Principle design elements of the radiation protection systems of the ELI-ALPS

(**E**xtreme **L**ight **I**nfrastructure-**A**ttosecond **L**ight **P**ulse **S**ource)

„ELI The Power of Light"

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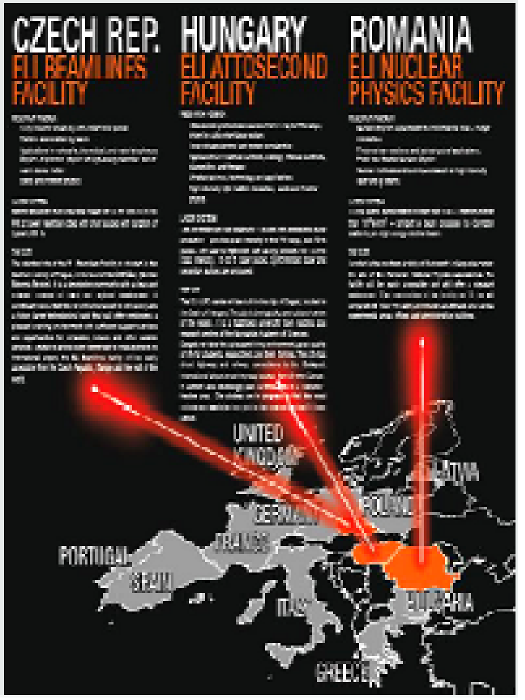
ELI – Three-site structure

NEW SZÉCHENYI PLAN

- The three-site site structure is based on specificity and complementarity
- All the three facilities provide for world leading facilities, but with different characteristics, and focus:
  - **Beamline Facility (ELI-BL, Czech Republic)**: short pulse x-ray generation and particle acceleration with applications
  - **ELI Attosecond Facility (ELI-ALPS, Hungary)**: generation and application of supershort pulses with very high repetition rates
  - **ELI Nuclear Physics Facility (ELI-NP, Romania)**: ultra-intense optical and gamma ray pulses for investigations in nuclear physics
- The science covered by these sites shall match the scientific case of ELI
- The technology developments at the three sites will contribute to the generation of ultra-high intensity laser pulses (200 PW class)



National Development Agency

ELI-HU Nonprofit Kft.

The projects are supported by the European Union.

Location of ELI-ALPS and a planned Scientific Park

NEW SZÉCHENYI PLAN

National Development Agency

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The projects are supported by the European Union.

The ELI: Europe's largest and most powerful laser facility

eli attosecond

ÚJ SZÉCHENYI TERV

MAGYARORSZÁG MEGÚJUL

A projekt az Európai Unió támogatásával, az Európai Regionális Fejlesztési Alap társfinanszírozásával valósul meg.

The ELI-ALPS buildings and experimental halls

The task is to design the radiation protection systems of the largest, most powerful laser facility in the world

extreme light infrastructure

- -To design the radiation protection first of all we have to understand the processes and the interactions that occours at the ELI-ALPS
- -Not only the laser light, but the secondary sources will be also extreme at the ELI-ALPS
- -We will have to handle this beams somehow to avoid the harms, that these beams can cause
- -The solution is to design and build a so called beam dump to stop these secondary sources
- -The radiation protection systems of the ELI-ALPS have to satisfy the internatinal (IAEA, ICRP, ICRU) and national standards, laws

IAEA dose limits

Table 6. Recommended dose limits in planned exposure situations[a].

Type of limit	Occupational	Public
Effective dose	20 mSv per year, averaged over defined periods of 5 years[e]	1 mSv in a year[f]
Annual equivalent dose in:		
Lens of the eye[b]	150 mSv	15 mSv
Skin[c,d]	500 mSv	50 mSv
Hands and feet	500 mSv	–

Processes, interactions at the ELI-ALPS

- -During the laser-matter interaction high energy proton (250 MeV) and (2 GeV) electron beams are generated (first of all) by the so called TNSA (Target Normal Sheath Acceleration) mechanism (and shock, front-surface acceleration)
- -The caracteristics of the secondary sources can be extrapolated by previous measurements or calculated by these „simple” equation:

$$N(x) = \begin{cases} 0 & \text{for } x \geq E^{MAX} \\ \sum_i \frac{N_i^T}{T_i} \exp\left(-\frac{x}{T_i}\right) + \sum_j 2\frac{N_j^G}{\Delta E_j^G}\sqrt{\frac{2\ln 2}{\pi}} \exp\left[-4\ln 2\left(\frac{x-E_j^G}{\Delta E_j^G}\right)^2\right] & \text{for } x < E^{MAX} \end{cases}$$

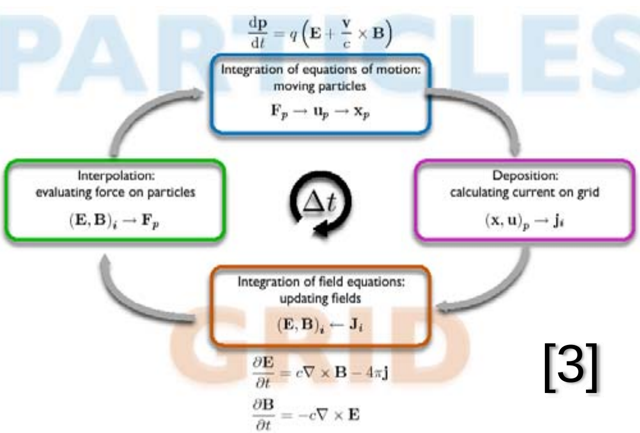
N_i^T the total number of particle per steradiant N_j^G

T_i temperature in MeV

E_j^G the central energy in MeV

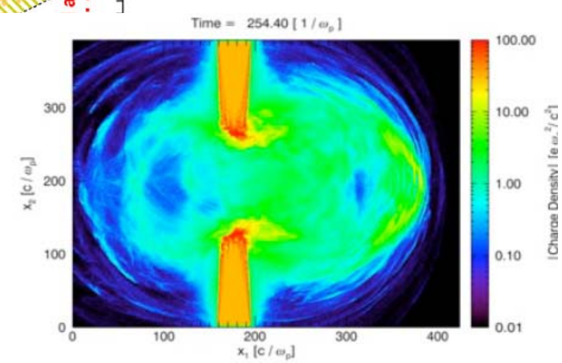
[3]

- -Another solution to determine the parameters is to make calculations with the Osiris code, this code use the Maxwell-Lorentz equations step by step, one simulation is 100 Tbyte large!

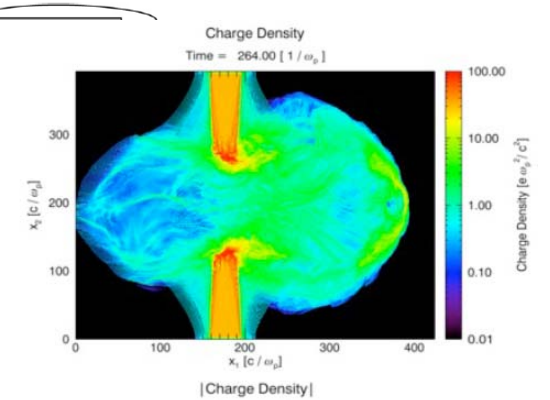


[3]

Electrons



Protons



Design stages

•-1: normal operating: the laser system works properly, the shielding do it's task: eliminates the secondary sources and the harms that these beams could cause

•-2:Design Basic Accident (DBA): When the laser operating abnormally: somehow the secondary beams don't interract with the beam dump (the beam don't hit the beam dump): in these situations the built in logical electricity tilt the laser light beam

•- 3: Worst case: The high energy secondary beam hit the most sensitive part (testicles, ovaries, etc.) of the human body. This is a hypothetical case, if the access control system works properly this is an impossible case.

