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FIRST RESULTS ON SIMULATION OF RADIATION ENVIRONMENT AT BTeV ELECTROMAGNETIC CALORIMETER

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Abstract

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We present the preliminary results of the radiation environment calculations for BTeV electromagnetic calorimeter. Two problems associated with this background are considered – the absorbed dose accumulation in the lead tungstate crystals ($PbWO_4$) and hadron fluence formation in electronic zone of the electromagnetic calorimeter.

Аннотация

Узунян А., Васильев А., Ярба Ю. Первые результаты моделирования радиационной обстановки на электромагнитном калориметре эксперимента BTeV: Препринт ИФВЭ 2001–24. – Протвино, 2001. – 9 с., 6 рис., библиогр.: 11.

В работе представлены предварительные результаты расчетов радиационной обстановки на электромагнитном калориметре эксперимента BTeV. В связи с этим рассмотрены две проблемы – накопление поглощенной дозы в кристаллах вольфромата свинца (($PbWO_4$) и формирование флюенса адронов в зоне электромагнитного калориметра.

1. Introduction

BTeV is a dedicated B-physics experiment in the $C\oslash$ interaction region at the Fermilab collider to study direct CP-violation, mixing and rare decays in B-mesons. The BTeV Proposal was approved in June 2000 [1]. BTeV is an international collaboration to which IHEP joined in 1999. The IHEP group's interest, together with FNAL, Syracuse University and University of Minnesota, is an Electromagnetic Calorimeter (EMCAL) of the BTeV setup. EMCAL is planned to consist more than 20,000 of $PbWO_4$ crystals.

The study of the radiation environment formation is the essential part for the BTeV upcoming Technical Design Report preparation. The following subjects could be under the consideration:

- absorbed dose and radiation hardness of detectors;
- background particle (charged hadrons, neutrons, gammas, electrons and highly ionizing particle) rates and its tolerable levels for detecting elements and electronics;
- residual levels of induced radioactivity, safety issue and access procedures;
- gamma/electron background due to induced radioactivity;
- possible ways for background reduction and shielding requirements.

In this paper we present the first results of radiation background calculations in BTeV EMCAL. To define conditions for normal operation of the detector, it appears to be an important task to estimate the expected levels of the absorbed dose and the fluences of neutrons and charged particles in the EMCAL elements (crystals, phototubes, read-out electronics).

To calculate the radiation levels, Monte Carlo simulation using MARS(IHEP) code was performed[2,3]. MARS is the standard IHEP package used (together with FLUKA code [4]) for radiation environment calculations for LHC project at CERN [5,6].

2. Conditions of simulations

The nominal luminosity of Tevatron, $2 \cdot 10^{32} cm^{-2}s^{-1}$, together with 1 TeV beam energy, assuming an inelastic cross-section of 60 mb, will generate $1.2 \cdot 10^7$ inelastic $p\overline{p}$ events per second. Together with particles produced in interactions with BTeV material, this create a hostile radiation environment. Each year of BTeV operation was assumed to be 10^7 seconds.

We used the PYTHIA generator to generate 2000 minimum bias events as input particles file for MARS.

2.1. Radiation transport code

MARS as Monte-Carlo code was designed for the simulation of hadron cascades, electron-photon showers and muon transport in heterogeneous matter of arbitrary complexity in energy range from several TeV down to thermal energy(for neutrons).

