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Space Radiation Shielding and Environment Applications with the SHIELD Transport Code

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Abstract

Besides the GEANT3.21/Geant4 packages there are other Monte Carlo codes for hadron transport simulation relevant to space radiation shielding and environment applications. In fact there are three independent types of these codes: several versions of HETC (High Energy Transport Code), the FLUKA code, and the Russian code SHIELD. All of them have similar fields of applications but differ in energy range and types of projectiles, in models of nuclear reactions included, and in some other respects.

The SHIELD transport code [1] has been used for several space applications [2-9]. Main goal of this presentation is to demonstrate that the SHIELD code is tuned for space shielding and environment applications and can be used for radiation effect simulation at long-term spacecraft missions.

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Exclusive transport codes

NMTC(ORNL, 1971)→HETC(ORNL,1972)→
LAHET(LANL,1989)→MCNPX(LANL,1997)→
HERMES(KFA,1989)
NMTC/JAERI
HETC-3STEP
HETC(PSI)
etc., up to 10 versions

SHIELD(JINR,1972)→SHIELD(INR,1989)→
SHIELDHI(INR,1997)→SHIELD-HIT(INR,KI,2002)→

FLUKA(1974,CERN)→
FLUKA82(CERN)→ FLUKA87(CERN)
FLUKA92(INFN,CERN)→

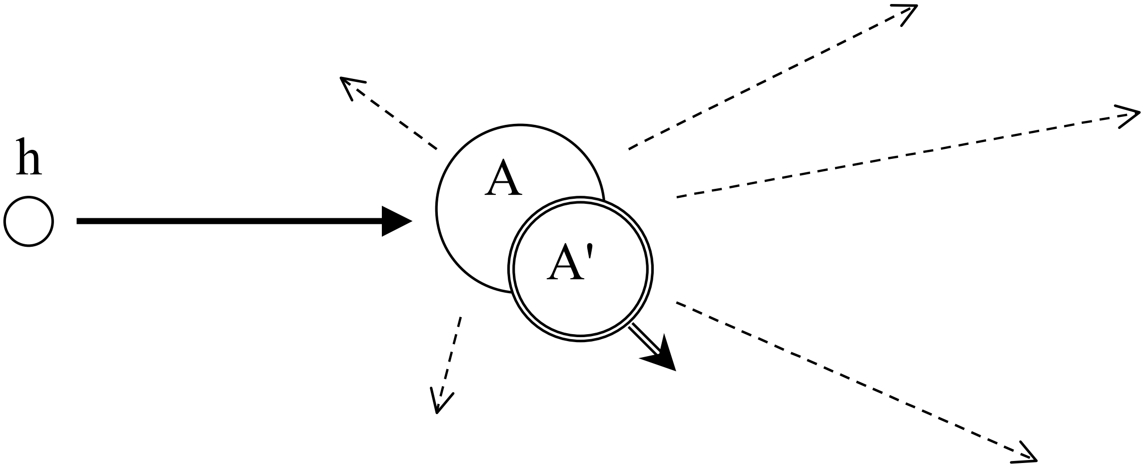
Inclusive transport codes

MARS(IHEP,1974)→…→MASR10(IHEP,1985)→…→MARS13(FNAL,1995)→
MARS14(FNAL,1997-2002)

Exclusive approach

$h+A \rightarrow 1+2+\ldots+n$

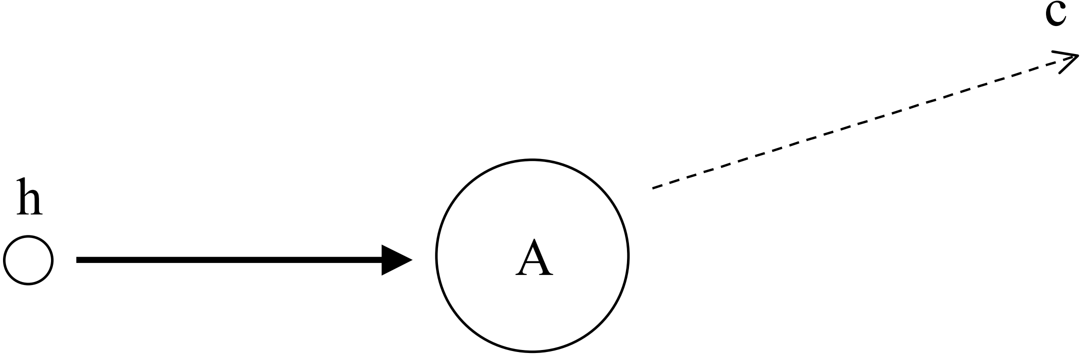
$$dW \sim dI_n = \prod_{i=1}^{n} d^4p_i \cdot \delta(p_i^2 - m_i^2) \cdot \delta(p_0 - \sum_{k=1}^{n} p_k) \cdot M^2(p)$$



Inclusive approach

$h+A \rightarrow c+X$

$$d^3\sigma_c \sim \sum_{channels} \sum_{c} (d^3p_c/E_c) \cdot \int dI_n$$

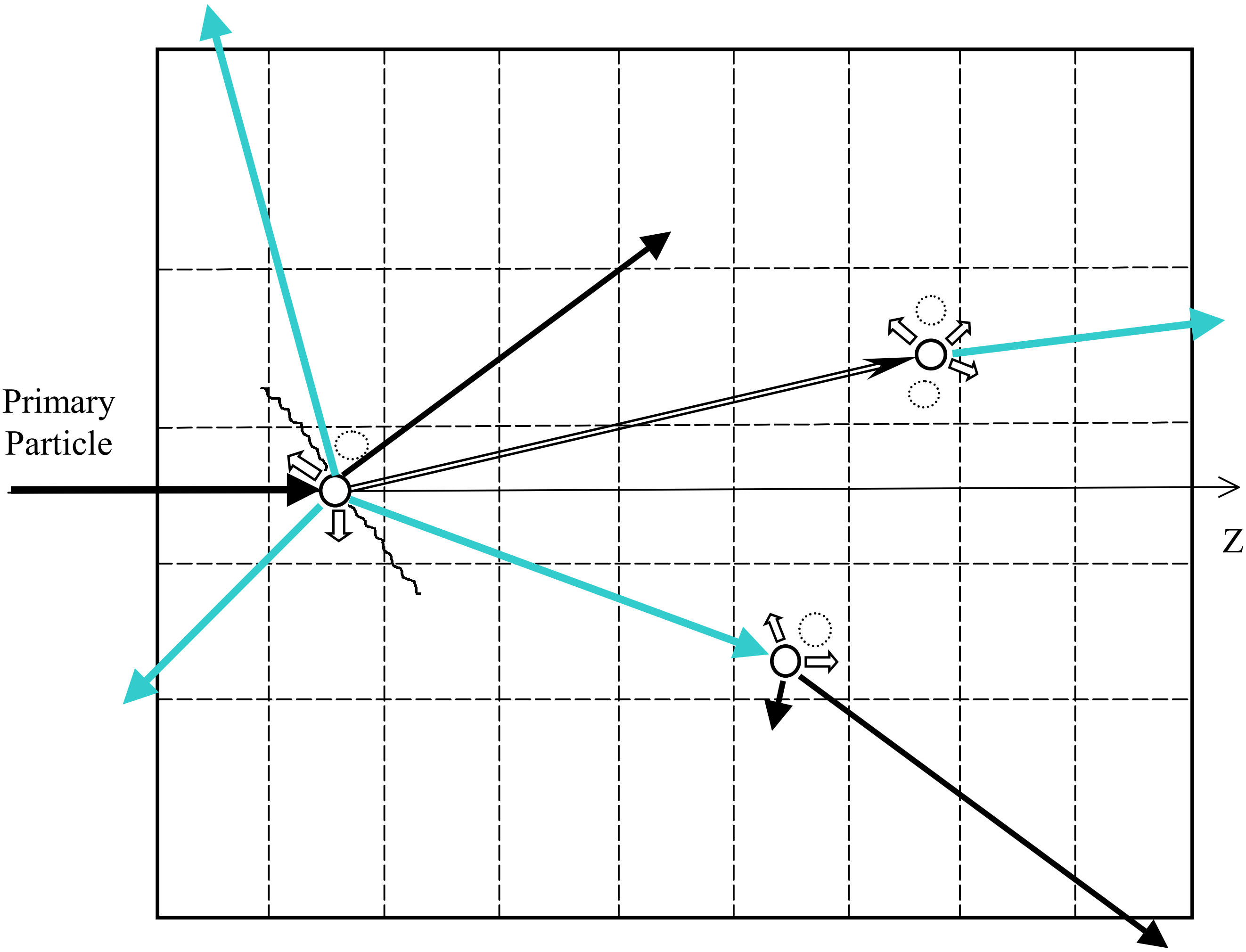


Modern version of the SHIELD code:

1. Transport of N, π, K, $\overline{N}$, μ up to 1 TeV and of arbitrary (A,Z)-nuclei.
2. Ionization loss of charged particles and nuclei.
3. Straggling and multiply Coulomb scattering.
4. 2- and 3-particle modes of meson decay.
5. Extended targets of arbitrary geometric configuration (CG-compatible).
6. Arbitrary chemical and isotope composition.
7. Exclusive simulation of nuclear reactions inside the target (the MSDM generator).
8. Complete storing of each cascade tree during its simulation.
9. Analog and weighted modes, open architecture of the code.
10. Neutron transport (En<14.5 MeV) on a basis of 28-group ABBN data library.

