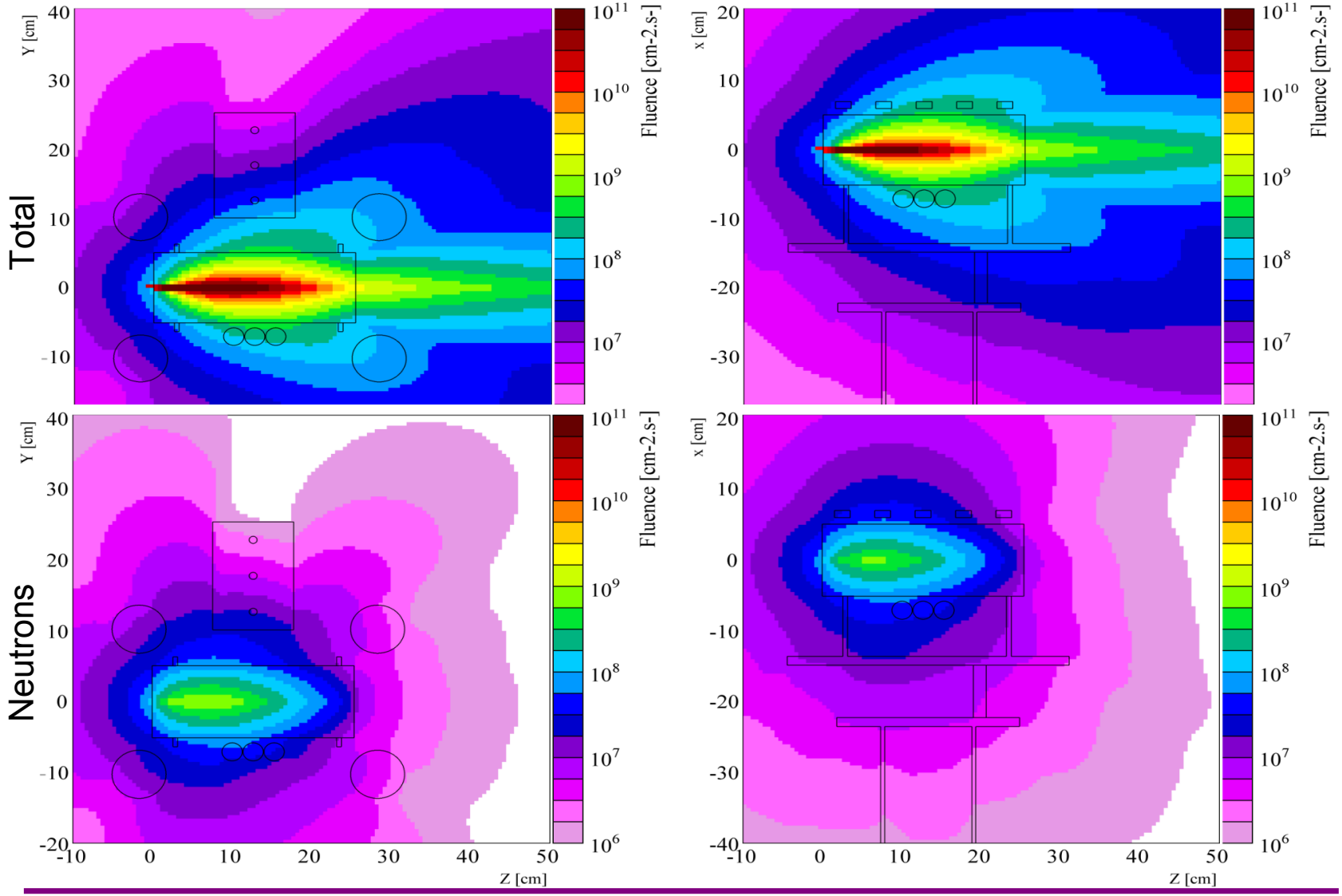


Specifications for sample holders, etc.