By its original philosophy MARS is a fully biased code, and as one of its features uses an inclusive approach for the Monte Carlo simulation of particle production. Within the inclusive Monte Carlo approach only a limited number of particles of fixed types are born in interaction act based on phenomenological formulae. The kinimatic characteristics of the secondary particles from the corresponding double differential cross-section are simulated. The real multiplicity of the generated particles is taken into account via the introduction of particle weights. Such an approach gives a possibility to use flexible tuning of a cascade tree construction algorithm providing a considerable gain in calculational efficiency depending on the kind of problem. The inclusive Monte Carlo version, although not useful for precise physics simulations, allows fast estimations of mean values, such as particle fluxes, spectra and absorbed energy, and is therefore well suited for background calculations. MARS uses a library of constants, consisting of 28 groups and covering neutron energy range up to 14.5 MeV (including one thermal group with $E_n < 0.215 \cdot 10^{-6}$ MeV) [8]. The energy thresholds in our simulation were $2 \cdot 10^{-9}$ MeV (thermal energy region) for neutrons, 10 MeV for charged hadrons and 100 keV for gammas and electrons.

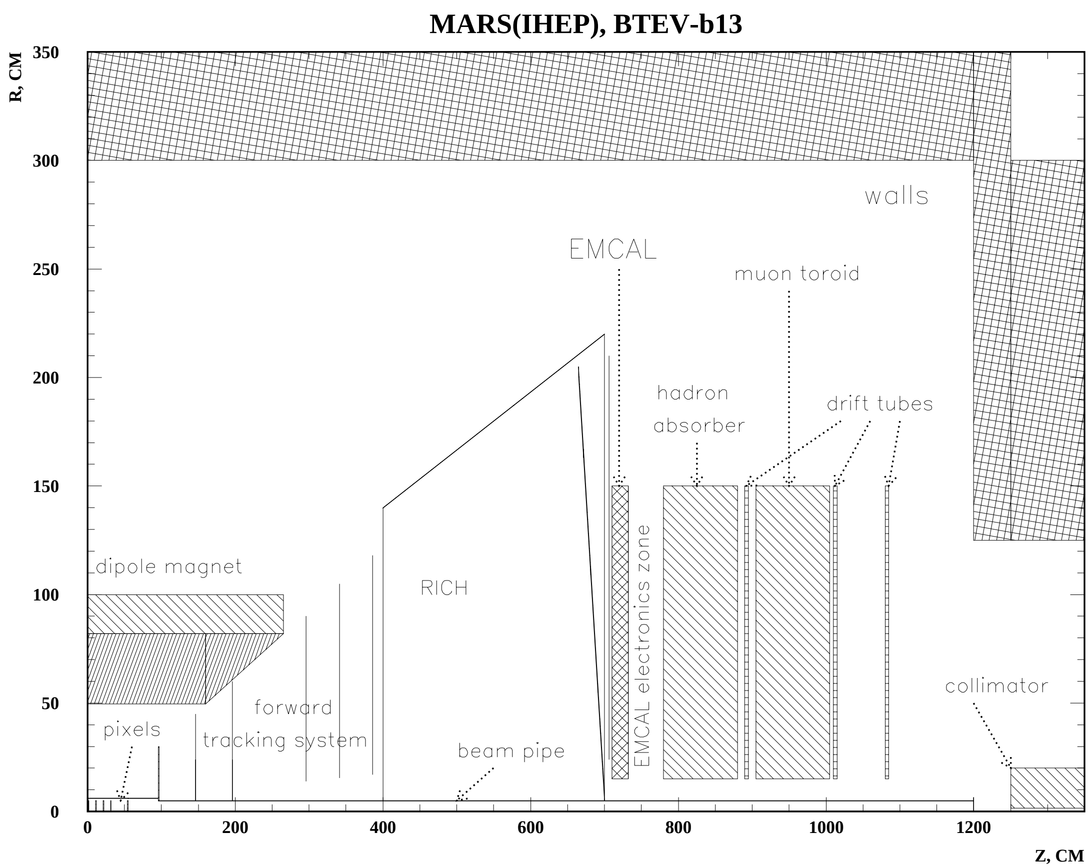

Fig. 1. BTeV geometry used for radiation background calculations.