Applications of the SHIELD code.

- Study of the "spallation" process in heavy targets under proton beam irradiation, including generation of neutrons, energy deposition and formation of nuclides in the target.
- Optimization of the targets of pulsed neutron sources on neutron yield.
- Study of direct transmutation of fission products by the proton beam.
- Simulation of heavy ion beam interaction with extended targets. Applications to proton and ion beam therapy.
- Optimization of the pion-producing targets.
- Study of primary radiation damage of structure materials under primary proton beam and secondary radiations.
- Calculations of radiation fluxes behind the shielding from galactic and solar cosmic rays. Modeling of secondary neutron fields inside a space orbital station.
- Study of accumulation of cosmogenic isotopes in iron meteorites.
- Study of background conditions in underground experimental halls, given by hadron cascades in the rock.
- Fluctuations of neutron yield in a hadron calorimeter under a single beam particles.
- Spreading of neutrons in the neutron moderation spectrometer ("leaden cube").



Schematic scene of a hadron cascade tree in complex extended target

The MSDM (Many Stage Dynamical Model) generator of hA- and AA-interactions.

Fast stage of the reaction:

- Dubna Cascade Model (DCM) [1].
- Independent Quark-Gluon String Model (QGSM) [2,3]
- Coalescence model [1].

Pre-equilibrium emission [4].

Equilibrium deexitation of residual nucleus:

- Fermi break up [5].
- Evaporation/fission [5,6].
- Multyfragmentation of higly excited nuclei (SMM) [7]

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V.S.Barashenkov. *Cross Sections of Interactions of Particles and Nuclei with Nuclei.* Dubna, 1993 (in Russian)
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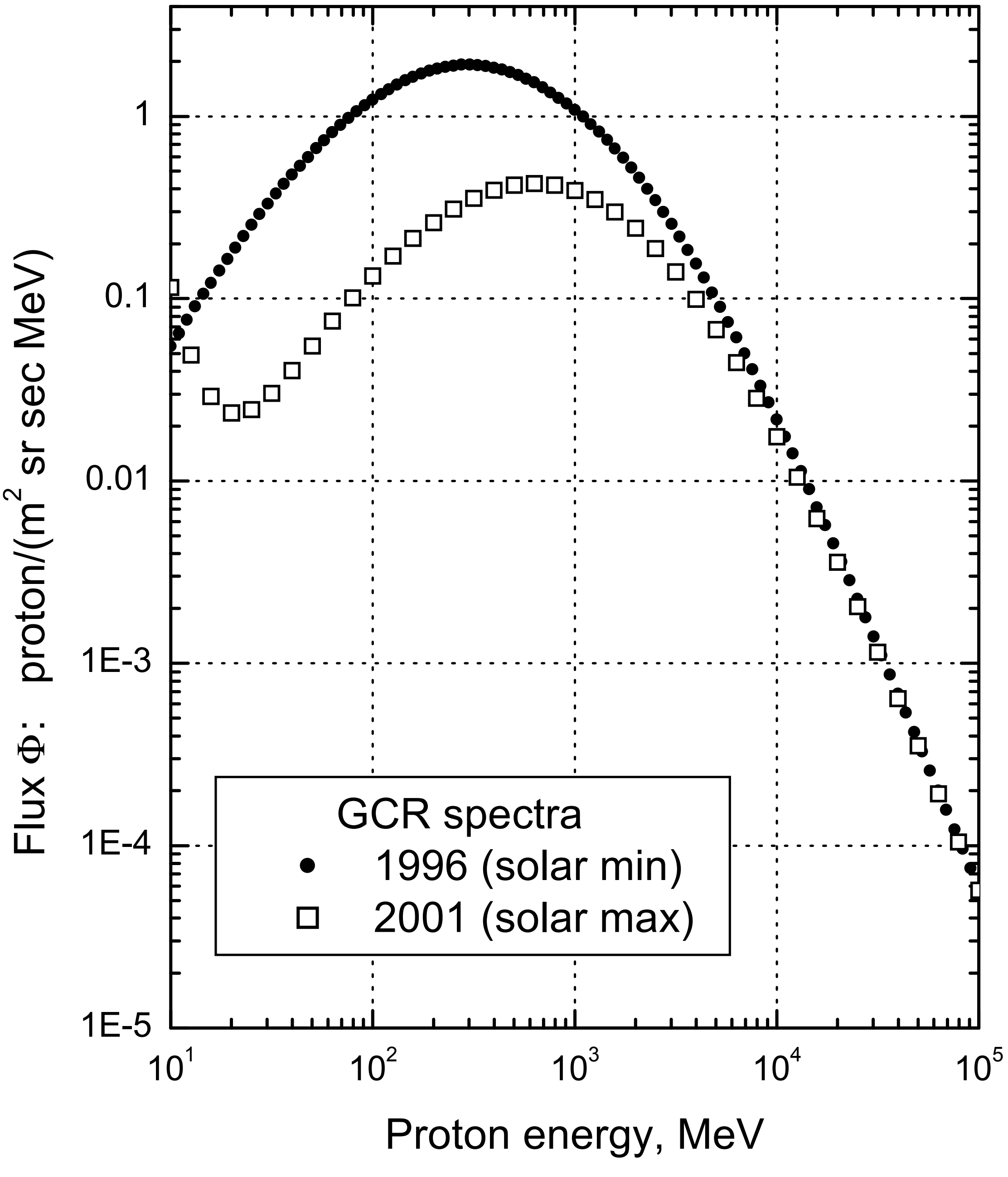


Differential fluxes of GCR protons at the Earth orbit during solar minimum (1996) and maximum (2001): R.Nymmik et al. Adv. Space Res. **17** (1996) (2)19.

Differential GCR flux:

$\mathbf{\Phi}(\mathbf{r},t,E,\mathbf{\Omega})$ p/(m^2 sr sec MeV)

At the assumptions of the stationary state, isotropy, and uniformity of the GCR irradiation the differential flux is:

$\mathbf{\Phi}(\mathbf{r},t,E,\mathbf{\Omega})\equiv\mathbf{\Phi}(E)$ p/(m^2 sr sec MeV).

GCR flux:

$$\Phi=\int_{4\pi}\int_{E_{min}}^{E_{max}}\Phi(\mathbf{r},t,E,\mathbf{\Omega})d\mathbf{\Omega}dE=4\pi\int_{E_{min}}^{E_{max}}\Phi(E)dE \quad \text{p/(m}^2\text{ sec).}$$

Flux $\mathbf{\Phi}$ is the number of particles which enter the sphere with the cross section S_0=1 m^2 per 1 second from all directions. Hence the number of particles entering the sphere of radius R with the cross section S=πR^2 m^2 is $\pi R^2\mathbf{\Phi}$ per 1 second. Finally, the time of irradiation T is

$$T=N/\pi R^2\Phi=N/4\pi^2R^2\int_{E_{min}}^{E_{max}}\Phi(E)dE \quad \text{sec,}$$

where N is the Monte Carlo statistics.