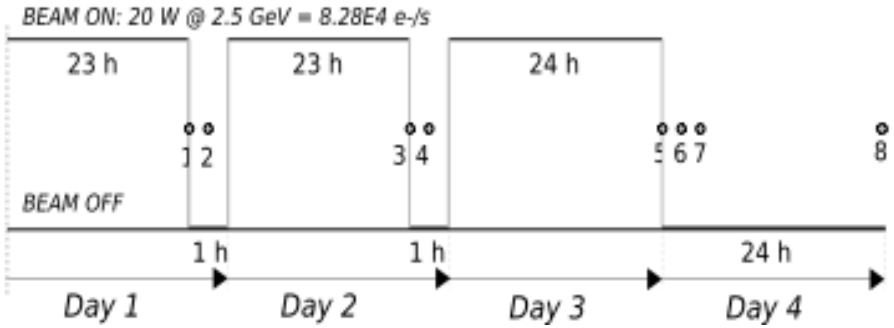
Test with ‘toy’ dump

Installation in dump area

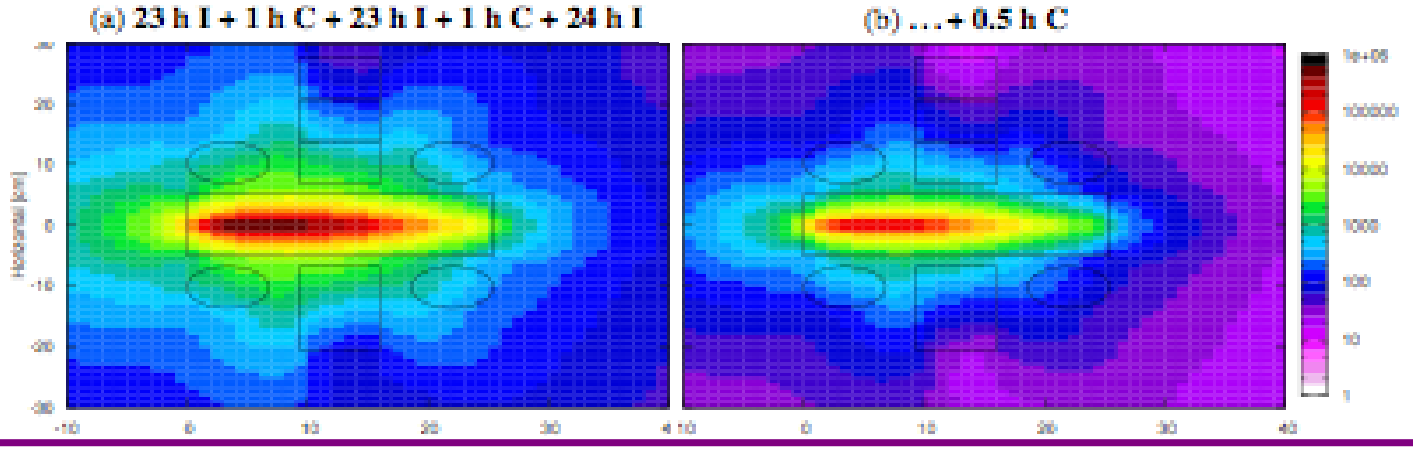
Preliminary design. Expected Fluences.



Preliminary design. Residual dose.

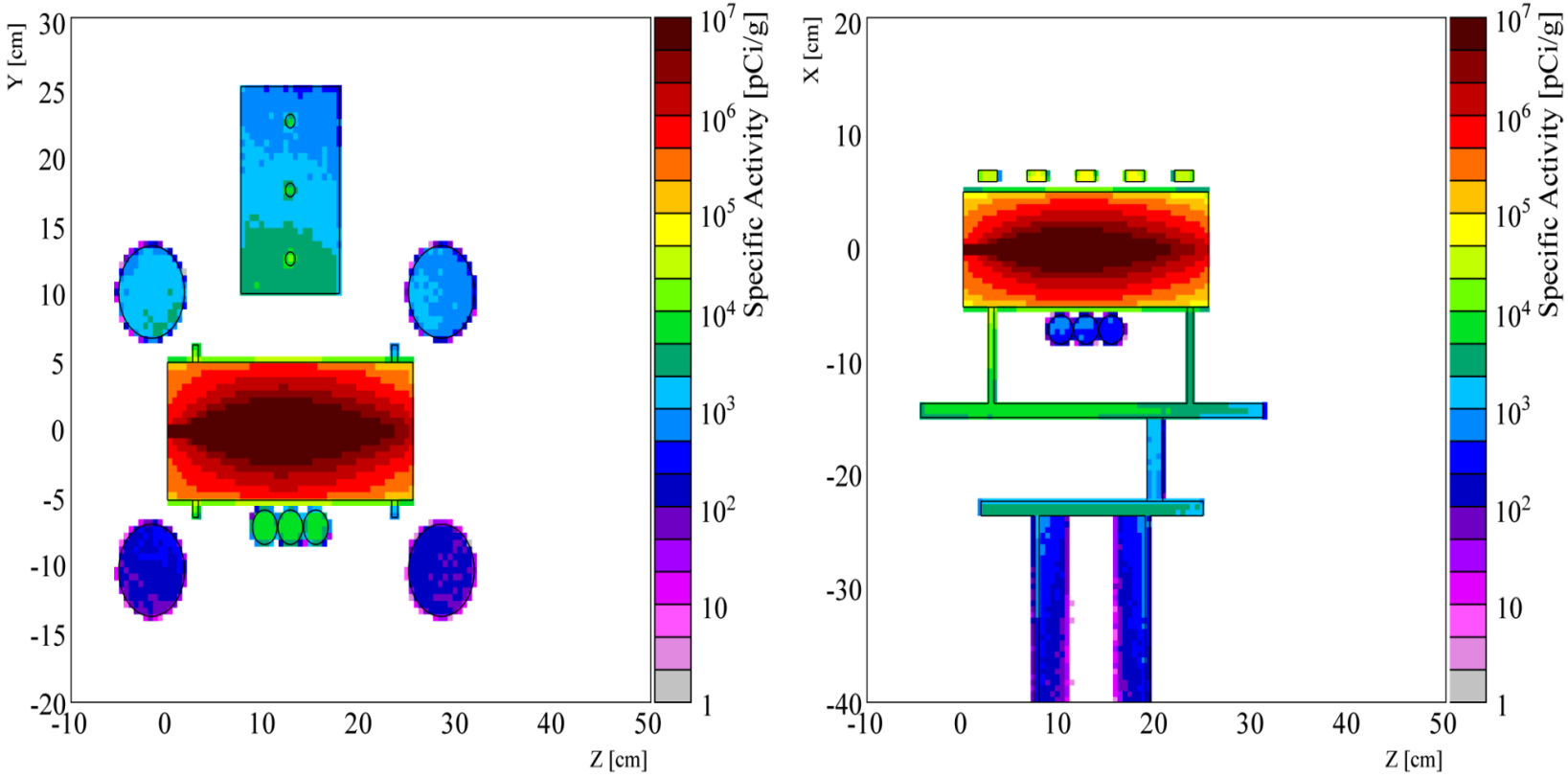



```
#if RESDOS
* Defining the irradiation profile
*                 23h     at 20W         1h        OFF        23h     at 20W
IRRPROFI     8.28e+04     5.0e10      3600.        0.0  8.28e+04     5.0e10
*                  1h        OFF        24h    at  20W
IRRPROFI         3600.        0.0  8.64e+04     5.0e10
* associating the irradiation profile to the scoring
DCYTIMES         3600.
*                -49h      -48.5h       -25h     -24.5h         0h       0.5h
DCYTIMES         3600.     28800.     86400.
*                  1h         8h         1d
*Scoring the dose rate around the TarGet
DCYSCORE            1.0                          EWT74011   EWT74012        9.0USRBIN
…
```