Radiation types

- *Prompt radiation:* short, transient, complex, most harmful radiation, occours during the laser operating only

- *Residual radiation:* the secondary sources activate the matters of the beam dump and air particles, this will be radioactive, the radiation of the activated matter is the residual radiation, the air should be ventillated out from the target area

- *Additional radiation:* radiation of the activated corrosive components in the cooling-heating pipe systems (this will be no „playing” at the ELI-ALPS because the cooling and heating system will be designed by air ventillation)

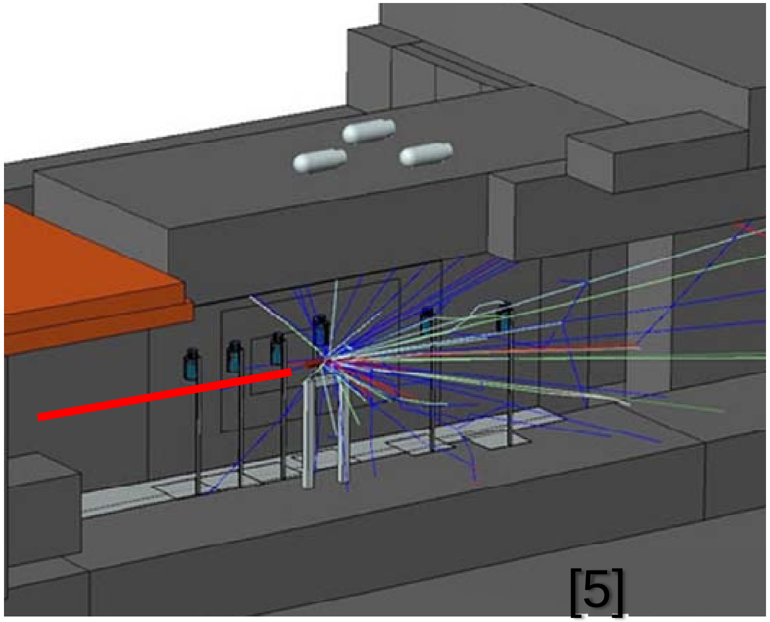
Main effects and processes during the interaction between the matter of the beam dump and the secondary sources

-In the simulation it can be seen that a proton beam interacts with a copper beam dump, the processes are very complex

-A multiplying "shower" is the result of both the electromagnetic cascade produce a hadronic cascade and the hadronic cascade produce an electromagnetic cascade

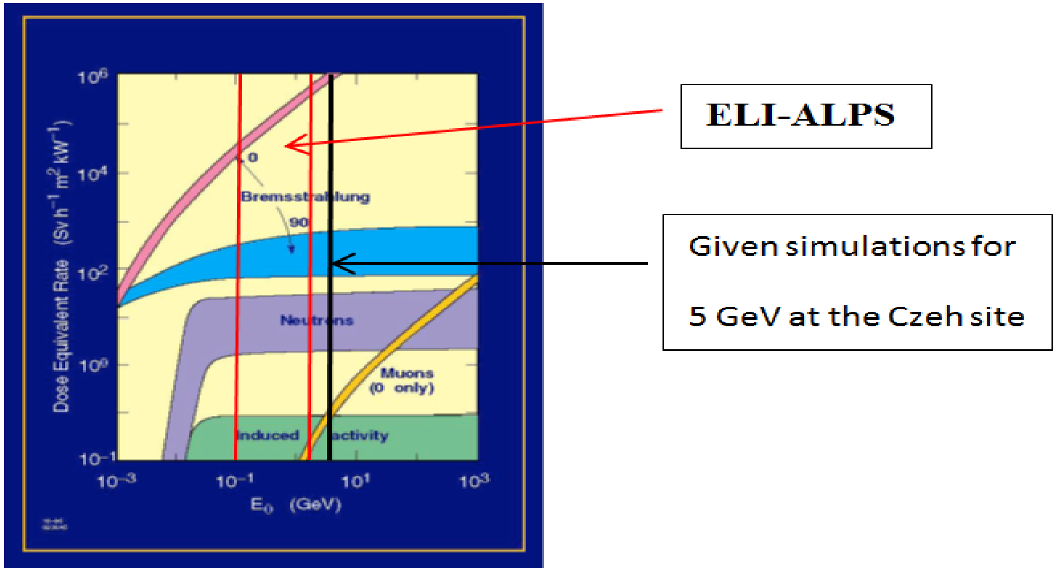
-And these effects produces induced activity

-To minimize these showers a complex beam dump design is necessary



New processes by high beam energies

- Increasing the beam energy some new processes are generated thet have a logaritmic shape (Giant resonance neutrons, induced activity, muons, Bremsstrahlung)
- It can be seen that below 100 MeV all these processes start alive and at the GeV regime there is no more increasing, only by muons



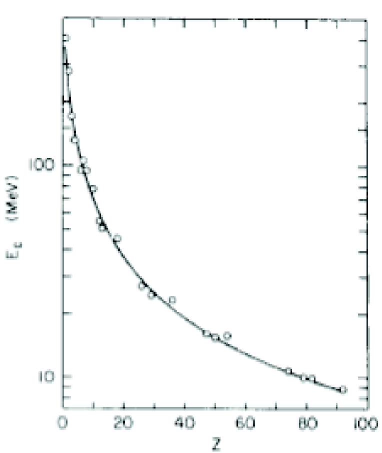
[2]

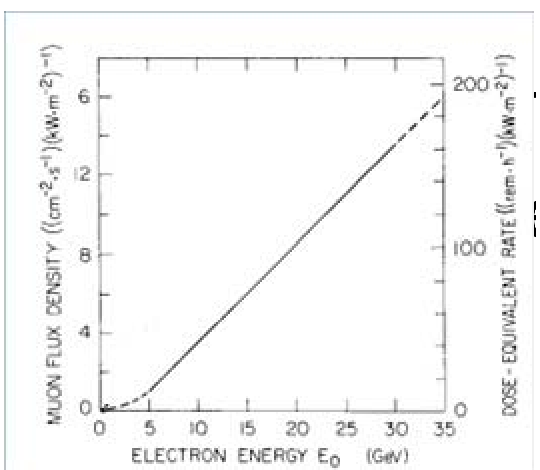
Electromagnetic cascade effects

•-The interaction between the high energy electrons and the matter generates bremsstrahlung, giant resonance neutrons, muons (at the ELI-ALPS there will be no muon generating by the electrons, because the threshold is from 2-5 GeV)

•-The cascade shower stop when the energy of the particles exceed the critical energy, it can be seen that the low and medium low atomic mass numbered matters have high critical energy, these matters can stop effectively the showers (Brems → pair → brems …)

•-It can be seen that the production of giant resonance neutrons is low at low, and medium low atomic mass numbered matters (C, Al, Fe)





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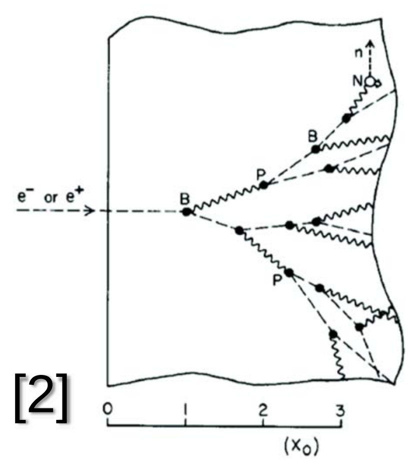
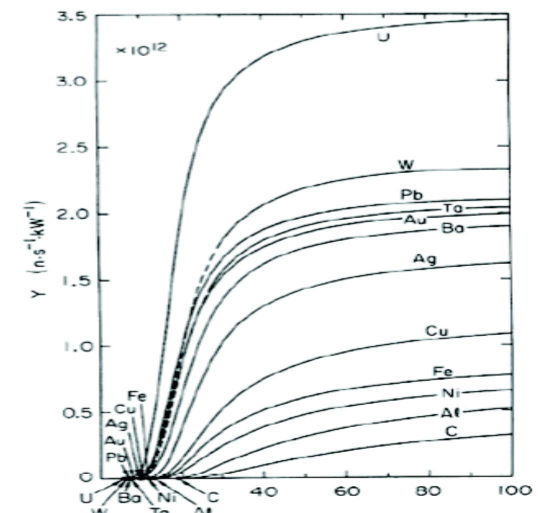