Surface flux estimation across area ΔS

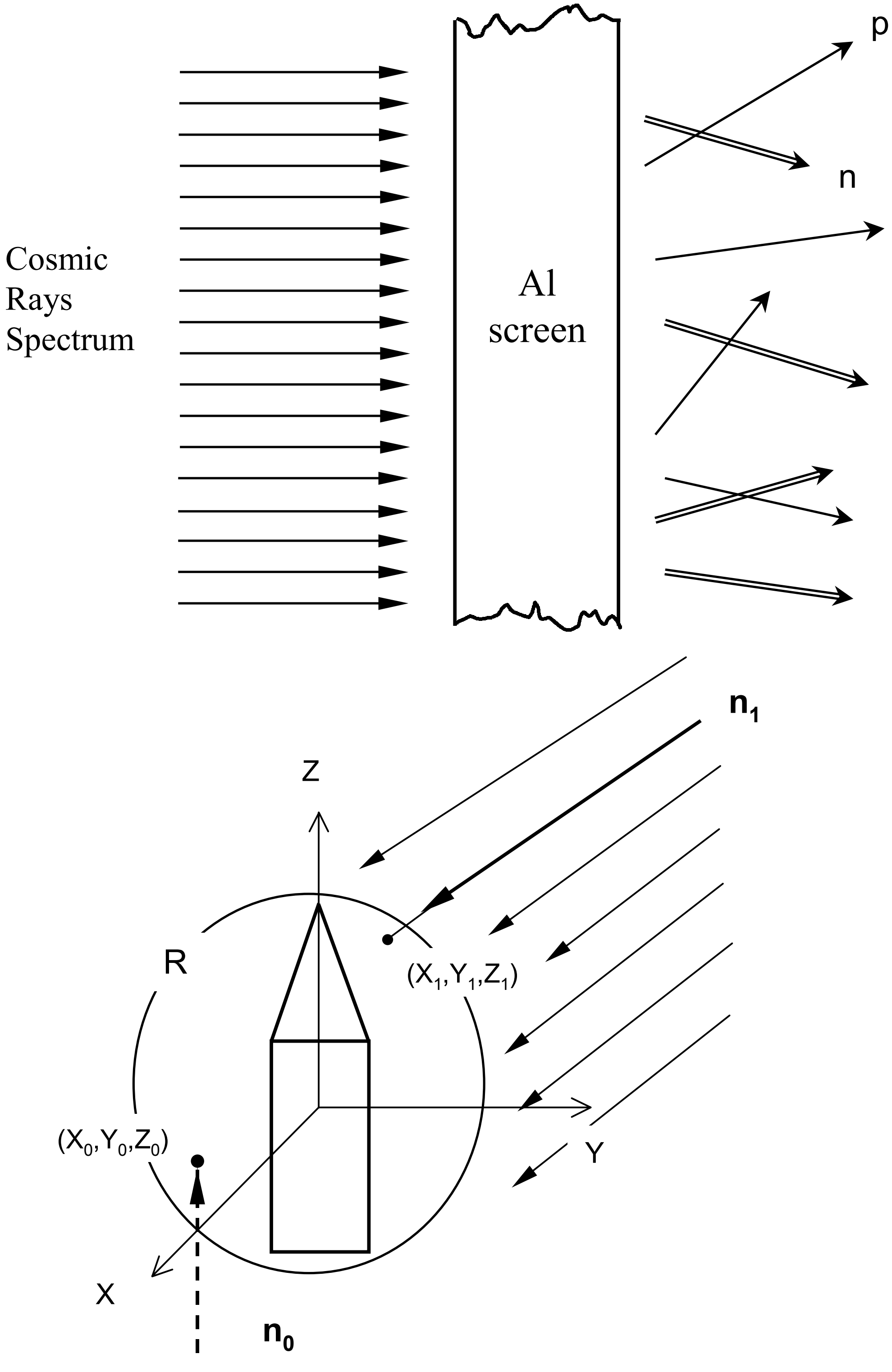
$$\mathbf{\Phi}(\mathbf{r},E,\mathbf{\Omega})=(\Delta S\cdot\Delta\Omega\cdot\Delta E\cdot T)^{-1}\cdot\sum_{\pm} w_i/|\mathrm{Cos}(k\cdot\Omega)_i|$$

One side surface current estimation

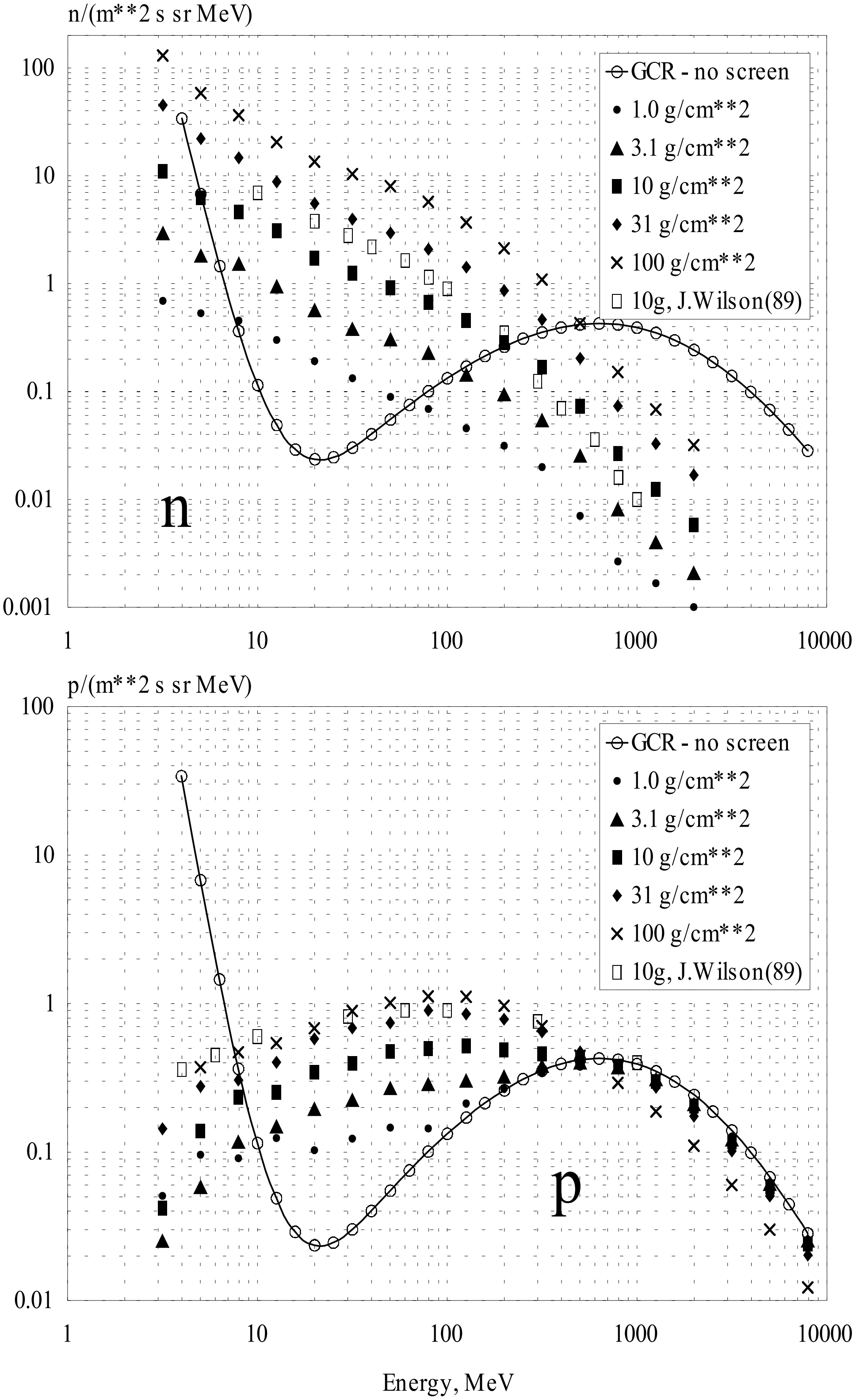
$$J_+(\mathbf{r},E,\mathbf{\Omega})=(\Delta S\cdot\Delta\Omega\cdot\Delta E\cdot T)^{-1}\cdot\sum_{+} w_i$$

In the isotropic irradiation field there are the simple relations:

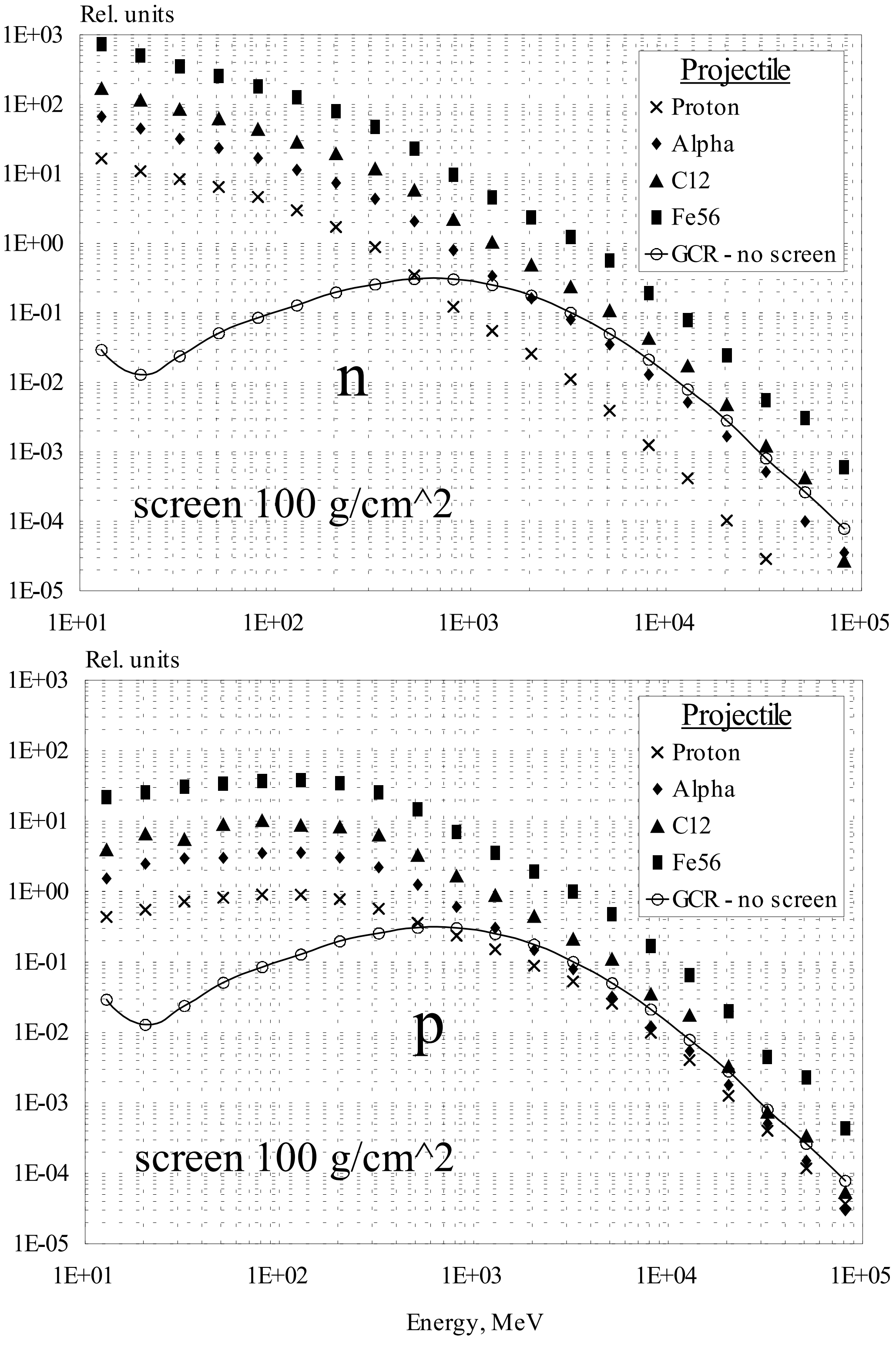
$$J_+=J_-=\mathbf{\Phi}/4$$



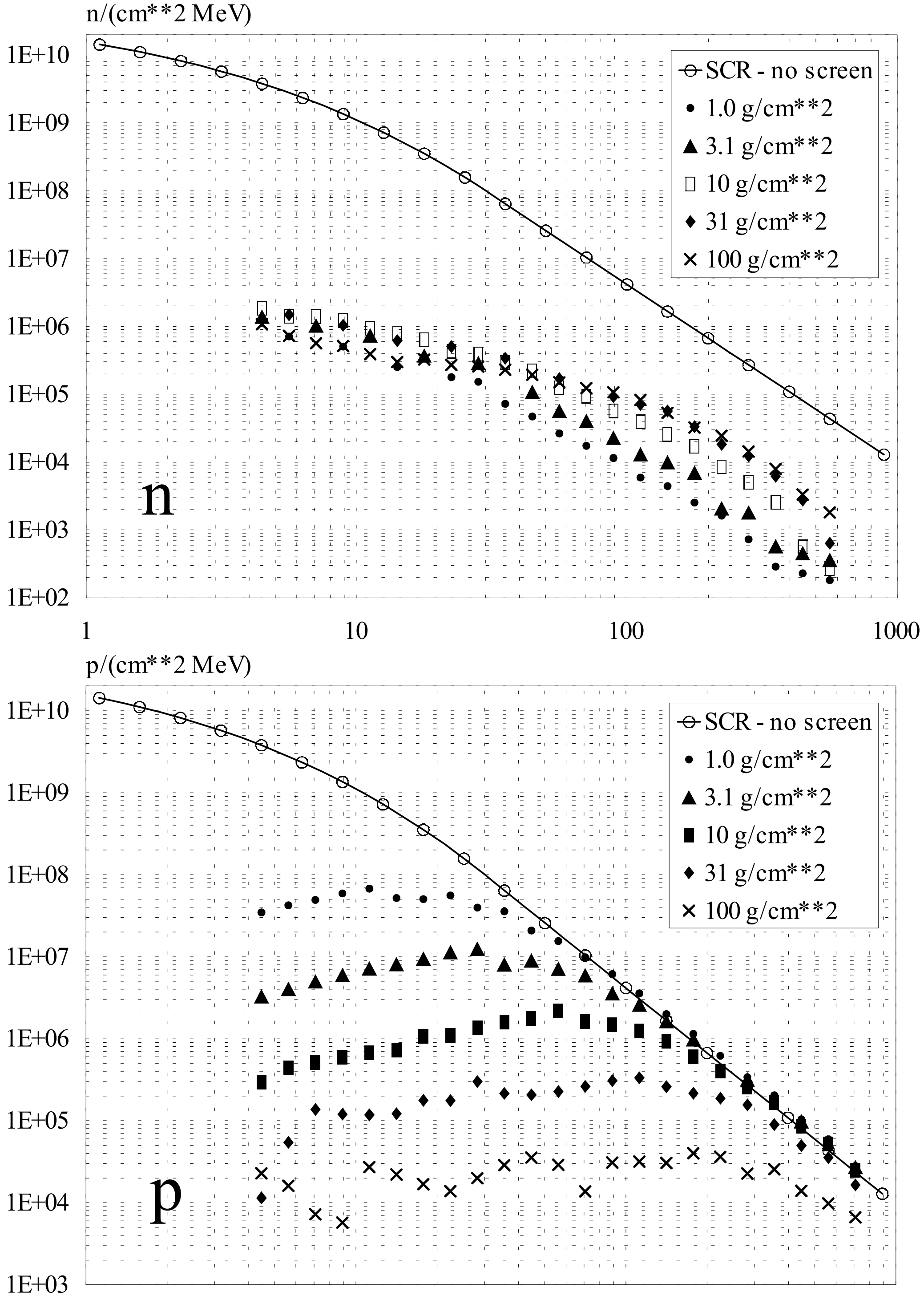
Top: Secondary particle spectra behind planar screen.
Bottom: Isotropic uniform irradiation of a vehicle surrounded
by sphere of radius R.



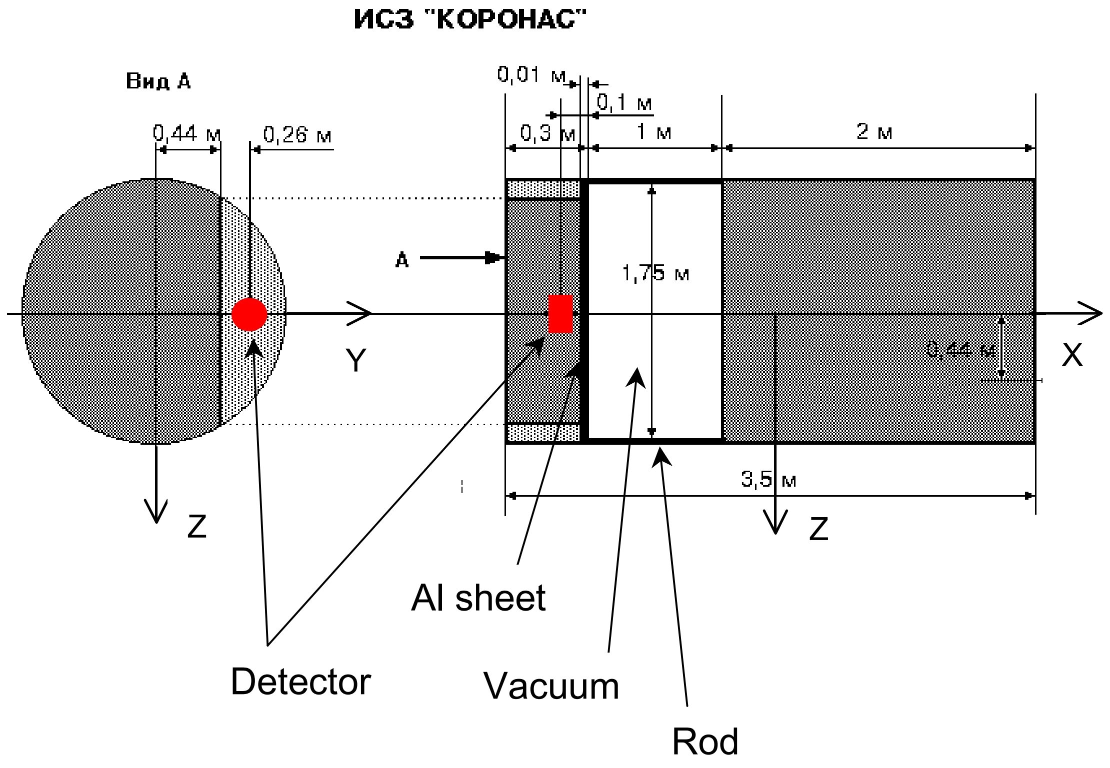
Energy spectra of neutrons (top) and protons (bottom) behind Al-screens of 1, 3.16, 10, 31.6 и 100 g/cm^2 in thickness under GCR (2001) protons irradiation. Squares – calculation by J.Wilson et al. (1989) using the BRYNTRN code for screen thickness of 10 g/cm^2.



Energy spectra of neutrons (top) and protons (bottom) behind Al-screens of 100 g/cm^2 in thickness under irradiation by p, ^{4}He, ^{12}C and ^{56}Fe. Energy of each projectile in MeV/A is distributed according to GCR (2001) proton spectrum.