Preliminary design. Expected Activity.

Total Activity after one hour



From Joachim Vollaire

Chemical Analysis - Soil Samples

- Soil(s), concrete, shotcrete and marble samples
  - pulverized and split.
  - sent to two companies (EAI and Becquerel) for different analysis:
    - PIXE: Proton-induced x-ray emission
    - CHN: Carbon, hydrogen, nitrogen analysis
    - NAA: Neutron activation analysis
- Metal samples (Cu and SS)
  - Analysis available from T-489 irradiation experiment (2007).

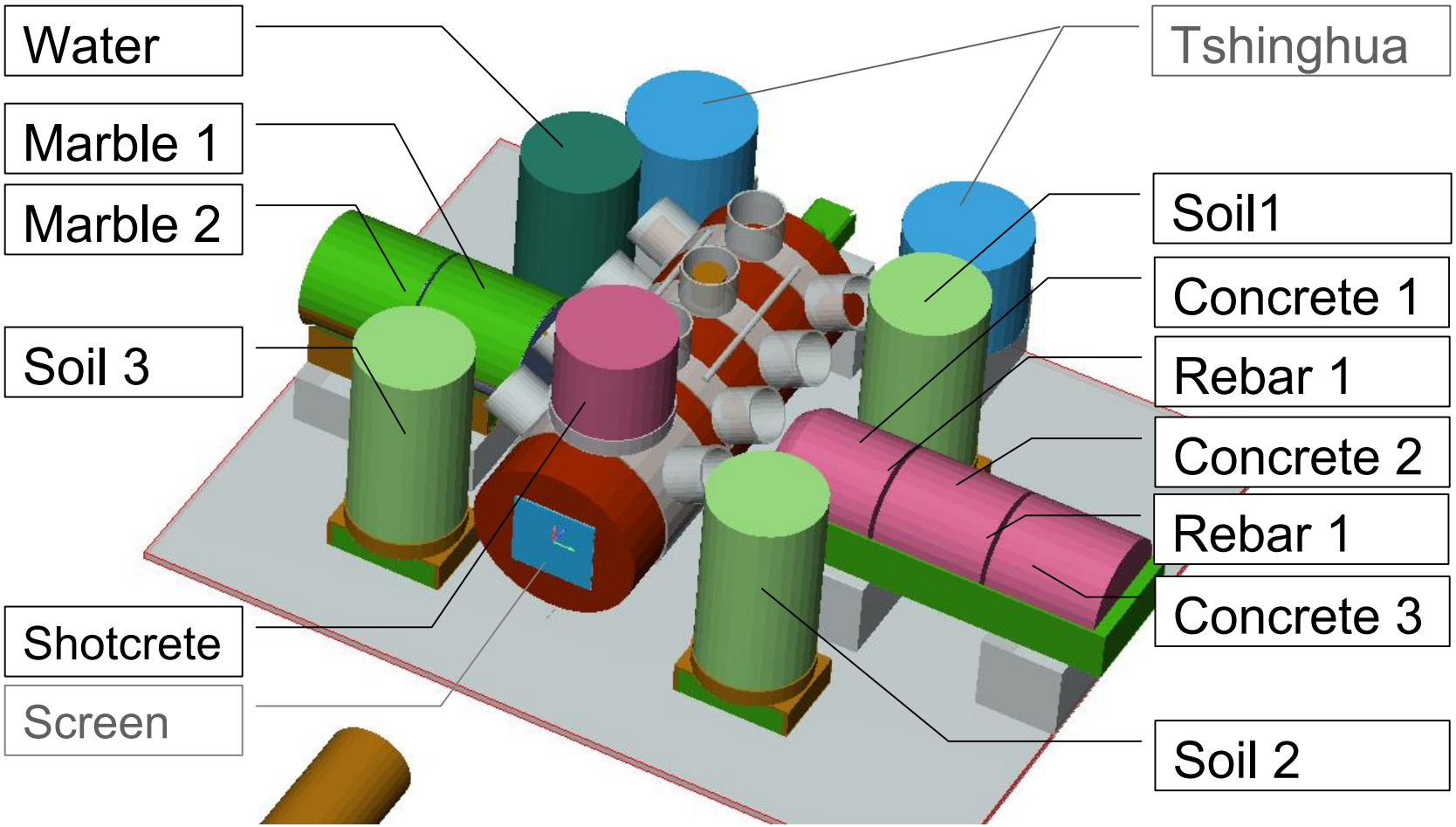
e.g. Marble

Company	EAI	EAI			Becquerel	
Date	4/29/14	4/8/14				
Method	CHN	PIXE			NAA	
Sample ID	S03302	S03302			S03302	