2.2. Geometry description

The first approximation of BTeV geometry implicated in MARS is shown in Fig.1. The following elements and subsystems were taken into account:

- beam pipe: R= 6 cm, 1.5 mm of thickness, Al, for $Z < 96\ cm$,
  and R= 4.85 cm, 1.5 mm of thickness, Al, for $Z \geq 96\ cm$;
- silicon pixel detector, forward silicon tracker, forward tracking system, RICH;
- dipole magnet, magnetic field components B_x, B_y, B_z and its dependence from Z-axis only (we have not the azimuthal structure of magnetic field in calculations);
- EMCAL ($PbW0_4$, density=8.28 g/cm^3), location: Z=(710-732) cm, R= (15-150) cm;
- phototube windows (quartz, density =2.64 g/cm^3), location: Z=(732-732.2) cm, R = (15 - 150) cm;
- hadron absorber, muon toroids;
- experimental cavern was approximated as cylindrical volume with walls made by the ordinary concrete (density =2.35 g/cm^3)

The same rough geometry description is quite enough for EMCAL absorption energy estimation. Here, it should be noted that the configuration is not final and is likely be revisited later.

3. Result of calculations

In the EMCAL (and in all BTeV environment) energy deposition effect will be induced by charged hadrons, electrons, gammas and neutrons (though the last two are not directly ionizing, they can induce ionizing energy deposition). Total absorbed dose effect is a typical case of cumulative effects. This happens during the whole time the device is exposed to radiation. The results of calculations in terms of absorbed dose and particle fluence are presented.

Absorbed dose unit in the International System is the Gray (Gy). (Note that $1\ Gy = 1\ J/kg = 100\ rad = 6.24 \cdot 10^6\ GeV/g$). The mathematical definition of the absorbed dose (D) is:

$$D = \lim(\triangle E/\triangle m);\ \triangle m \to 0,$$

where $\triangle E$ is the absorbed energy in the volume $\triangle V$, within of which we have the matter of mass $\triangle m$.

Fluence (F) is defined as the total tracklength of particles per unit of volume

$$F = \sum_i \frac{l_i w_i}{V},\ [1/cm^2],$$

were l_i is a particle tracklength within of the volume V and w_i is a particle weight.
Particle fluence and absorbed dose, although correlated for a given particle type and energy in given medium, should never be treated as synonyms.

For the real situation we need to take bounded volume and mass. In our case we have essentially different radiation field gradient along Z-axis of $PbWO_4$ and along azimuthal φ-angle (the effect of dipole magnet influence). Because of this we used the EMCAL segments (for which the absorbed dose was calculated) which is contained by
$R_i - (R_i + dR), Z_i - (Z_i + dZ)$:, $dR = 3\ cm,\ dZ = 1\ cm$,

$abs(Y) \leq 5\ cm$ for the vertical plane and $abs(X) \leq 5\ cm$) for the horizontal plane. We estimate the accuracy of calculational results (because not a "point-like" volume is used) as ~ 20 % for the worse case(the area with a big gradient of radiation field). For these conditions, the EMCAL absorbed doses at $\eta = 4.45(3., 2.27)$ versus Z-position are given in Fig.2. The maximum of the absorbed dose value occurs between 3 and 8 cm deep depending on the η-range considered. The dose profiles has a maximum on the PWO depth of $\sim 6\ cm$ at $\eta = 4.45$ (vertical plane). In this case the absorbed dose is equal to $\sim 1.8 \cdot 10^4\ Gy/year$ for luminosity $L = 2 \cdot 10^{32} cm^{-2} s^{-1}$. The minimal dose values of a few tens rad take place on EMCAL periphery. Fig.3 shows the azimuth structure of absorbed dose profiles for the EMCAL (in $PbWO_4$, at (4-8) cm deep) and for the phototube windows. The azimuth φ-angle starts from vertical axis and was divided in 40 bins. Note that for absorbed dose calculation in front face of the phototubes we used quartz(SiO_2, density=2.64 g/cm^3) of 2 mm thickness. We can see that the maximum absorbed dose in the phototube window is 10 kGy/year.