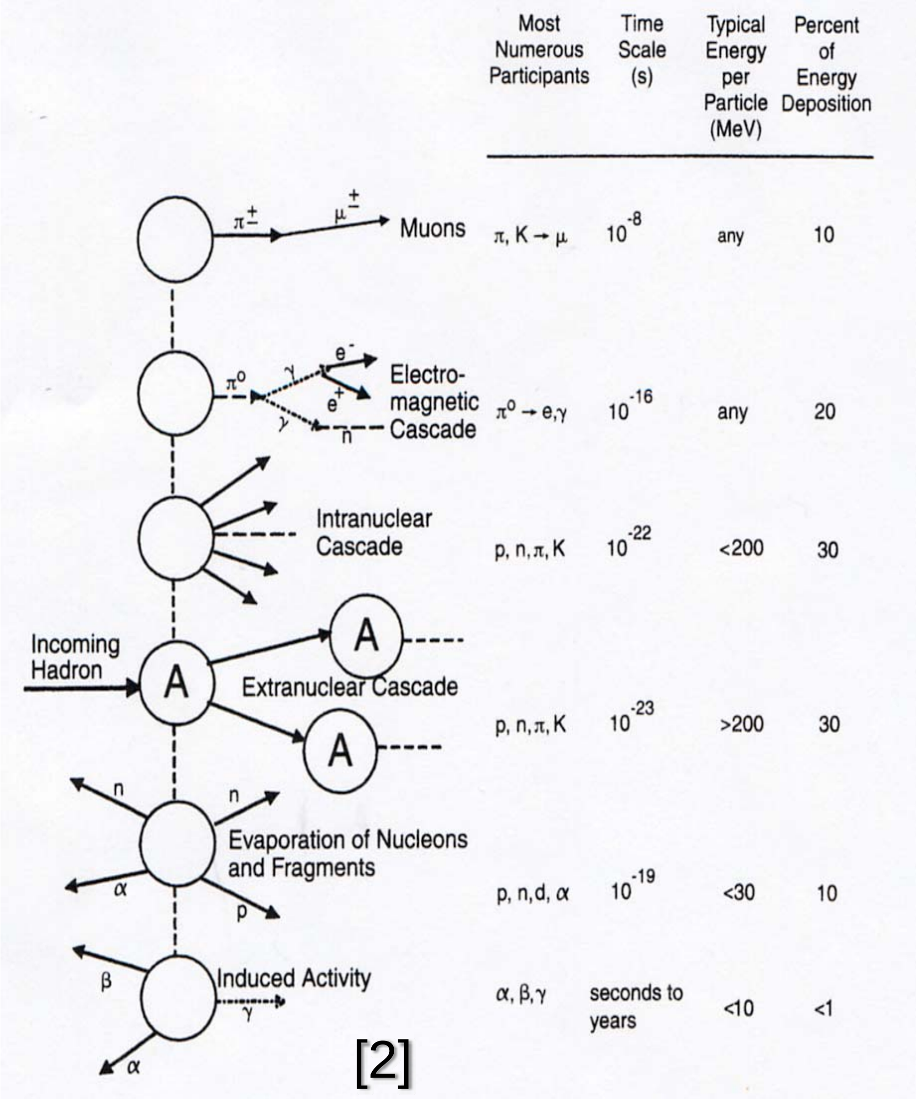


The hadron cascade

•-The hadron cascade is much more complex then the electromagnetic cascade. The collision of high energy nucleon with a nucleus gives rise to a large numbers of particles

•-The main means of energy transfer is due to the interaction of high-energy nucleon that is hadrons with energy higher than 150 MeV, that serve to propagate the cascade.

•-Nucleons in the energy range 20-150 MeV also transfer their energy mainly via nuclear interaction but at these energies charged particles are rapidly stopped by ionization and thus only neutrons predominate at lower energies.



[2]

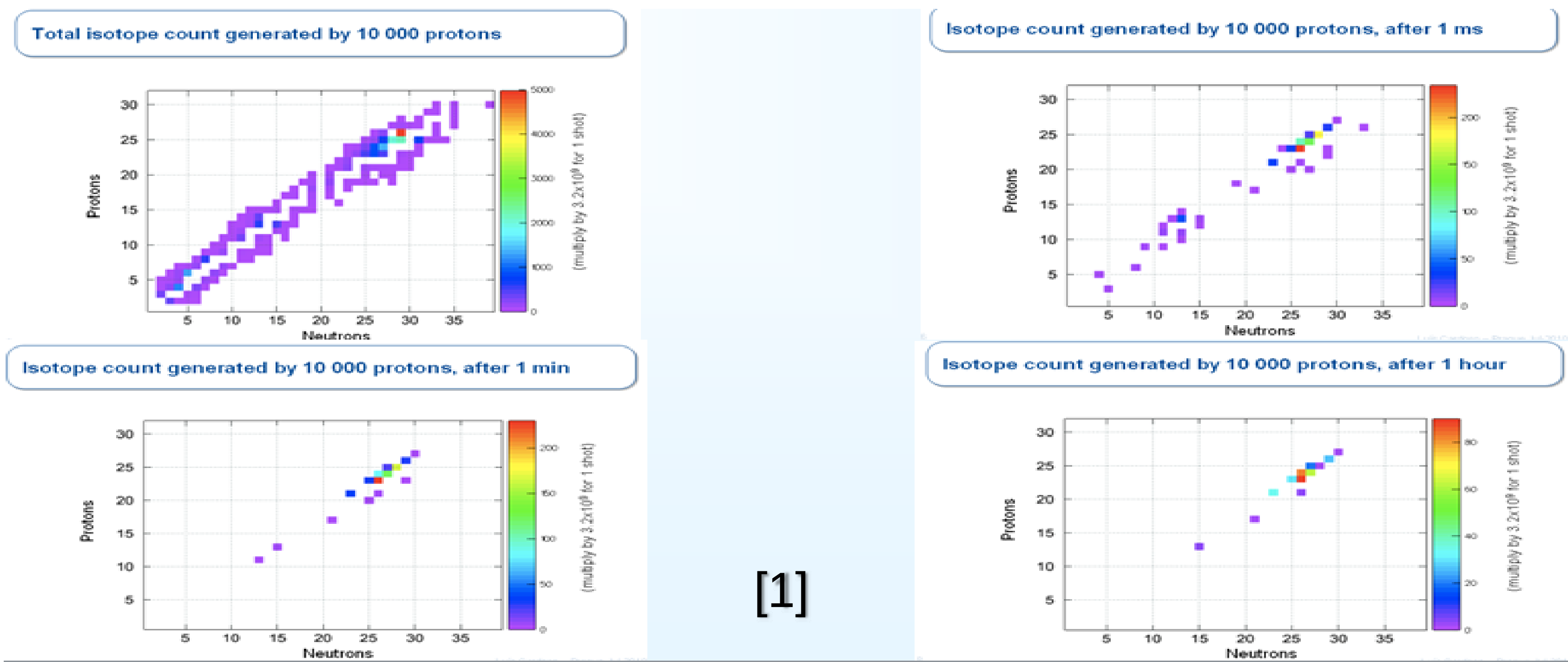
Induced activity

•-The generated neutrons by hadrons and electrons acitvates the matters of the beam dump

$$\bullet A(t)=\lambda N_{rad}(t)=\sigma\phi N_{target}[1-\exp(-\lambda t)]$$

•-Most of the activated matter have very short half lived isotopes, it decay in a few minutes

•-But the long half lived isotopes are accumulated



[1]

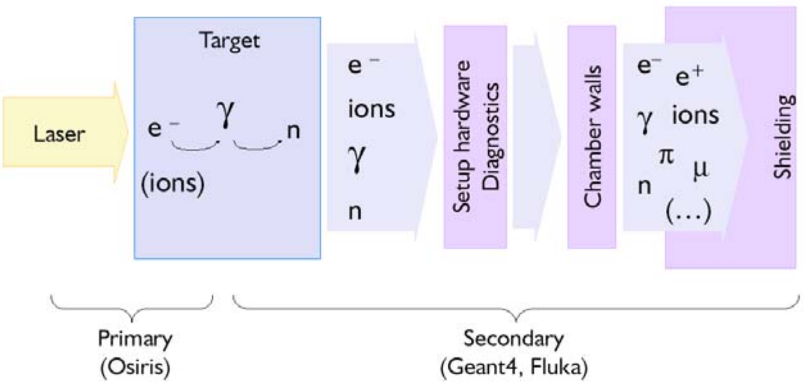
How to choose the matter and design the beam dump

•-To design the dump, the Fluka monte carlo code is the best solution, the simulated and measured values are very similar

•- The main absorber of the beam dump should be a special matter that do not generates to much giant resonance neutrons, the critical energy is not low and cheap, the possible matters are low, medium-low atomic mass numbered matters (C, Al, Fe, Copper)

•-The best choice is to investigate the amount of the induced activity of these matters, the winner will be the most lower induced matter, this is how the life time can be maximalized and the residual radiation of the dump minimized

• -At the Czech site the „winner" was the stainless steel:



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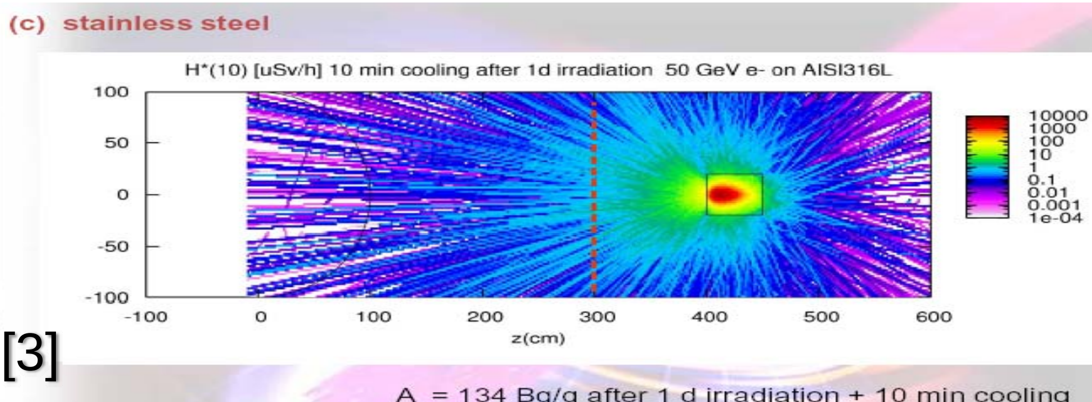
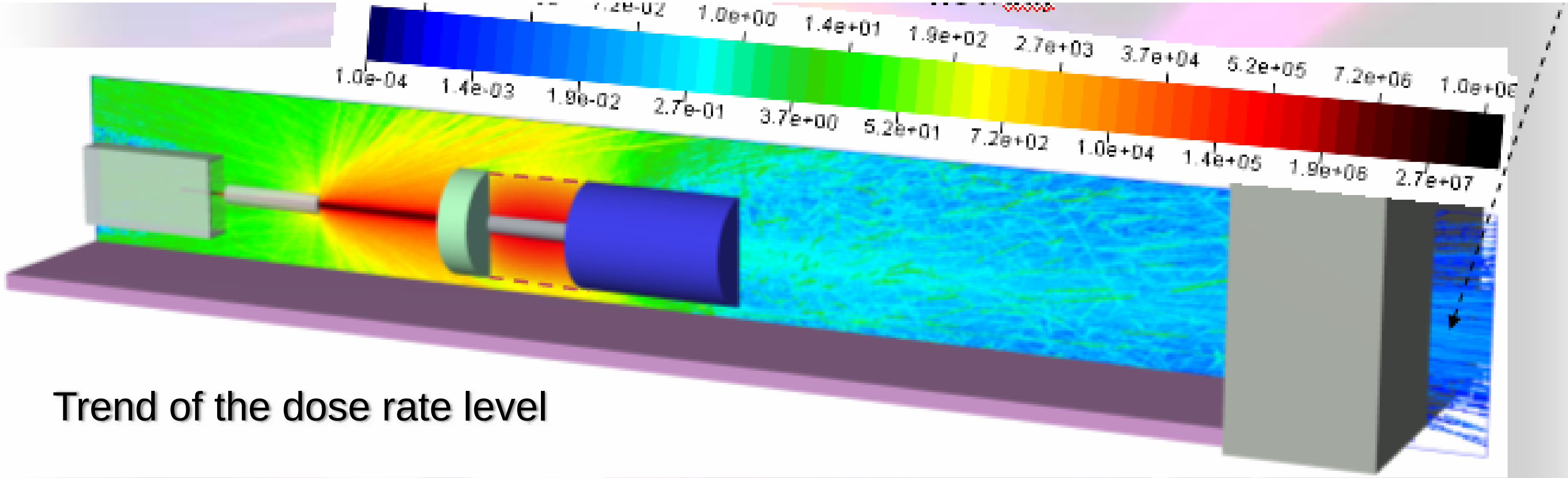
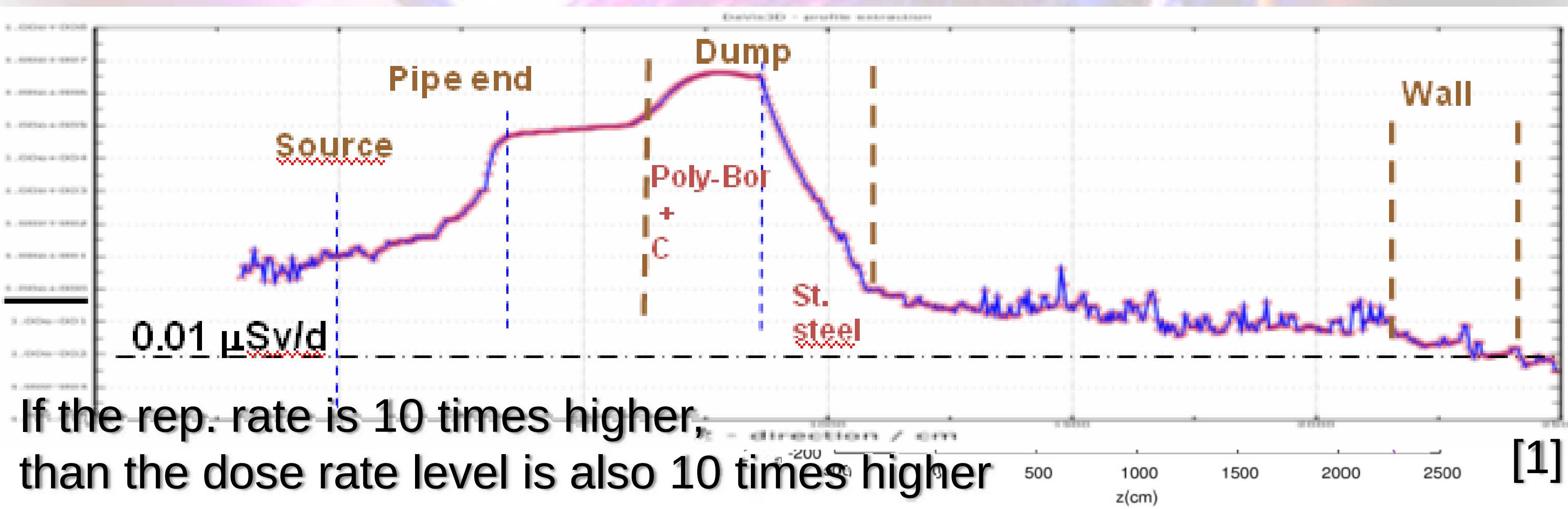


How the beam dump stop the different particle beams



Trend of the dose rate level

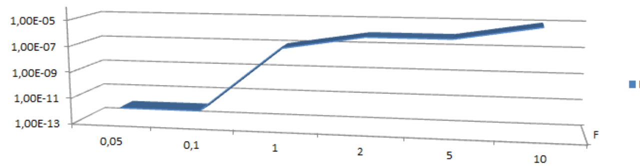


If the rep. rate is 10 times higher, than the dose rate level is also 10 times higher

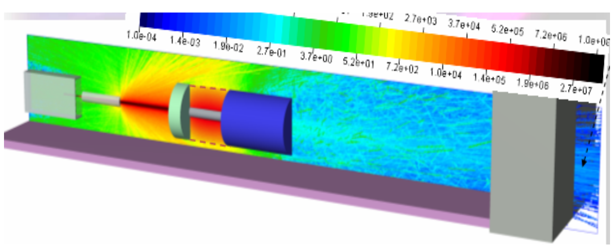
[1]

Comparison of the shielding solutions at the ELI sites

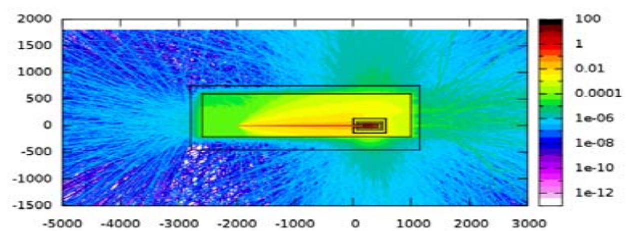
- For 5 and 50 GeV previous simulations are available
- By the parameter sensitivity analises, it can be seen that the max. dose rate on the outer surface of the wall is increasing in the MeV energy range, in the GeV range it is not increasing rapidly:



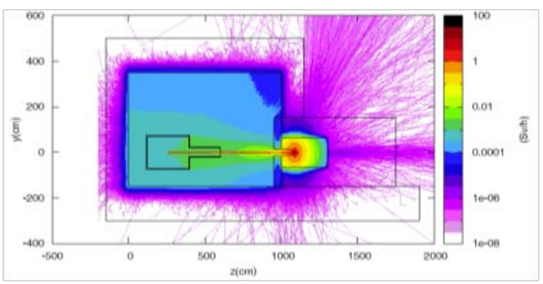
Czeh Republik



Hungary

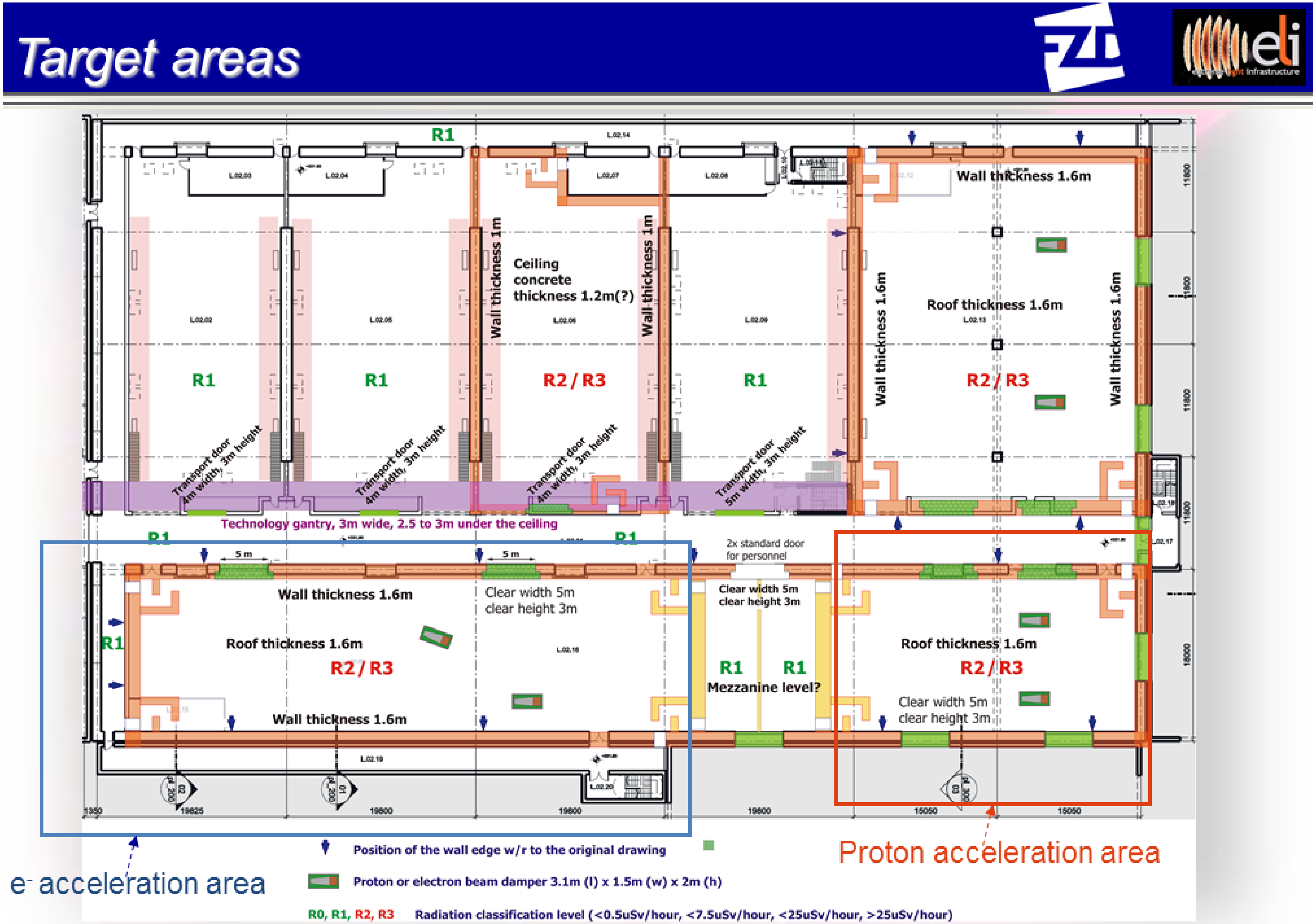


Romania



Site/parameters	Depth (m)	Hight (m)	Lenght (m)	Approx. weight (t)	Additional info	Max. electron energy (GeV)
Hungary	2,7	2,7	5,7	130	RPP, with lead+concrate+polyethylen accessories	2
Czeh Republik	3,2	3,2	5,6	108	RCC, with no lead, concrate and radial polyethylen shielding	50
Romania	3	3	7,5	262	RPP, lead at the center	38

The Czeh site, the Laser Control Room (LCR) is located between the proton and electron accelerator rooms (moun showers)



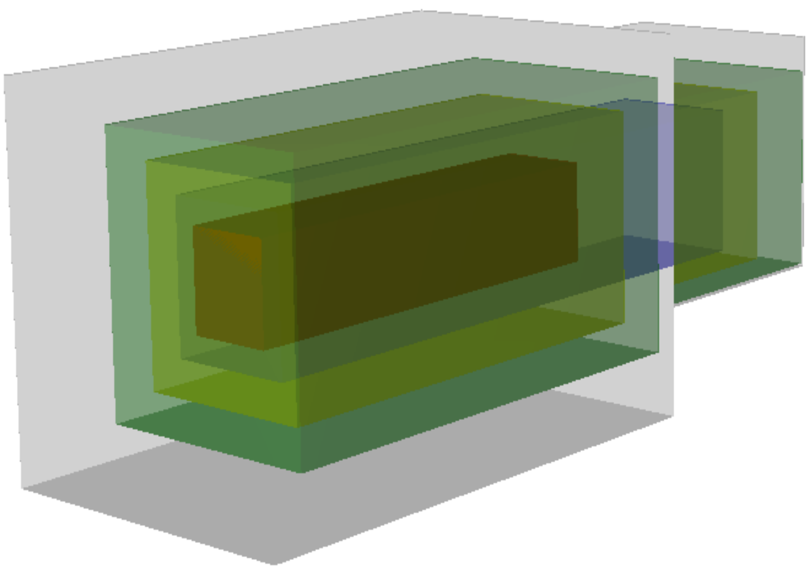
Advanced beam dump at the ELI-ALPS

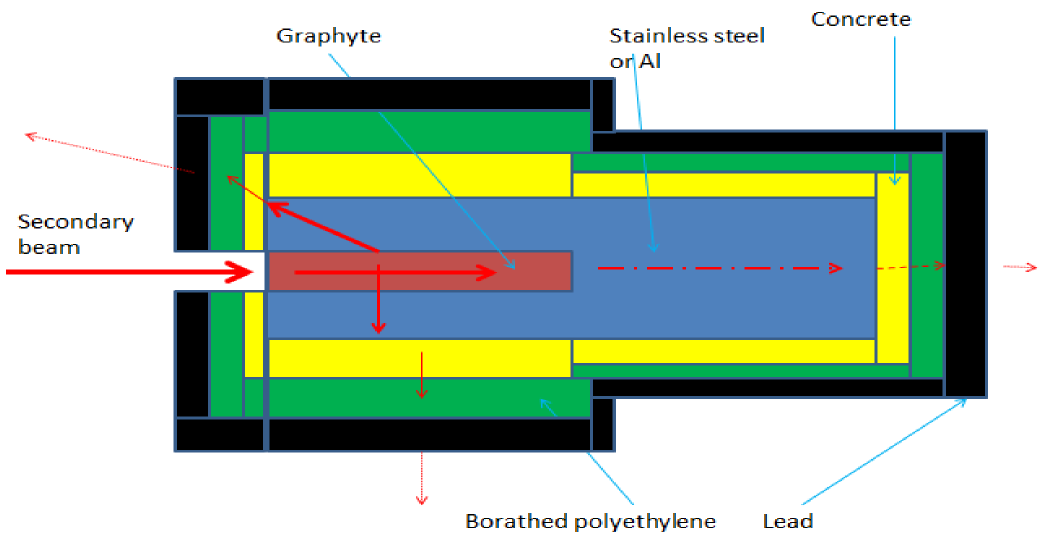
•-Now we have a conservative idea about the ELI-ALPS beam dump, but this is changeable

•- It contains stainless steel, or Al, graphyte, concrete, borated polyethylene and lead to shield all types of the particle beams

•-The dump size has a minimum value because below this size the cascade effectes can start again