Nuclides		Det. Limit	Results	Error	Results	AVERAGE (ppm)
C	11.96%		11.983%			119830.00
Ca		460.400 ppm	35.239%	0.352%		352390.00
Fe		4.046 ppm	81.741 ppm	2.918 ppm	<0.2%	81.74
Mn		5.120 ppm	46.372 ppm	3.283 ppm		46.37
O			52.664%			526640.00
Si		133.900 ppm	926.839 ppm	84.898 ppm		926.84
Sr		2.364 ppm	51.983 ppm	3.098 ppm		51.98
Zn		2.006 ppm	35.689 ppm	1.485 ppm	<100 ppm	35.69

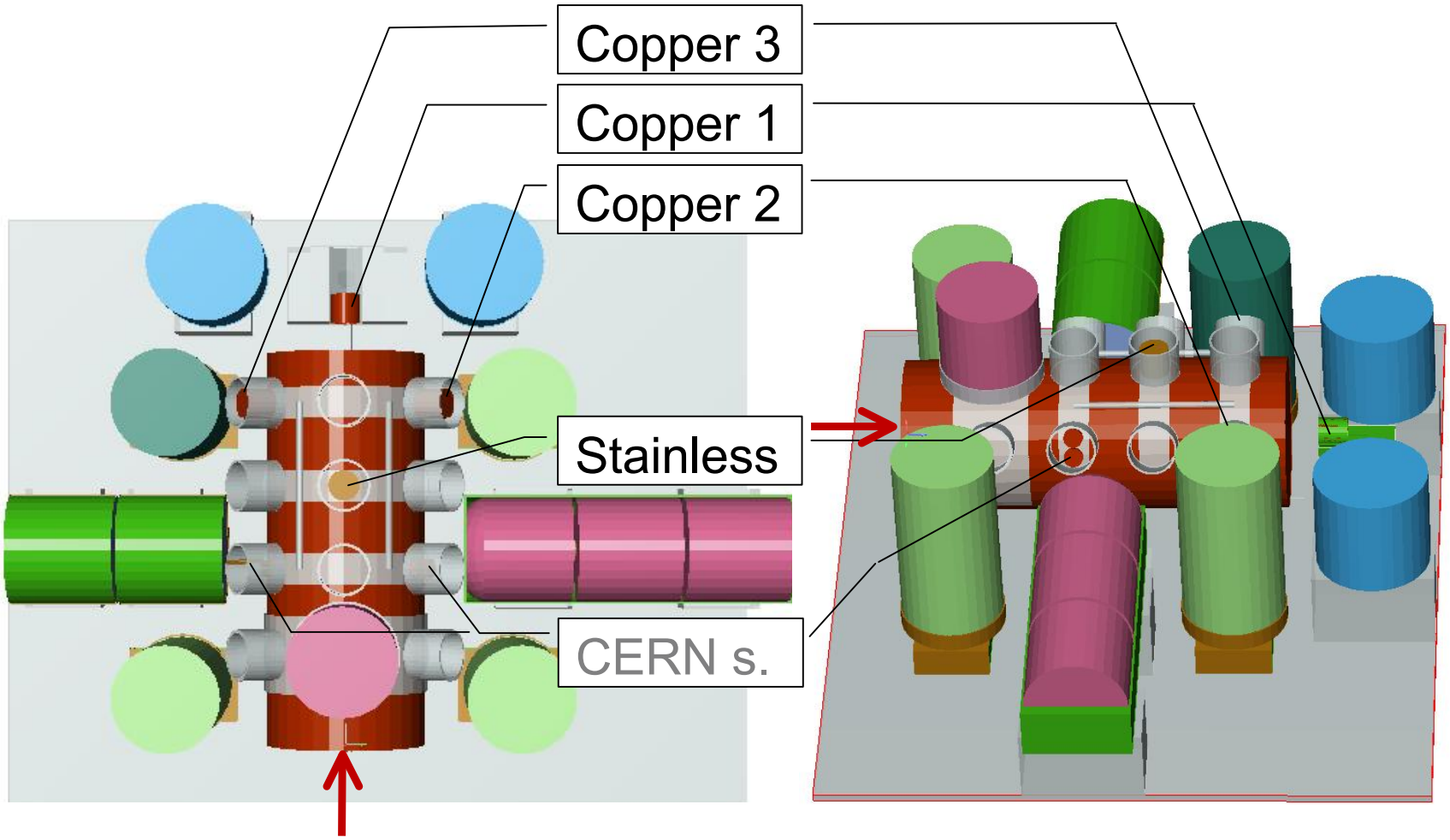
Fluka.inp

```
COMPOUND   -3.569D-5      ZINC  -8.174D-5      IRON -3.524D-1  CALCIUMMARBLE
COMPOUND   -4.637D-5 MANGANES  -9.268D-4   SILICON -5.266D-1   OXYGENMARBLE
COMPOUND   -5.198D-5 STRONTIU  -1.198D-1    CARBON                 MARBLE
```