Differential fluences of neutrons (top) and protons (bottom) behind Al-screens of 1, 3.16, 10, 31.6 и 100 g/cm^2 in thickness under SCR proton irradiation (mean annual solar proton flux during solar max).

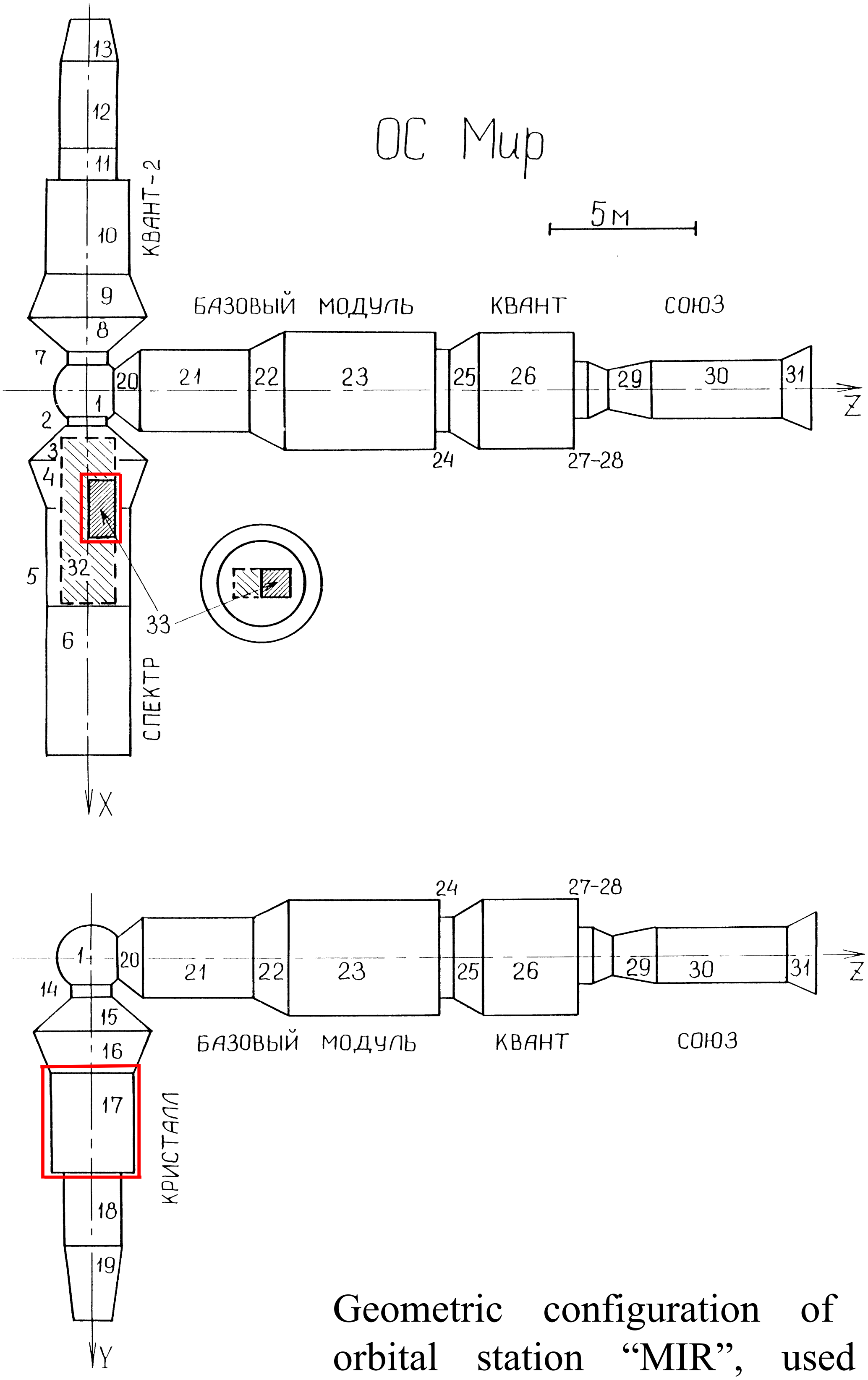


Geometric configuration of the Earth satellite “CORONAS”, used at calculations.

The satellite consists of two parts which are separated by vacuum and are connected by means of metallic rods. The larger part has cylindrical shape, the smaller part is cylinder minus cylindrical segment. Total mass is equal to 1.4 ton.

It is supposed that satellite material is aluminum with effective density 0.2476 g/cm^3. The aluminum sheet of 1 cm in thickness has natural density and mass of 65 kg. The rods which connect two part of the satellite are not taken into account at calculations.

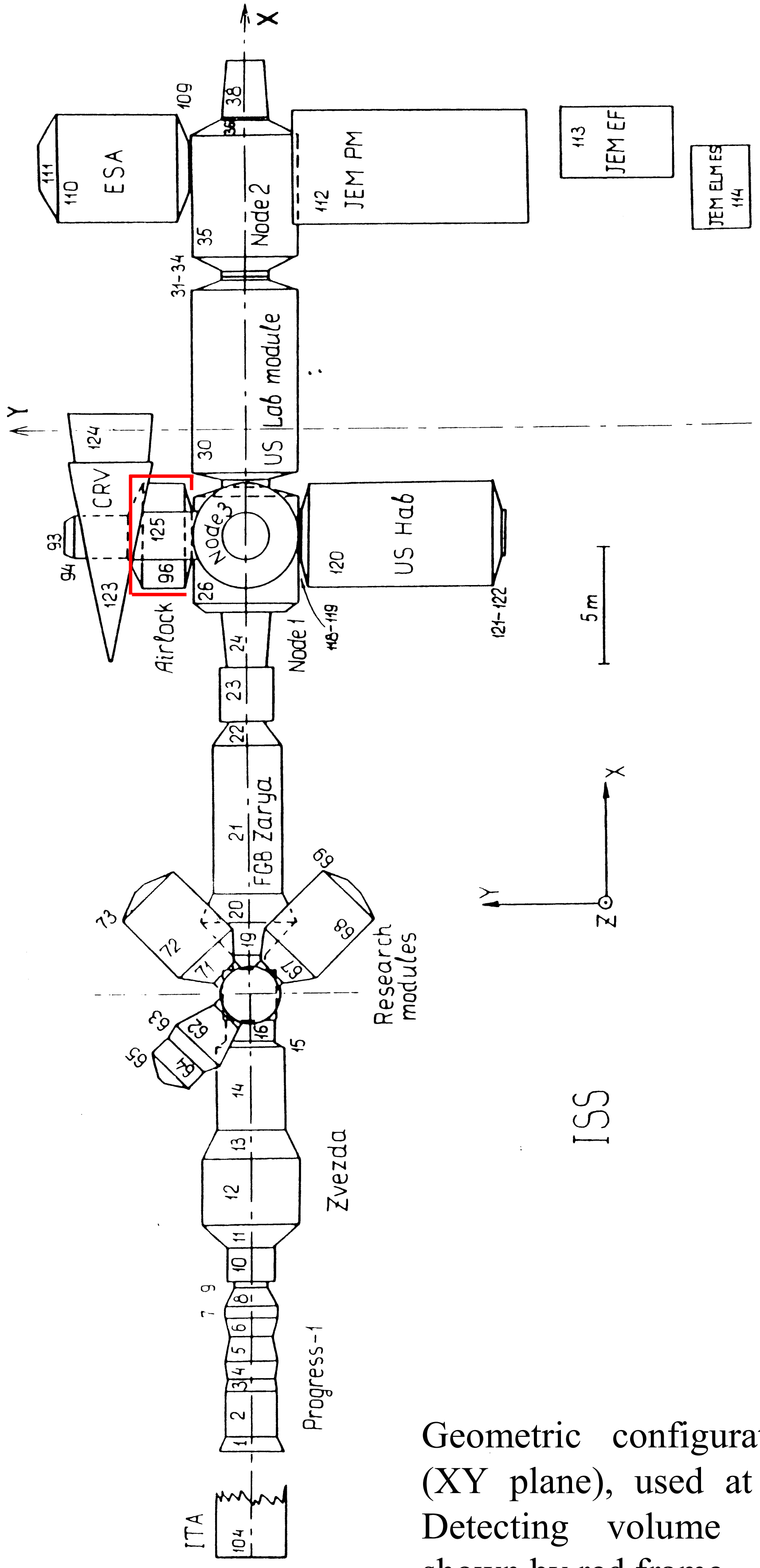
The detecting volume has cylinder shape with parameters R=10 cm, H=10 см. Particles which enter the detecting volume have been scored in the simulation.



Geometric configuration of the orbital station "MIR", used at calculations. Detecting volumes are shown by red frames.