The maximum radiation level occurs close to the beam pipe.There is also a relatively narrow vertical band (were the absorbed dose higher than average dose) caused by the sweeping action of BTeV dipole. Fig.4 gives the crystals number distribution as a function of the absorbed dose accumulated by crystals during the operation year (here dose means the maximum dose in any part of the crystals). The calculations indicate that $\sim 90\%$ of the crystals have a yearly accumulated dose of less than 1000 Gy.

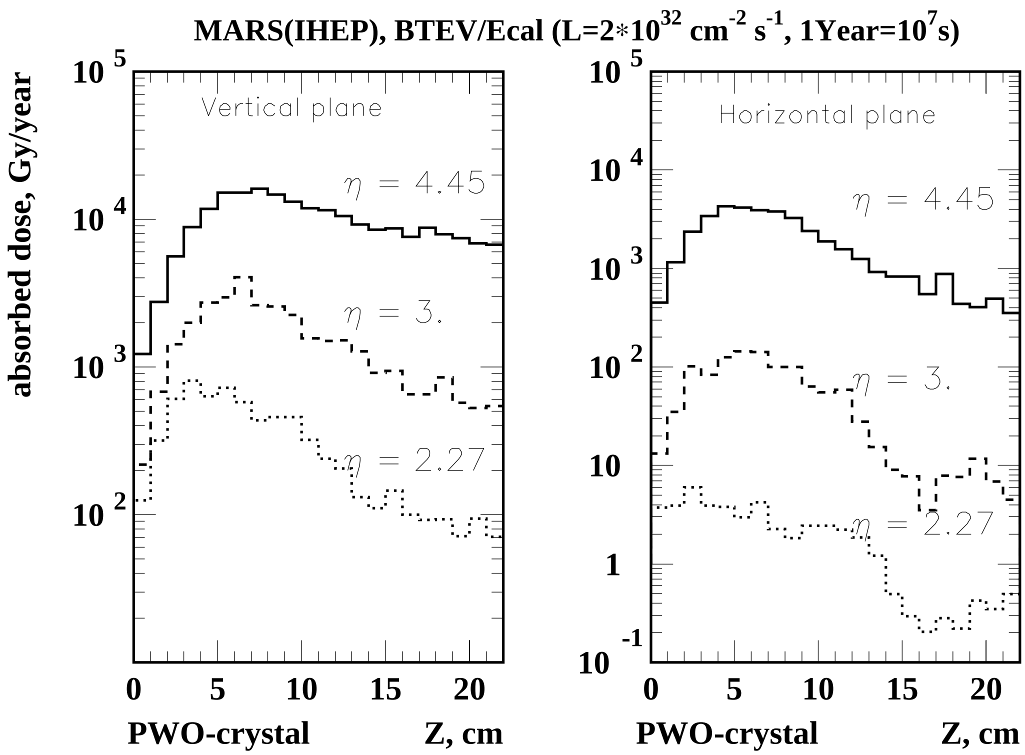

Fig. 2. PWO-crystals absorbed doses at $\eta = 4.45(3., 2.27)$ versus of crystal depth for the vertical and horizontal planes.