Target and samples (I)



Target and samples (II)



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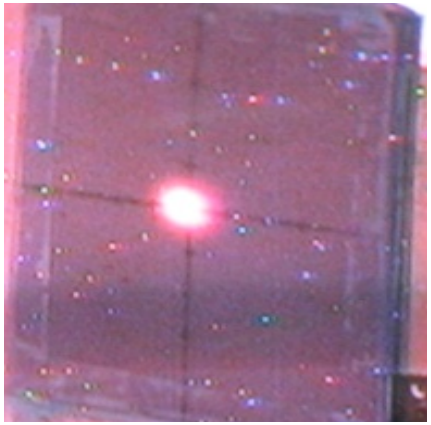
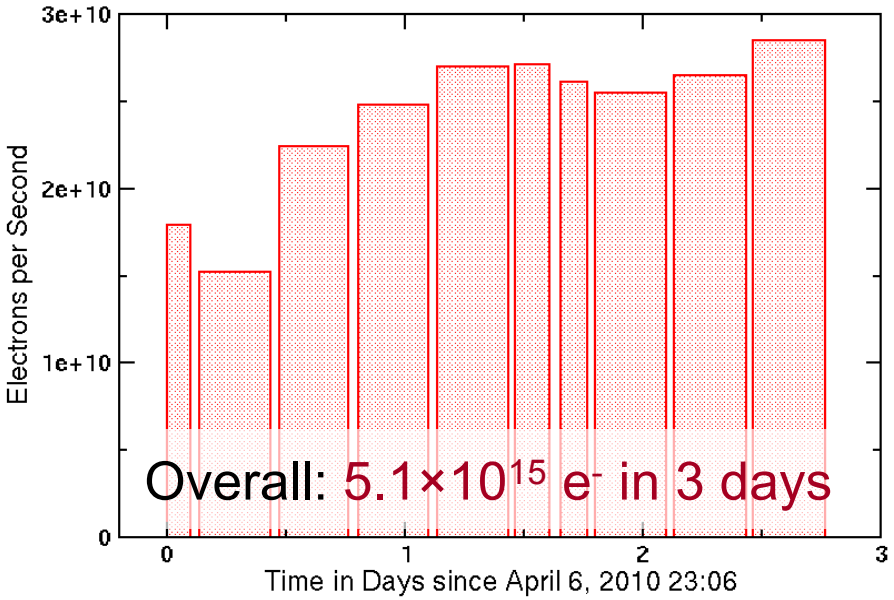
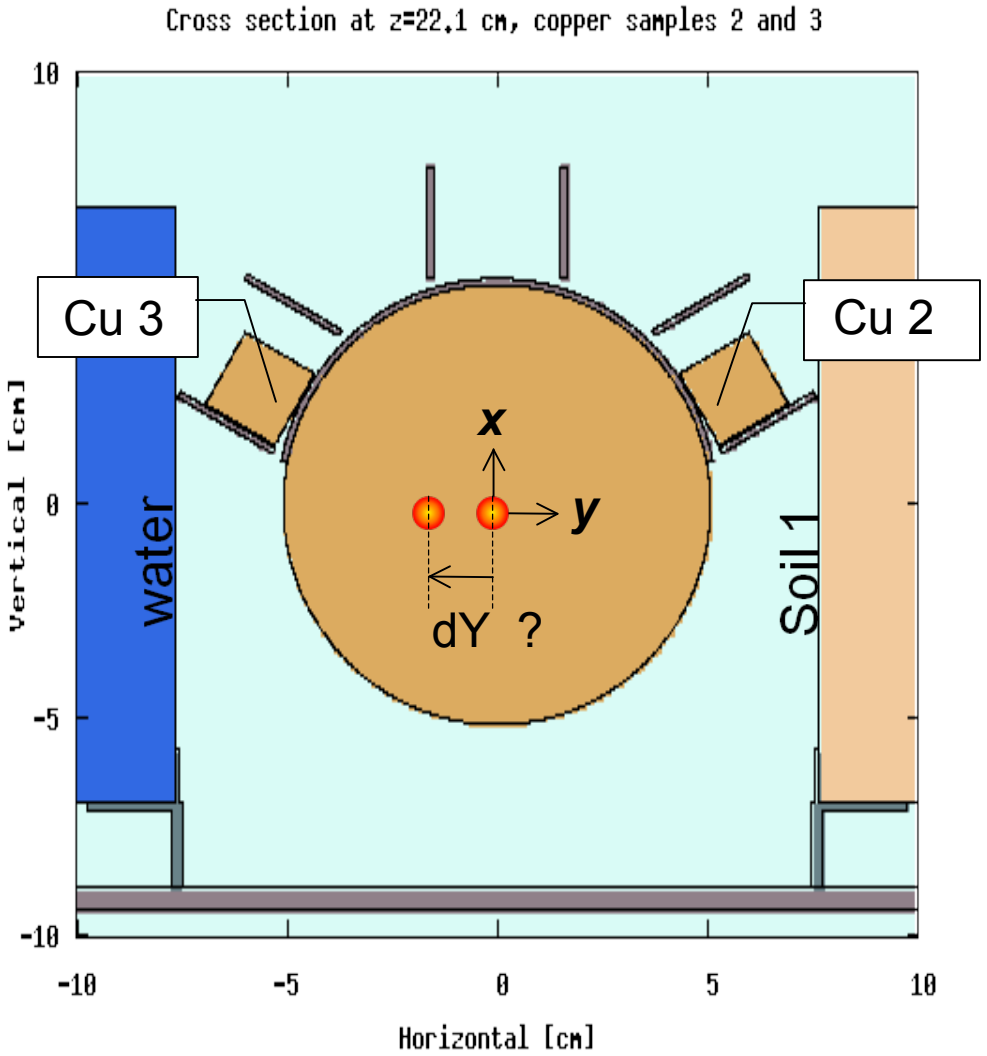
Beam Monitoring