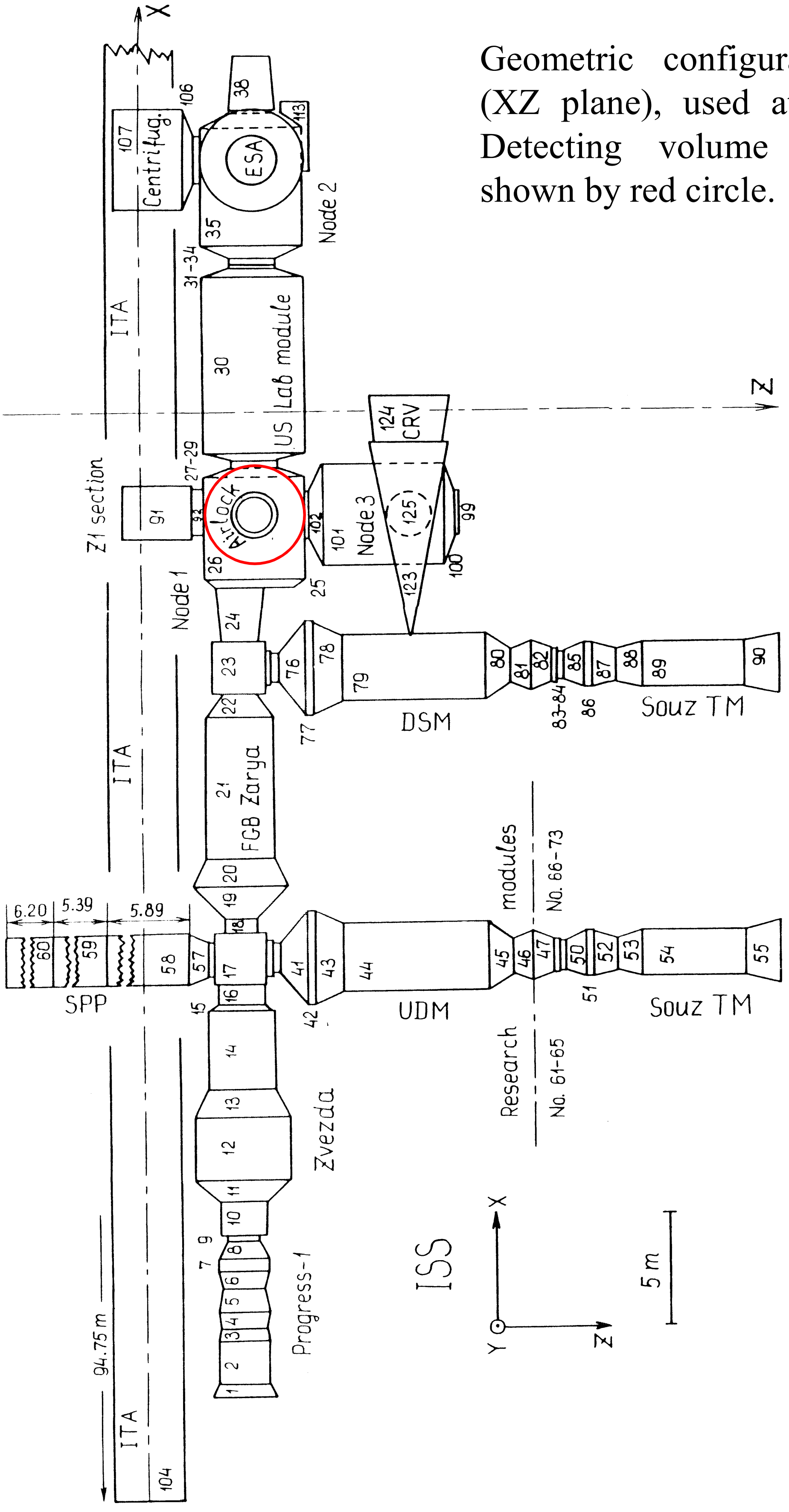
Masses and effective densities of modules of the orbital station “MIR”, used at calculations.

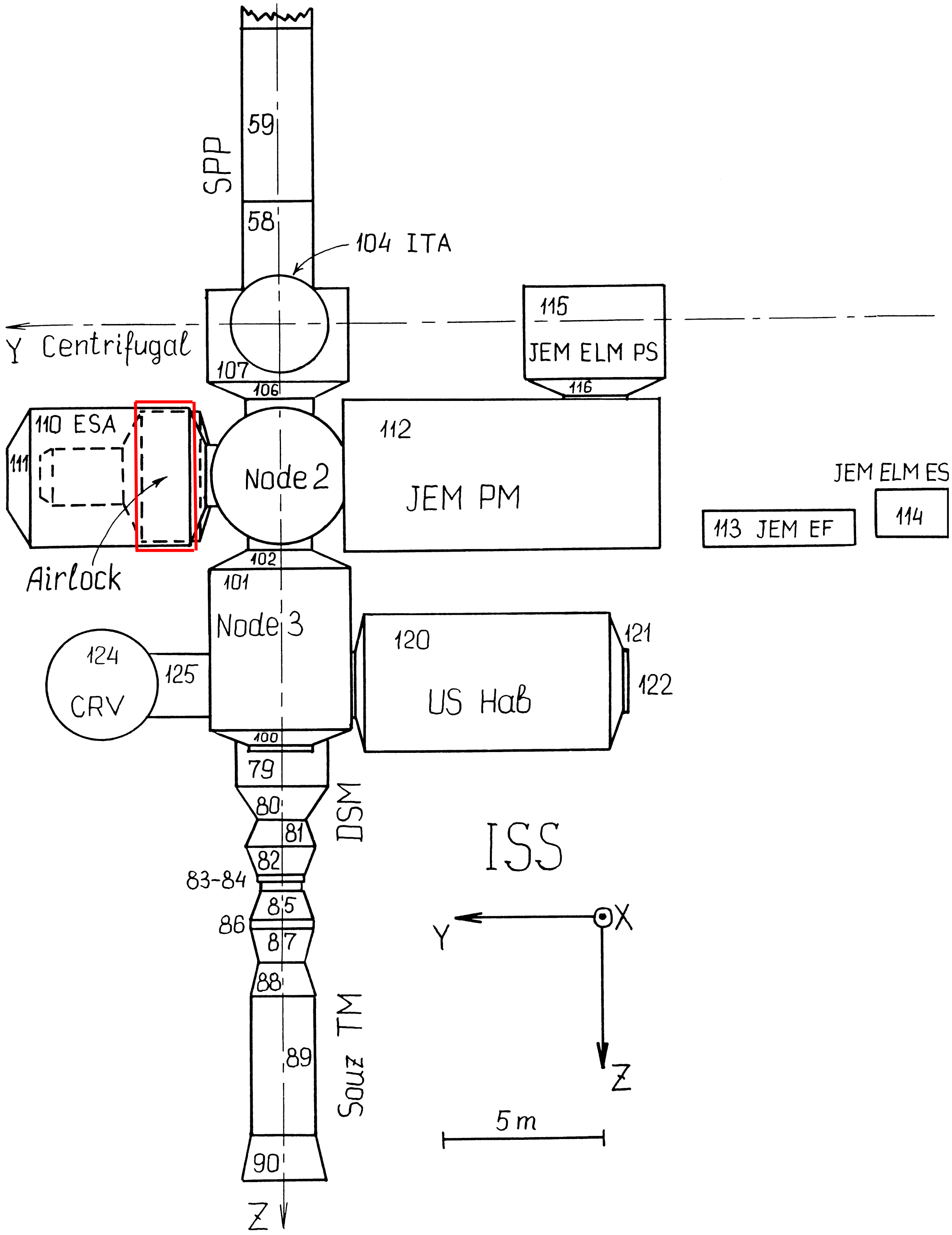
Module of the “MIR”	Bodies №№	Mass (ton)	Density of Al (g/cm^3)
1. Node	1	1.9	0.40
2. Module «Spectrum»	2÷3	2.4	0.29
	4	2.9	0.18
	5	7.1	0.31
	6	4.0	0.11
3. Module «Quantum-2»	7÷8	1.9	0.22
	9	2.4	0.17
	10	6.9	0.31
	11	2.0	0.58
	12÷13	3.4	0.26
4. Module «Crystal»	14÷15	2.4	0.28
	16	2.9	0.20
	17	7.1	0.31
	18	2.1	0.26
	19	1.9	0.31
5. Base module	20	0.5	0.14
	21	6.3	0.25
	22	3.6	0.31
	23	14.5	0.21
6. Module «Quantum»	24	0.6	0.18
	25	2.5	0.26
	26	10.8	0.25
7. «Souz»	27÷28	0.7	0.22
	29	1.1	0.32
	30	4.4	0.31
	31	1.5	0.32
Cavity in «Spectr»	32	0	0
Detecting volume	33	0	0
Sum		97.8	



Geometric configuration of ISS (XY plane), used at calculations. Detecting volume (Airlock) is shown by red frame.

Geometric configuration of ISS (XZ plane), used at calculations. Detecting volume (Airlock) is shown by red circle.





Geometric configuration of ISS (YZ plane), used at calculations. Detecting volume (Airlock) is shown by red frame.

Masses and effective densities of modules of the International Space Station, used at calculations [1].