•-The thickness of the walls of the target rooms will be between 0,5-2 m





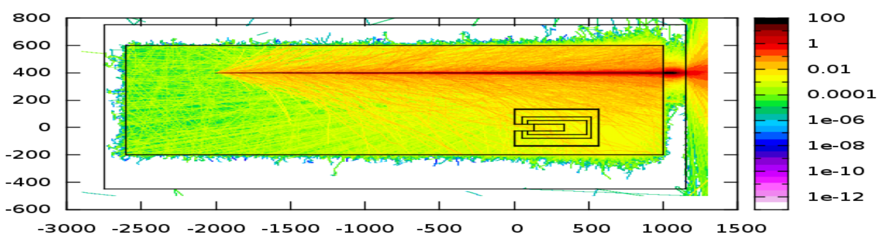
- **The main principal equation for shielding calculations:**
  - $D \times U < DC$
- D: Dose Rate (calculated by FLUKA)
- U: Operational parameters (contains: $N \times F \times T \times G$)~$10^{16}$
- $N=10^{9}$ particle/shoot
- F=10 Hz repetion rate of the laser
- T=1 hour/day operation time of the laser
- G=200 day/year
- DC: Dose Constraint by Hungarian Authorities & IAEA, it is 100 µSv/year
- It means the maximum dose rate should be lower than **10^{-5} fSv** outside

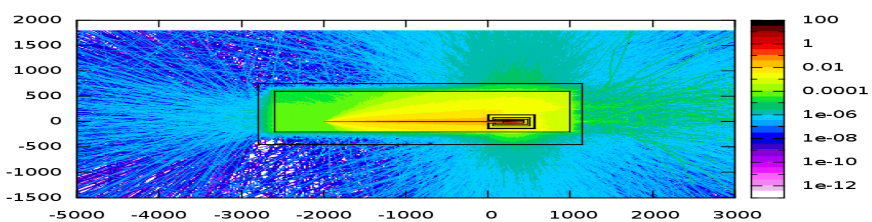
- The air also can be activated, with this simple equation the amount of the produced radioactive particles in the air can be calculated:
  - $A_{\text{total radioactivity in the air}}(t)=\Sigma_i B_i * C_i * [1-\exp(-\lambda_i t_{\text{ventillating}})]*[\exp(-\lambda_i t_{\text{decay}})]$
- Where :
- B: beam intensity
- C: activation rate

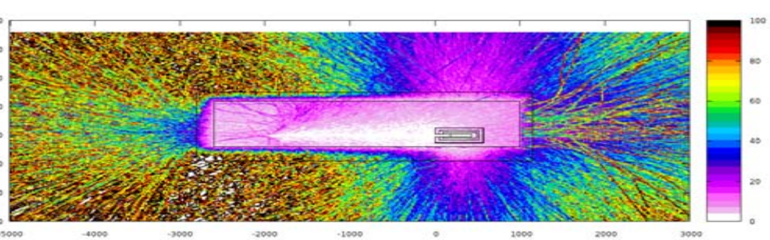
Shielding against 2 GeV electrons

- 1,5 m concrete wall it seems to be necessary+the beam dump (dose rate in fSv)
- The graphyte was sent deeper into the dump, that causes lower back scattering

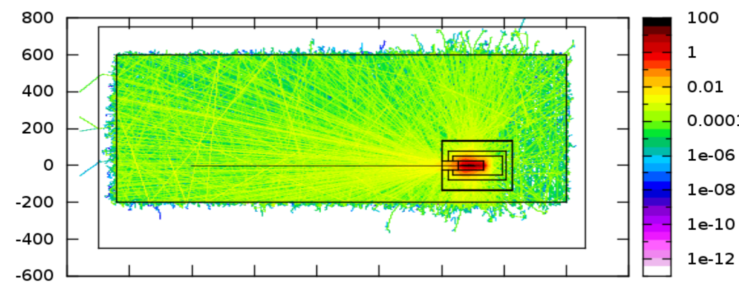
The beam hit the wall

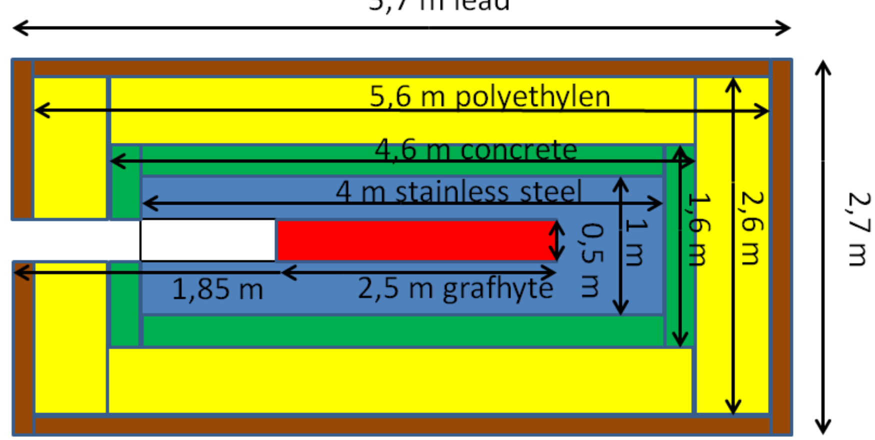






Vacuum in the room

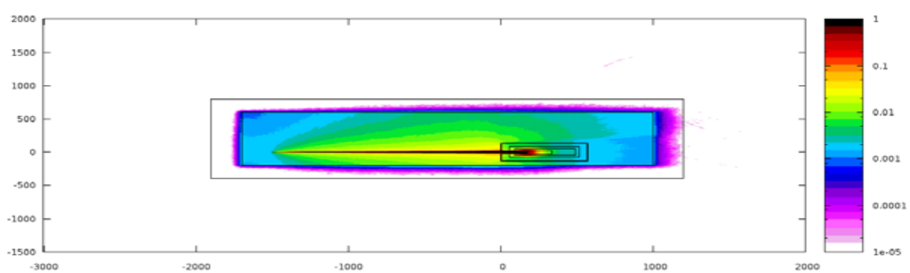




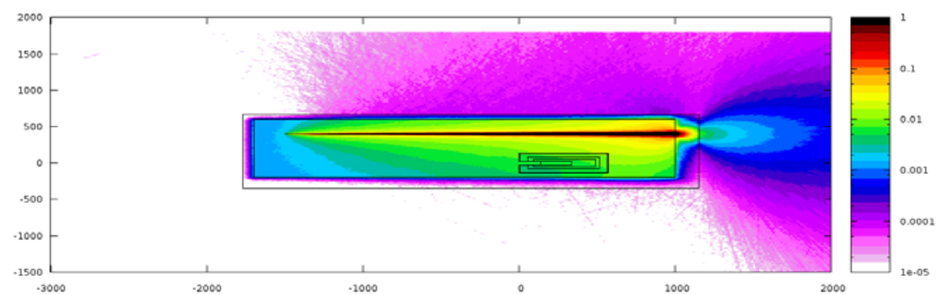
250 MeV Proton and 100 MeV C^{12} shielding

- The planned max. proton energy is 250 MeV, it can be foreseen by scaling laws
- For heavy ions the FLUKA dosen't have fluence-dose equivalents, for 100 MeV protons 1,3m thick concrete wall is nedded
- 250 MeV proton shielding is now under investigation, more than 1,5 m concrete wall is necessary if beam dump is not used
- The velocity of the heavy ions are lower than the protons, also the heavy ions have higher cross-sections, that causes the beam propagates and stop at lower distances
- So the proton beam is the limitation factor