- **Position:**
  - Al2O3 screen & camera
  - Maximum apparent shift: dY=-0.2 cm
- **Intensity:**
  - Borgos toroid upstream of dump
  - 1 Hz reading
  - Discriminator + scaler counting pulses (10 Hz max)
  - Rated precision ~5 %



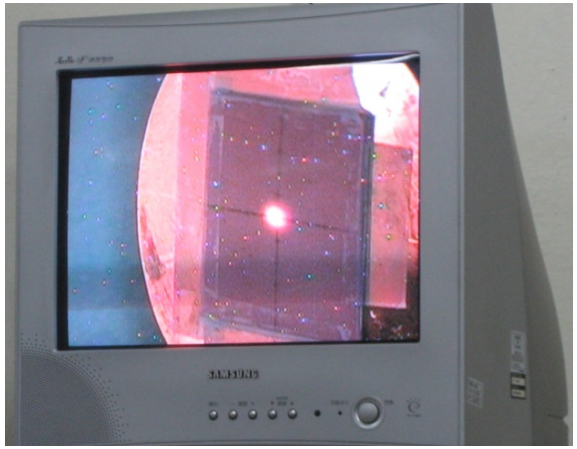


Beam Position (I)



Comparison of Gamma Spec measurements [BQ/G] for the two symmetric (?) Cu samples

Isotope	Cu 3	Cu 2	Cu 3/Cu 2
K-40	1.247646	5.97E-01	2.09E+00
Sc-46	0.011359	8.65E-03	1.31E+00
Cr-51		9.76E-03	-
Mn-54	0.042941	2.04E-02	2.10E+00
Co-56	0.026731	1.17E-02	2.28E+00
Co-57	0.049634	2.27E-02	2.19E+00
Co-58	0.352508	1.47E-01	2.40E+00
Co-60	0.052365	2.10E-02	2.49E+00
Sr-85	0.006986		-
TOT	1.790169	0.83821	2.14E+00



Beam Position (II)

	Cu 3 / Cu2	Soil 3 / Soil 2
FLUKA Y=0	0.98	1.26
FLUKA Y=-1	1.91	2
measurement	2.14	1.46

```
BEAMPOS      0.0      0.0     -1.0      0.0      0.0      0.0
BEAMPOS      0.0     -1.0     -1.0      0.0      0.0      0.0
```

- Total simulated activities for each sample can be obtained directly from the "*_sum.lis*" files
- The beam seems off from the center. The effect looks bigger at the end of the target
  - Wrong alignment? (angle)
  - Offset + beam size effect?

Gamma spectroscopy

- Two low-background high-efficiency Germanium detectors
  - 1: n-type with 50% efficiency, 4096 channels and analog processing
  - 2: p-type with 40% efficiency, 8192 channels and digital processing
- Four calibration sources, depending on the geometry
  - Monoenergetic point source: used for rebar samples
    - Eu-152 point source
  - Mixed nuclide sources to cover the full-scale of the detector energy:
    - mixed nuclide epoxy
    - mixed nuclide sand
    - mixed nuclide air swipe
- All measurements and calibrations performed on contact
- GammaVision 6.01 software package for analysis with user-defined nuclide library
- ISO-plus software and/or MCNP/FLUKA will be used to account for self-absorption
- Detectors able to pinpoint lines below 100 keV with little error
- SLAC gamma-spectroscopy biannually tested against blind samples. Results within 20% limit of reference value, typically within 5 %
- CERN and SLAC gamma spectroscopy agree within ~15 % (T-489)

- Introduction and setup
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FLUKA options