Module of ISS	Bodies №№	Mass (ton)	Density of Al (g/cm^3)
1. "Progress-1"	1÷9	6.7	0.271
2. Service module "Zvezda"	10÷17	21.6	0.224
3. FGB "Zarya"	18÷23	22.4	0.291
4. Node 1	24÷27	10.8	0.137
5. US Lab module	28÷32	26.3	0.208
6. Node 2	33÷38	17.7	0.1805
7. Universal docking module (UDM)	39÷48	17.8	0.238
8. "Souz TM"	49÷55	6.9	0.240
9. Scientific Power Platform (SPP)	56÷60	18.6	0.271
10. Docking compartment N2 (DC2)	61÷65	3.9	0.318
11. Research module 2 (RM2)	66÷69	6.8	0.226
12. Research module 1 (RM1)	70÷73	6.8	0.226
13. Docking-Storehouse mod. (DSM)	74÷83	17.8	0.238
14. " Souz TM "	84÷90	6.9	0.240
15. Section Z1	91÷92	8.7	0.411
16. Airlock	93÷98	6.7	0.162
17. Node 3	99÷103	16.6	0.1805
18. Integrated truss assembly (ITA)	104	96.5	0.137
19. Centrifugal	105÷107	14.4	0.275
20. ESA Module	108÷111	16.6	0.1805
21. Japan module (JEM PM)	112	24.6	0.137
22. Japan module (JEM EF)	113	4.3	0.238
23. Japan module (JEM ELM ES)	114	1.9	0.154
24. Japan module (JEM ELM PS)	115÷117	9.4	0.178
25. US Habitation	118÷122	19.4	0.154
26. Rescue vehicle (CRV)	123÷125	10.9	0.271
Sum		421.0	

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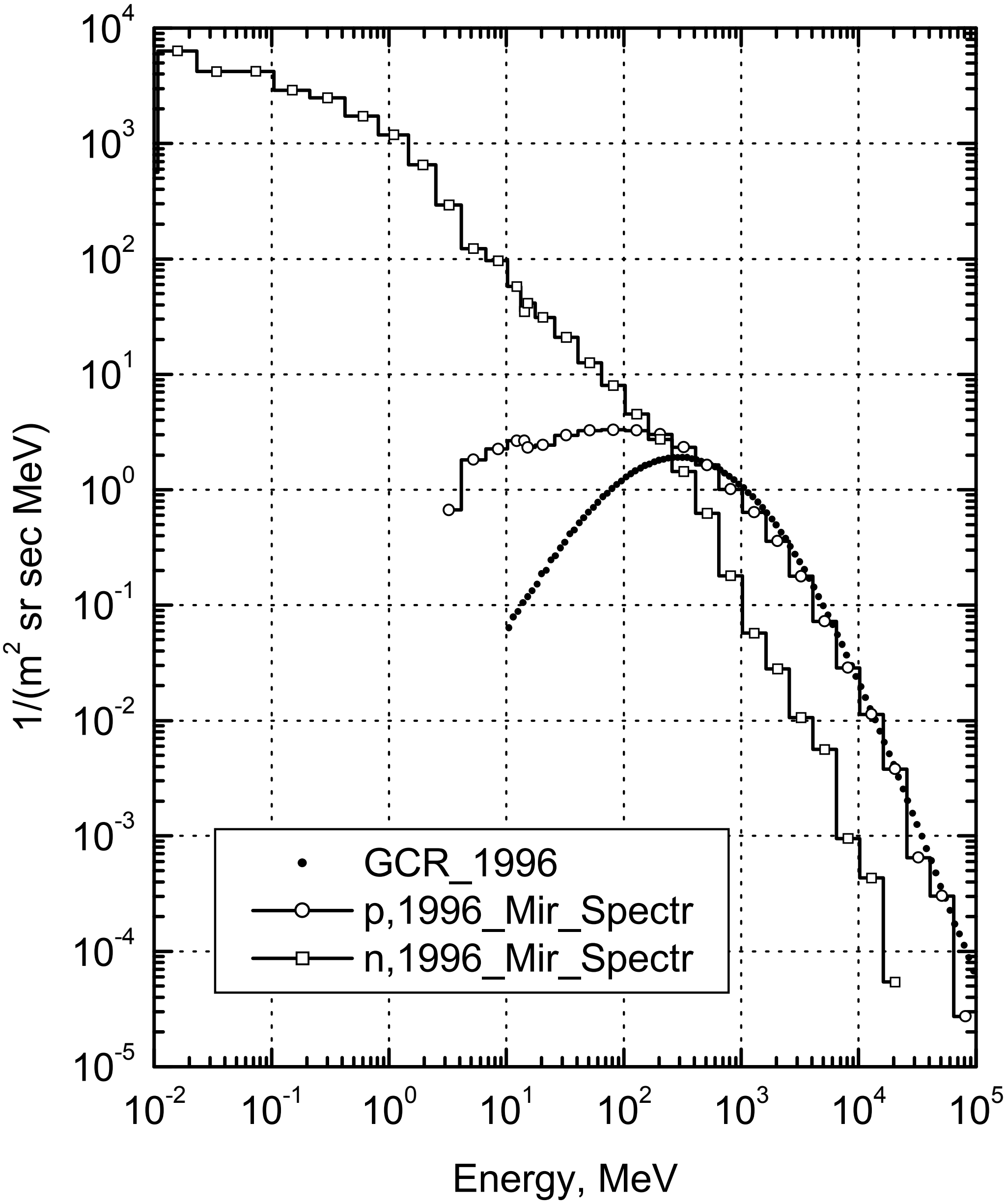
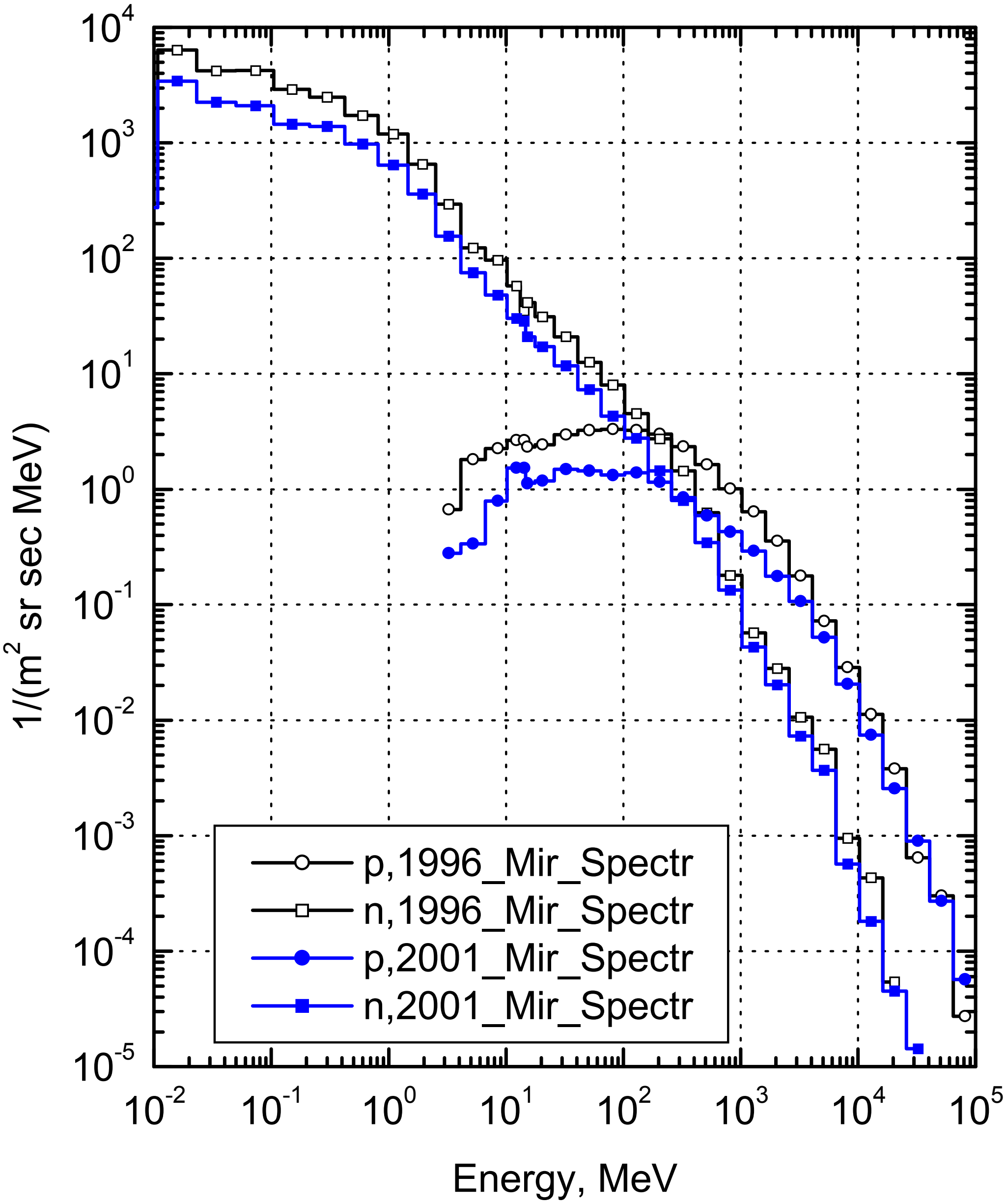
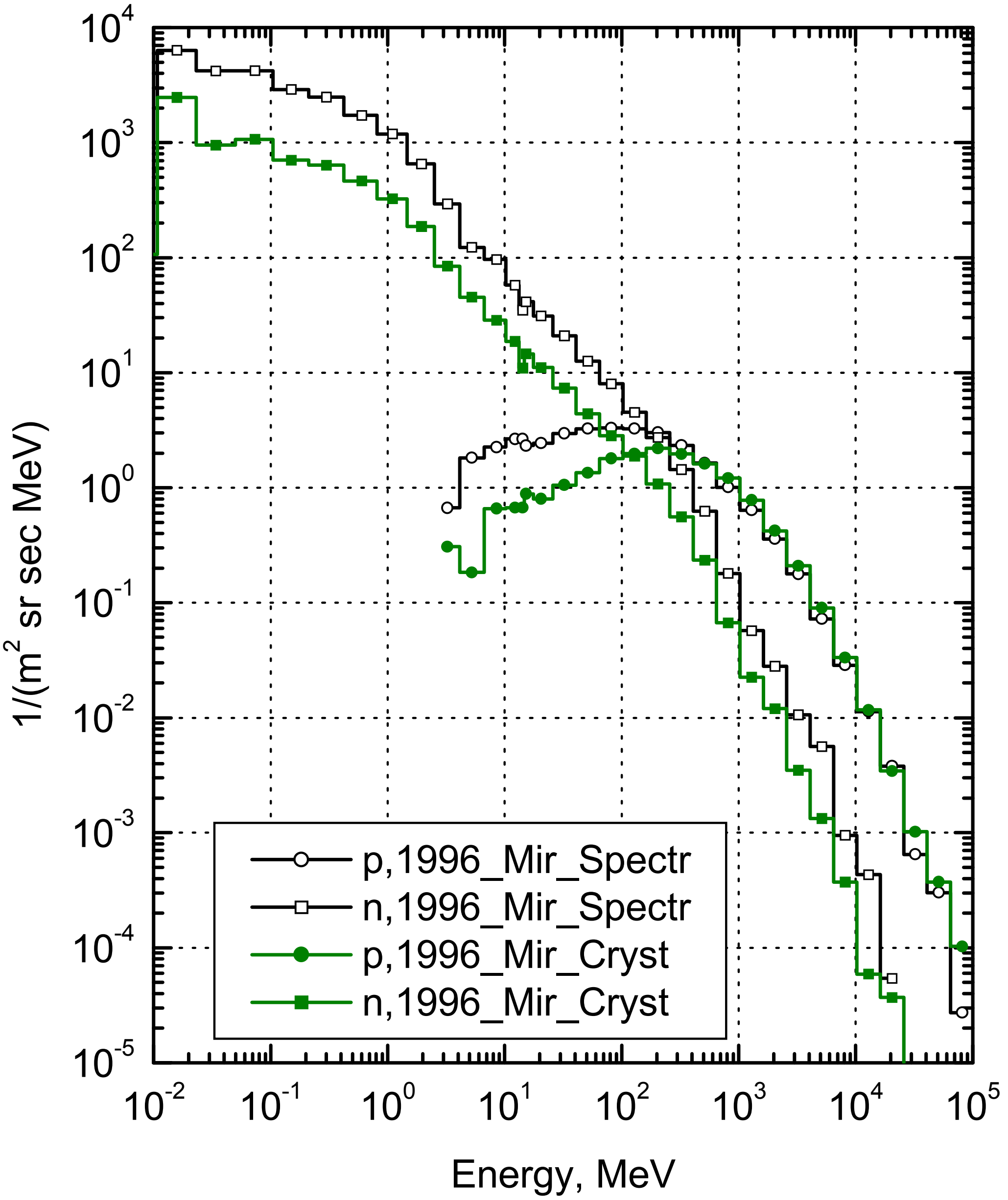
[1] NASA, JSC-26557, Rev. H, Volume 1, 1997