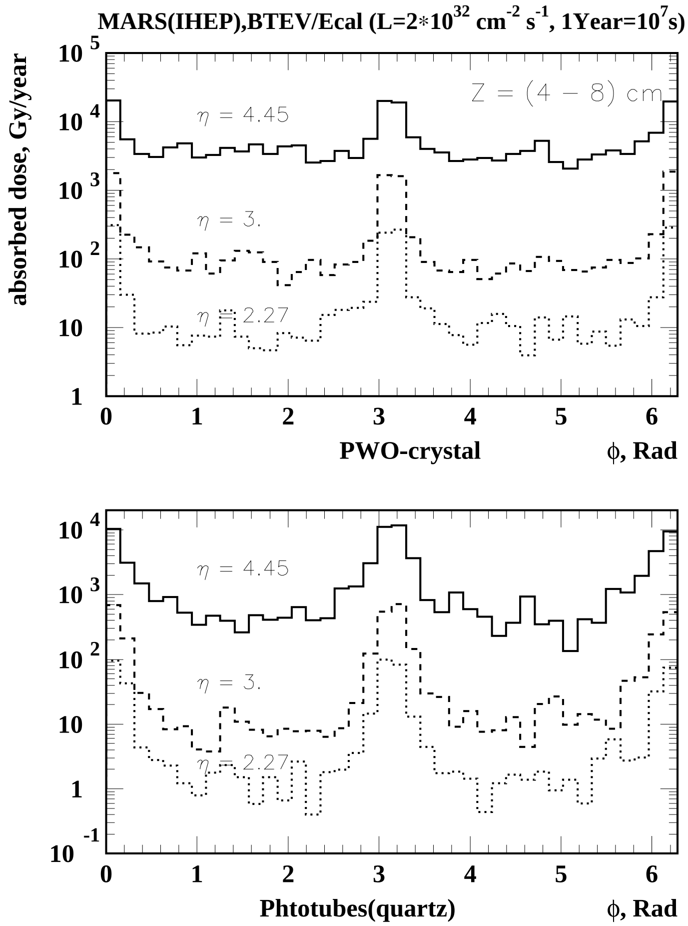

Fig. 3. Azimuth profiles of the PWO-crystals maximal absorbed doses (top figure), and absorbed doses in the phototube windows (bottom). φ-angle starts at vertical axis.

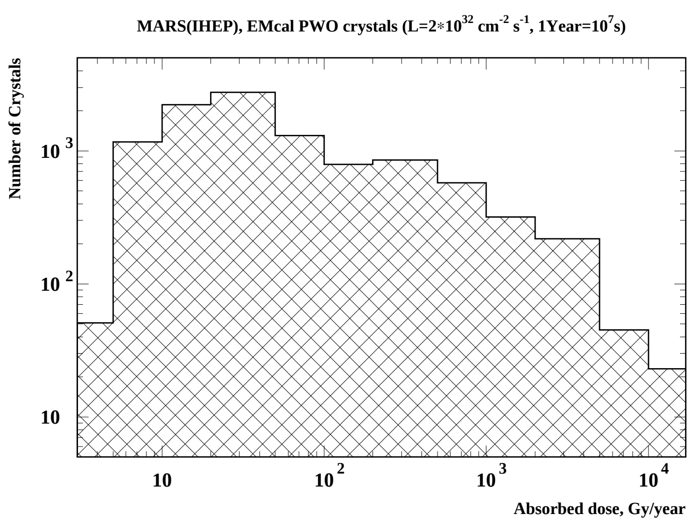

Fig. 4. Crystals number distribution as a function of the maximal value of absorbed dose.