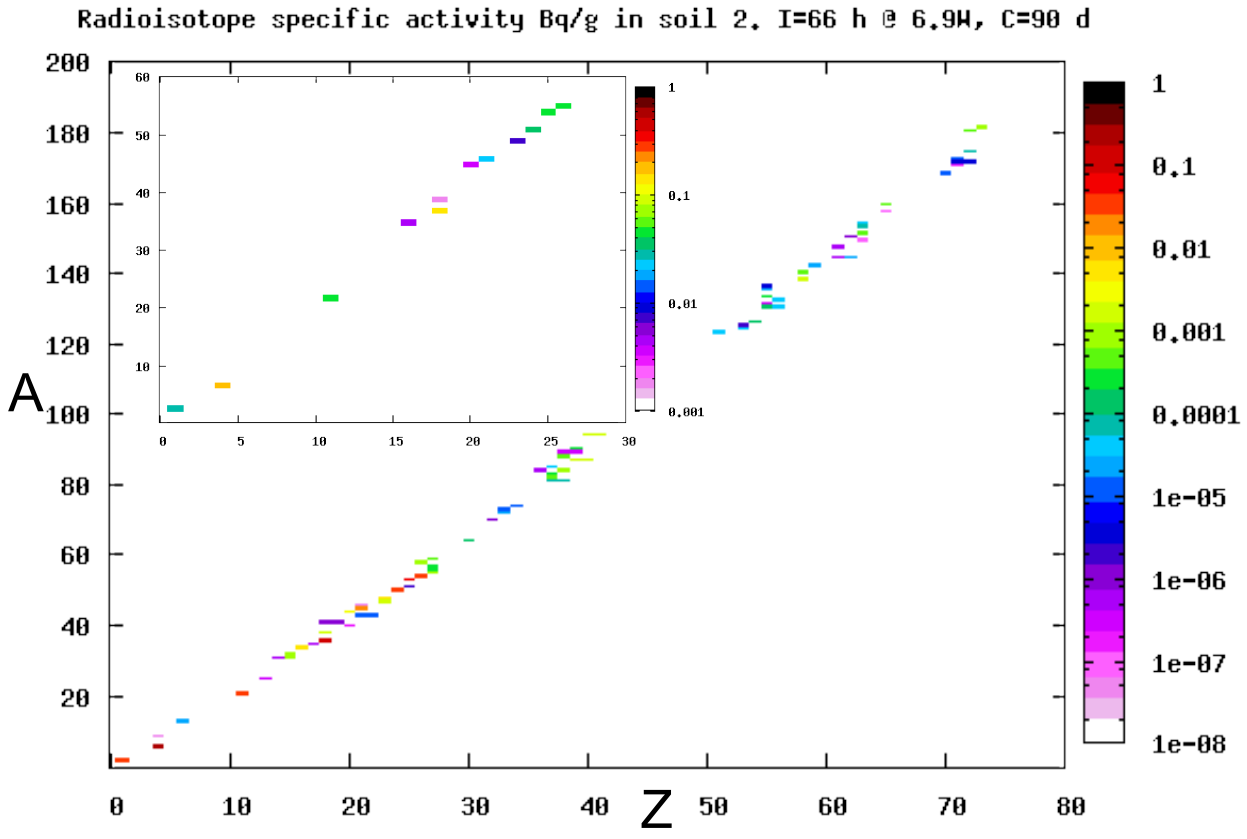
- **Geometry** graded implementation approach:
  - very accurate description of dump assembly, including all the samples and supports, cup holders, etc
  - Fair implementation of the (open) bunker
  - Coarse description of the larger BSY area
- **Beam profile and beam shape** kept simple for first iterations to better understand sensitivity of results to each parameter. Detailed implementation in 'final' run
- **Biasing**
  - region importance biasing into samples (1 to 3)
  - leading particle biasing turned ON and OFF to identify its impact to results
  - Lam-biasing on (PHOTONUCLEAR)
- **Thresholds**
  - e+/e-: 10 MeV, photons: 5 MeV
  - neutrons: thermal
- **Physics**
  - PEANUT model at all energies
  - coalescence OFF for draft results
  - No photo-muon production

FLUKA options

```
*  1 keV for all particles, except n
PART-THR     -1.0E-6        1.0        2.0
PART-THR     -1.0E-6        9.0       39.0
*  discard muons
DISCARD          10.0       11.0

EMF
EMFCUT      -100E-06    50E-06        0.0        3.0  @LASTMAT           PROD-CUT
EMFCUT      -100E-06    50E-06        0.0        1.0  @LASTREG

#if RESDOS
*       activated_for_Tc isomers  replicas  prompt 100xDecay,1xPrompt
RADDECAY          1.0        1.0        3.0        1.0 100000010
#else
*       activated_for_Tc isomers  replicas  prompt  1xDecay,10xPrompt
RADDECAY          1.0        1.0        3.0        1.0   1000100
#endif
*      all_reactions                              all_regions
PHOTONUC       1111.0                             1.0  @LASTMAT
*                  increase_factor all_regi  photons
LAM-BIAS          0.0       0.02        0.0        7.0

*  transport of heavy recoils (w/o re-interaction) YYY (needed?)
EVENTYPE                             2.0                              EVAP
*  evaporation of heavy fragments
PHYSICS           3.0                                                EVAPORAT
*  coalescence activated
*PHYSICS           1.0                                                 COALESCE
*  Peanut for all energies
PHYSICS        1000.0    1000.0    1000.0    1000.0    1000.0    1000.0PEATHRES

#if ANALOGUE
EMF-BIAS          -1.        0.0        0.0        2.0  @LASTREG           LPBEMF
#elif
*       all_effects         all_energies          all_regions
EMF-BIAS        1022.        0.0        0.0        2.0  @LASTREG           LPBEMF
#endif
```