250 MeV protons with beam dump, the wall thickness is 2m



250 MeV protons without beam dump, only the more than 10^{-5} fSv higher doses are shown

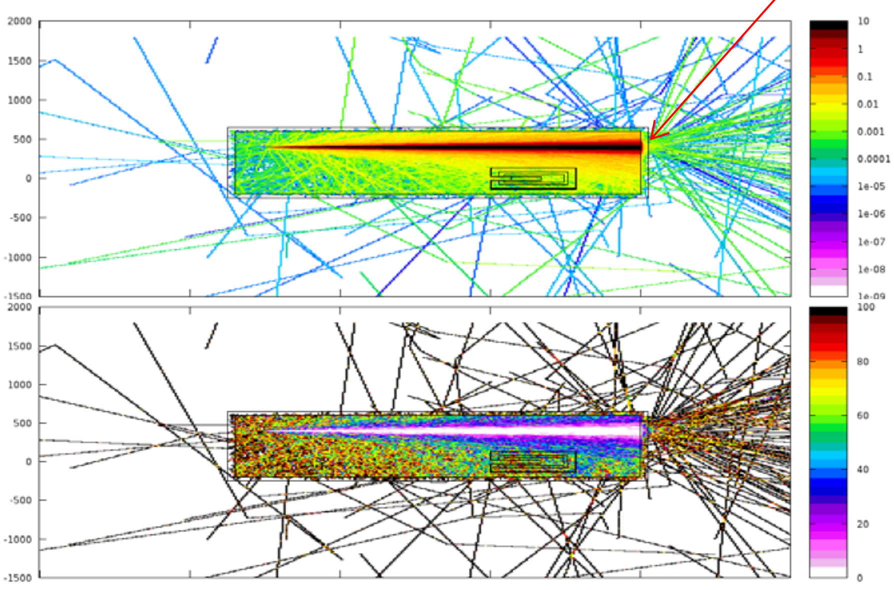


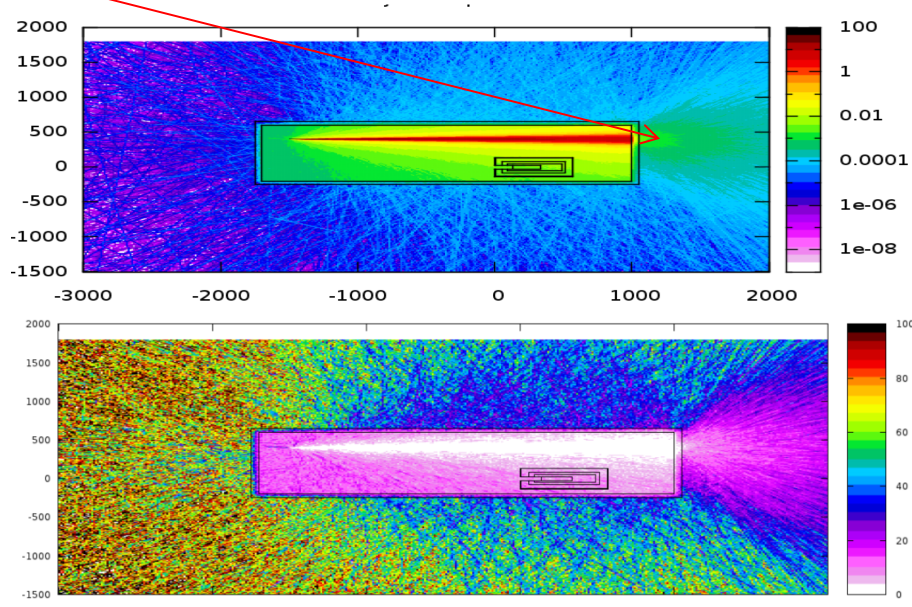
In situ calculations

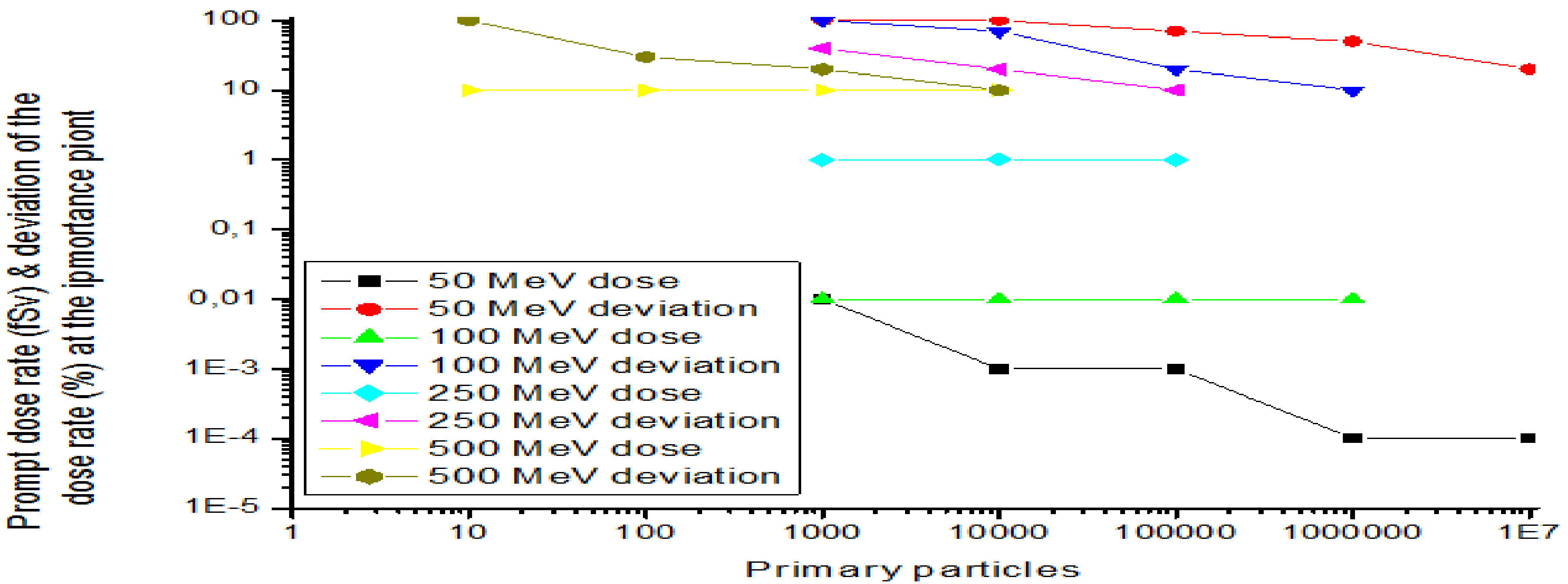
- Every exercise is a new problem that have to be solved
- Not only one solution is exsiting
- Before starting a simulation, it is recommended to look after for similar cases, from these knowledge and from the parameter sensitivity studies the results will be able to predicted
- In some cases (if there is an accident, or at a new experiment) quick results can be necessary at the site immediately
- In this cases without clasters or high performance PC-s and the calculation time is limited a good approximation method is useful to determine the max values
- In this cases high primary number is slowing down the calculations, but if there is no too much primary the deviation will be high

- At the shielding design exercises often only the max. values are important
- It can be seen from the sensitivity analises calculations that the max. value every time is different by the primary increasing, but the value every time is between two magnitudes
- If every time the higher magnitude is choosen then it can be seen the max. result is independet from the primary even if the deviation is high
- If there is no enought info. (50 MeV) the FLUKA shows conservative higher values

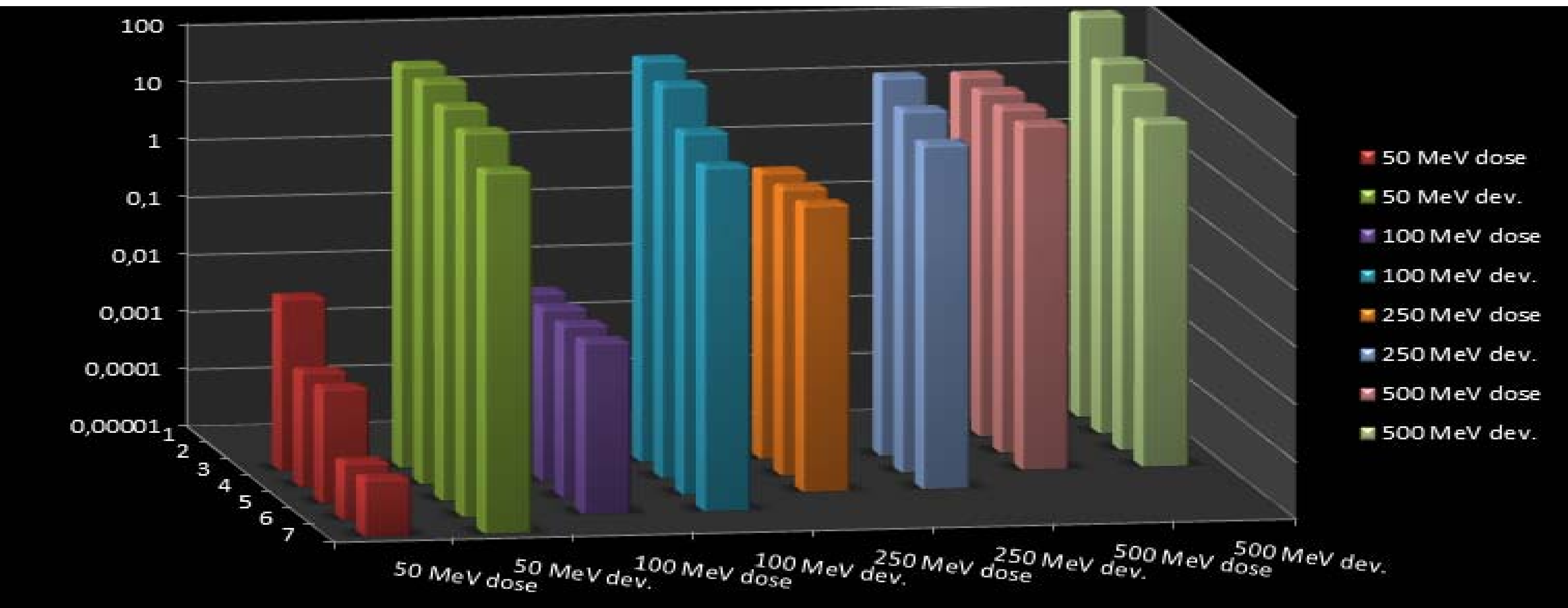
100 MeV protons 10^4 primary   Point of importance   100 MeV protons 10^6 primary