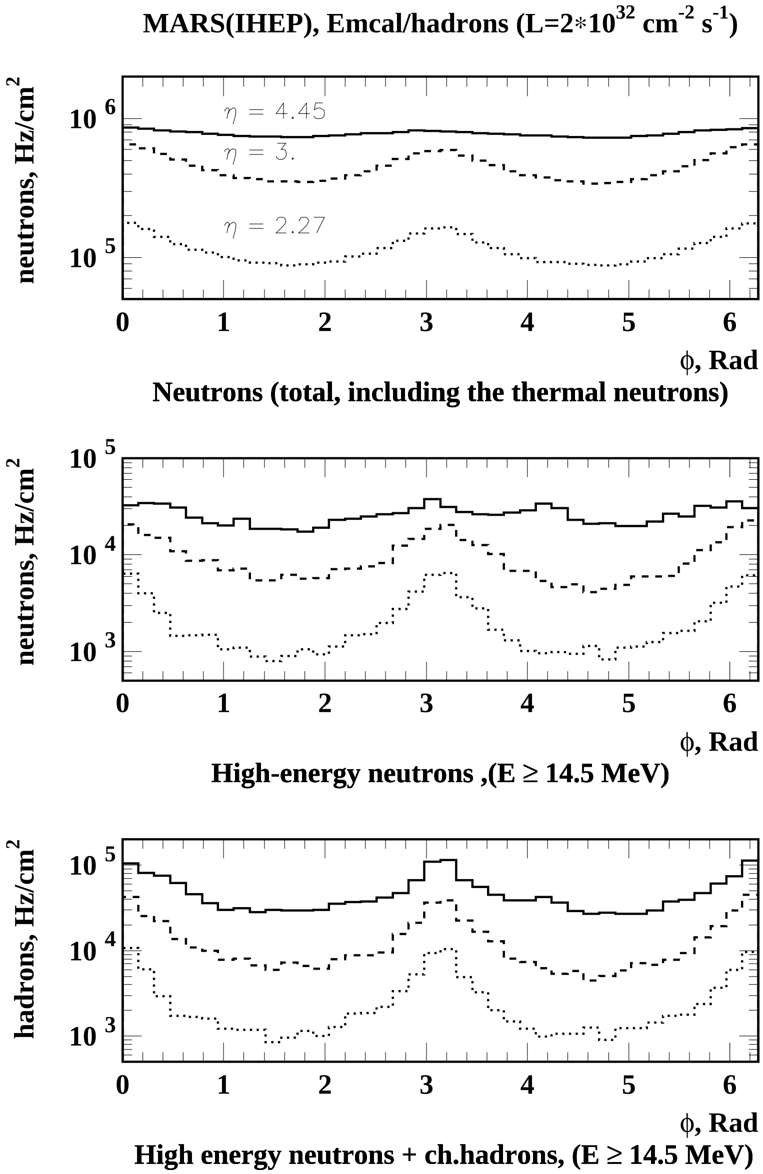

Fig. 5. Azimuth structure of the hadron fluence distributions just behind EMCAL.

The radiation hardness studies of detectors and electronics are the important part of collider experiments activity[9,10]. The experimental data, available from LHC project activity, mainly from photon and neutron ($E < 20\ MeV$) irradiation,indicate that only the light transmission of the crystals is affected by irradiation and not the scintillation mechanism itself. Usually, the hypothesis is that the light loss due to decreased transparency has no direct dependence on the types of incident particles, but only on the absorbed dose.

However, in general case the radiation damage of $PbWO_4$-crystals and electronics is not only a function of absorbed dose, but also sensitive to the type of irradiation. So, the properties of bulk silicon are significantly degraded by displacement damage effects, i.e. distortions of the crystal structure.Thus, it is very useful to know both the hadron fluence/spectra and absorbed dose to provide the radiation damage study.

We need to emphasize (together with [11]) although photon and neutron irradiation have indicated that the damage in crystals is only a function of dose rate, this cannot be considered as a proof that high-energy hadrons (with energy greater than a few tens MeV) could not cause some new type of damage. Compared to photons or reactor neutrons, high-energy hadrons will be able to induce the inelastic nuclear reactions which will locally destroy the crystal lattice. In particular they can create nuclear fragments with very high linear energy transfer and lead to extended clusters of crystal lattice distortion. Thereto we will have the process of the new types of isotopes generation. This process can lead to deterioration or improvement of the crystal radiation hardness. Therefore the radiation hardness studies of $PbWO_4$-crystals should be provided using a hadron environment which is similar to the BTeV/EMCAL expectations.

The azimuth distributions of the hadron fluence at different η for region of the EMCAL electronics are presented in Fig.5. We have considered the neutrons fluence and the charged hadrons one separately to estimate its contribution in the total hadron radiation. One can find that the maximal value of the neutron fluence (including the thermal energy neutrons) is about of $10^6\ n/(cm^2s)$ and of $4 \cdot 10^4\ n/(cm^2s)$ for the neutrons with energy greater than 14.5 MeV (luminosity $= 2 \cdot 10^{32} cm^{-2}s^{-1}$).