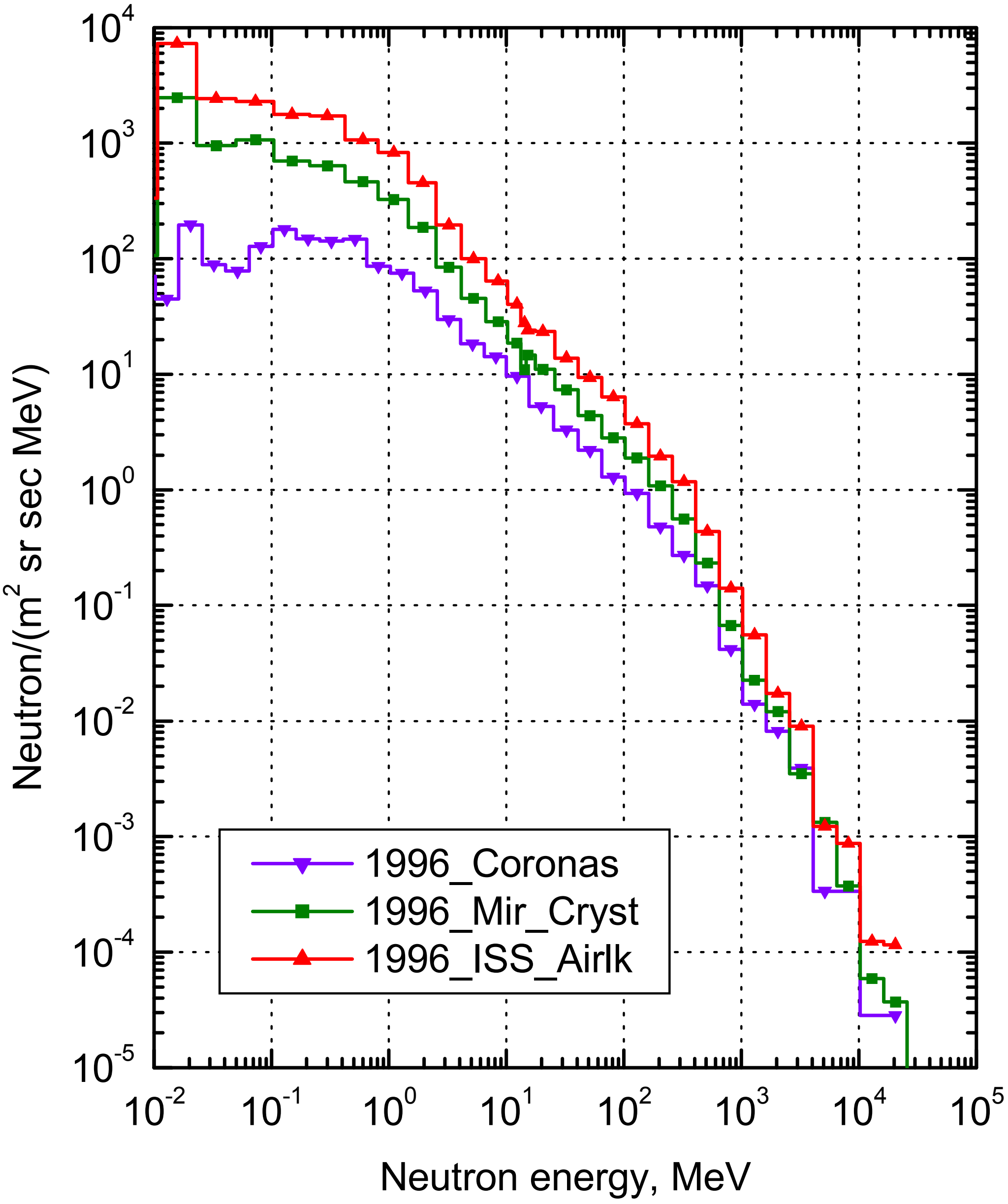
Spectra of protons and neutrons which enter the detecting volume (cavity No.33) in the module “Spectrum” of the “MIR” station under irradiation by GCR proton spectrum of 1996 (solar min).



Comparison of spectra of nucleons which enter the detecting volume (cavity No.33) in the module “Spectrum” of the “MIR” station under irradiation by GCR proton spectra of 1996 (solar min) and of 2001 (solar max).



Comparison of spectra of nucleons which enter two different detecting volumes in the MIR station: cavity No.33 in the module "Spectrum" and cylinder No.17 in the module "Crystal". Irradiation: GCR proton spectrum of 1996 (solar min)



Comparison of spectra of neutrons which enter detecting volumes of three different vehicles: CORONAS (detector), MIR ("Crystal") and ISS (Airlock). Irradiation: GCR proton spectrum of 1996 (solar min).