Prompt dose rate (fSv) & deviation of the dose rate (%) at the ipmortance piont
100
10
1
0,1
0,01
1E-3
1E-4
1E-5
1
10
100
1000
10000
100000
1000000
1E7
Primary particles
50 MeV dose
50 MeV deviation
100 MeV dose
100 MeV deviation
250 MeV dose
250 MeV deviation
500 MeV dose
500 MeV deviation



100
10
1
0,1
0,01
0,001
0,0001
0,00001
1
2
3
4
5
6
7
50 MeV dose
50 MeV dev.
100 MeV dose
100 MeV dev.
250 MeV dose
250 MeV dev.
500 MeV dose
500 MeV dev.

What about the radioactive wastes?!

extreme light infrastructure

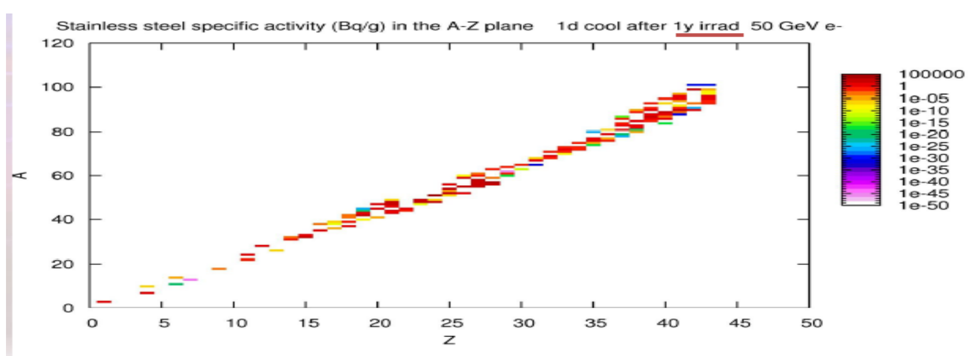
•-The matter of the beam dump is activated by the cascade effects, long and short lived radioactive isotopes are produced.

•– The long lived isotopes are accumulated, if the activity concentration reaches the *Activity Concentration Exemption Level* (ACEL), then these matters are officially radioactive materials or wastes

•-To avoid this event, the parts of the beam dump should be replaced once in a while to new ones, the used parts should be stored in a „cooling" storage.

•-After the relaxation the old parts can be used again in the beam dump

•-With this method the amount of the radioactive wastes and the operational costs can be minimized at the ELI-ALPS



A = 364 Bq/g after 1 y irradiation + 1 d cooling

[3]

Radiation safety systems

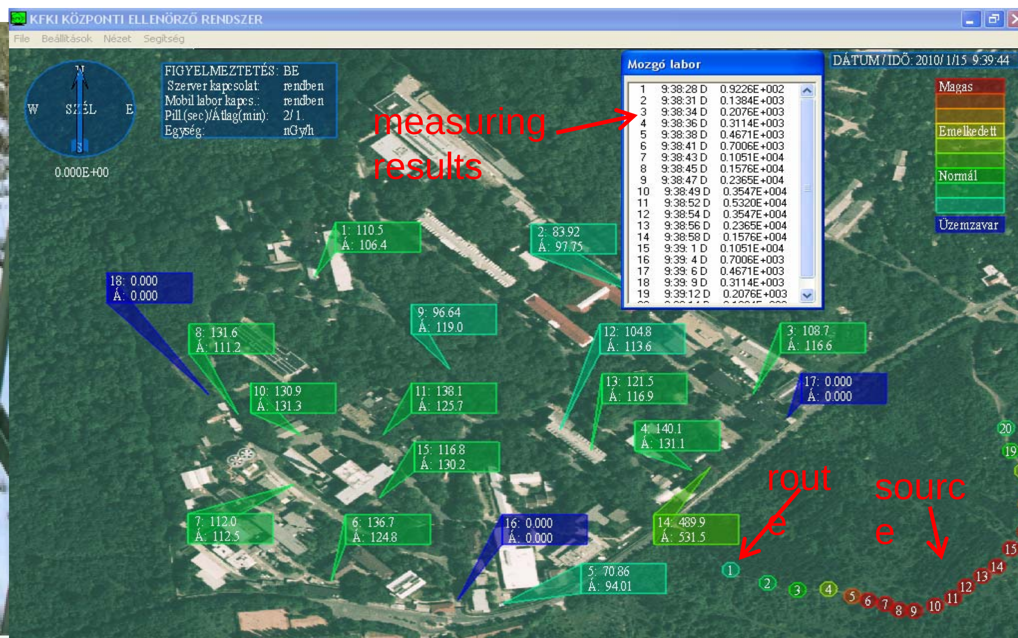
•-The prompt radiation hazards associated with the laser operation can be high. The primary goal of the Radiation Safety System is to protect people from prompt radiation hazards with a fully interlocked, engineered passive/active system that is reliable, redundant, and fail-safe. A personnel protection system can be considered as divided into two main parts:

•-(1) An access control system intended to prevent any unauthorised or accidental entry into radiation areas. The access control system is composed by physical barriers (doors, shields, hutches), signs, closed circuit TV, flashing lights, audio-visual warning devices, including associated interlock system, and a body of administrative procedures that define conditions where entry is safe

•-(2) A radiation alarm system. The system includes radiation monitors, which measure radiation field directly giving an interlock signal when the alarm level is reached.

Environmental monitoring at the ELI-ALPS

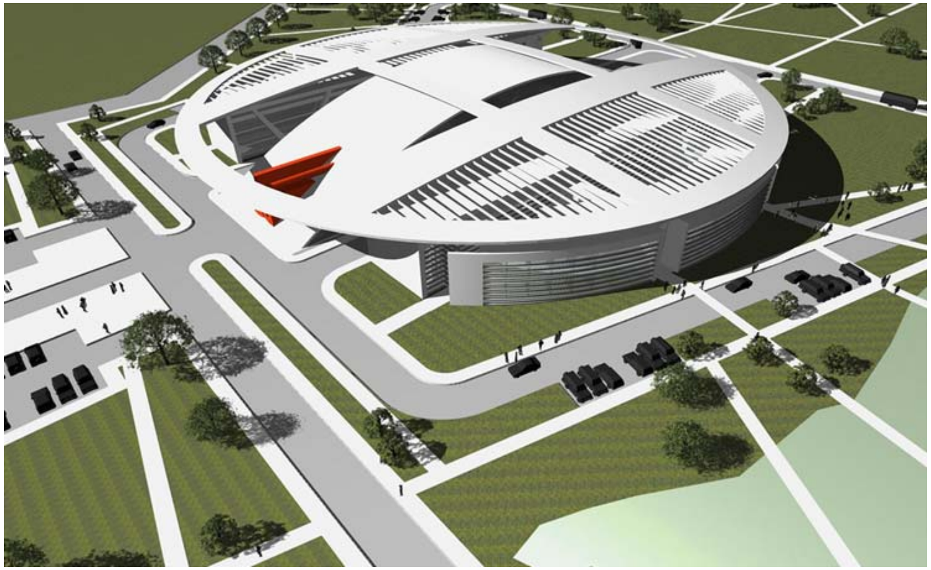
- -For the public and for the authorities the minimal environmental effect of the ELI can be demonstratable by measured environmental data
- -GM tubes in-out side, fall-out, aerosol sampling, in-situ gammaspectrometry
- -Soil, plant, water sampling 2-3 times/year
- -Central signal system



Thank you for your attention!

extreme light infrastructure

And thank you for the FLUKA & FLAIR team!



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