Data analysis

> ls *fort.$1 > temp; echo ' '>>temp; echo "usrsuw_$1">>temp; **usrsuw** < temp



usrsuw_$i

FLAIR

usrsuw_$i_sum.lis
usrsuw_$i_tab.lis

COMPARISON

Experimental data

Some preliminary results (I)

Soil (1)

		Measurment	error (%)	FLUKA	error (%)	FLUKA/EXP
Be-7	53.4 d	0.1780	2.2609	0.1207	0.8535	0.678
Na-22	2.6 y	0.0523	1.7358	0.0300	0.7733	0.574
Sc-46	83.9 d	0.0326	1.9844	0.0140	2.861	0.428
V-48	16 d	0.0013	21.8497	0.0008	5.45	0.616
Cr-51	27.7 d	0.0294	9.7508	0.0217	1.994	0.738
Mn-54	312 d	0.0858	1.1184	0.0321	1.086	0.374
Co-56	77.3 d	0.0011	19.3988	0.0005	12.73	0.506
Fe-59	45.1 d	0.0013	34.3868	0.0006	18.62	0.494
Co-60	5.27 y	0.0009	36.6811	0.0003	13.08	0.325
Sr-85	64.7 d	0.0111	7.0681	0.0005	10.55	0.049
Y-88	107 d	0.0021	8.3522	0.0011	8.934	0.537
Zr-88	83.4 d	0.0011	24.0372	0.0009	10.88	0.787
Nb-95	35.2 d	0.0014	28.4611	0.0011	4.493	0.811

Measured and simulated specific activities (Bq/g) for SOIL 1

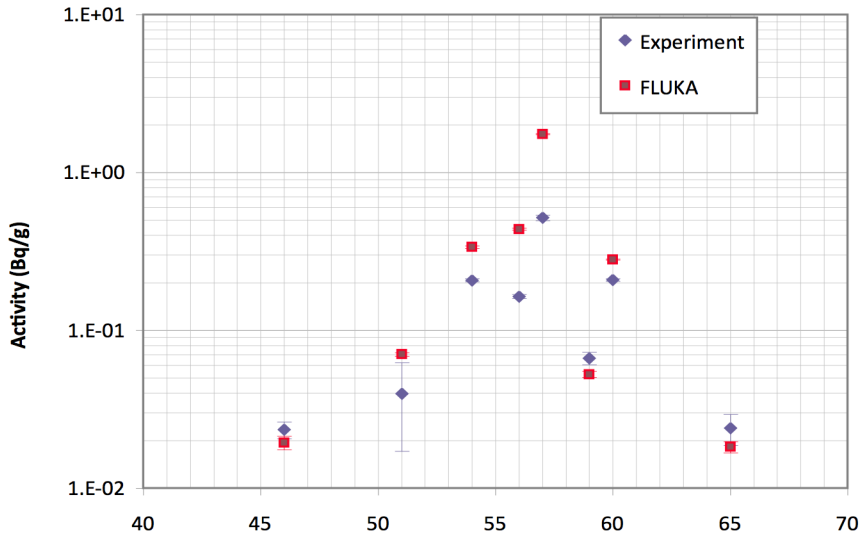
Water

- ^{7}Be ratio is FLUKA/exp = 0.56 (centered beam)
  = 0.74 (Y=-1 cm)
- FLUKA predicts other isotopes difficult to measure, e.g. ^{14}C, ^{10}Be
- Gamma analysis shows ^{40}K and ^{44}Ti that do not show in FLUKA results
- ^{3}H measurements to be done

Some preliminary results (II)

Copper (1)

- Unlike for powder/liquid samples, FLUKA prediction higher than measurement.
- Discrepancy could be explained by self absorption within the 2 cm tall copper cylinder, not accounted for the copper geometry.



- ISO-PLUS software can be use to calibrate gamma-spec for geometries where gamma absorption is important but radioisotope generation is uniform. FLUKA simulations show this is the case for copper
- FLUKA simulations sample/detector can be used to correct for self absorption in larger solid samples where isotopes are unevenly created.

Caveats

- Trouble with RESNUC when using some transuranids, either defined generically, e.g. URANIUM, or by isotope, e.g. 238-U. Same issue with Thorium. Simulation runs, but analysis crashes:

```
..
..
Intensity:  1.73559992E+10 pr/s
 T_irrad. :  238812. s
 Nrnmx: 1
Type the input file:   Type the output file name:
Subscript out of range on file line 847, procedure usrsuw.f/MAIN.
Attempt to access the 261-th element of variable resnuc[subscript-2-of-2].
```

References

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- Theis C., Buchegger K.H., Brugger M., Forkel-Wirth D., Roesler S., Vincke H., *"Interactive three dimensional visualization and creation of geometries for Monte Carlo calculations"*, Nuclear Instruments and Methods in Physics Research A 562, pp. 827-829 (2006).
- V. Vlachoudis, *"BREX: Restructured Extended eXecutor Version 2.1"*, http://bnv.web.cern.ch/bnv/software/Brexx/
- *"The FLUKA code: Description and benchmarking"*, G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso`, J. Ranft, Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6--8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)
- *"FLUKA: a multi-particle transport code"*, A. Fasso`, A. Ferrari, J. Ranft, and P.R. Sala, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773


PAL