The neutron energy spectra shape for the internal (R=(15-70) cm from beam pipe axis) and peripheral ((R=(100-150) cm) regions of the EMCAL electronics zone in Fig.6 are given. In this case the neutron spectra are averaged over the azimuth φ-angle. The spectrum above 100 keV is characterized by the evaporation and cascade peaks at neutron energies of 1 MeV and a few tens of MeV, correspondingly.

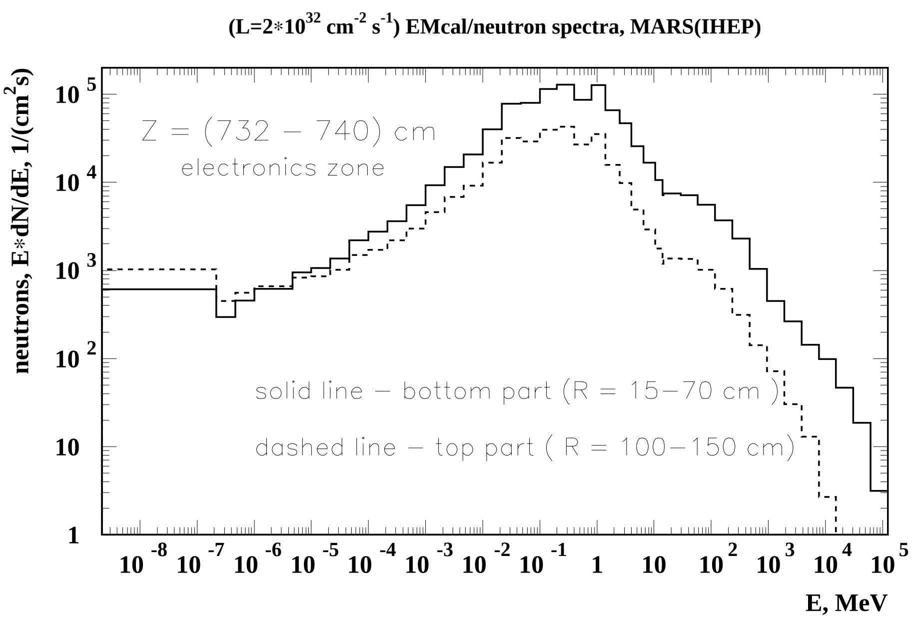

Fig. 6. Neutron energy spectra.

4. Conclusion

The expected maximal annual EMCAL absorbed dose is about of 20 kGy (2 $Mrad$) at a radius of 15 cm from beam pipe axis ($\eta = 4.45$) for luminosity $L = 2 \cdot 10^{32} cm^{-2}s^{-1}$. This absorbed dose value is at electromagnetic shower maximum, which is about 6 cm from the front face of the EMCAL. This dose falls down three orders of magnitude to the boundary of the EMCAL, which is 150 cm from the center in the lateral direction. The calculations of the EMCAL absorbed dose map indicates that $\sim 90\%$ of the crystals have a yearly accumulated dose of less than 1000 $Gy = 0.1\ Mrad$.

The hadron fluence just behind the EMCAL (EMCAL electronics zone) is essentially defined by the neutrons component. The low-energy neutrons ($E \leq 14.5\ MeV$) form approximately 90% of the hadronic field in this region.

It is necessary to provide the calculations of the particles (separately for charged hadrons, muons, gammas, neutrons, electrons+positrons) fluence and its energy spectra in the region where the sensitive elements are installed. It could help us to define the tolerable level of particle rates for counting systems and electronics. So, for the next stages of calculations it is very important to use the full scale BTeV geometry to take into account all possible sources of secondary particles including the BTEV-Tevatron interface(problem of machine generated background).

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