EFDA–JET–CP(08)04/19

V. Zoita, M. Anghel, T. Craciunescu, M. Curuia, T. Edlington, M. Gherendi,
V. Kiptily, K. Kneupner, I. Lengar, A. Murari, A. Pantea, P. Prior, S. Soare,
S. Sanders, B. Syme, I. Tiseanu and JET EFDA contributors

Design of the JET Upgraded Gamma-Ray Cameras

Design of the JET Upgraded Gamma-Ray Cameras

V. Zoita[1], M. Anghel[2], T. Craciunescu[1], M. Curuia[2], T. Edlington[3], M. Gherendi[1],
V. Kiptily[3], K. Kneupner[4], I. Lengar[5], A. Murari[6], A. Pantea[1], P. Prior[3], S. Soare[2],
S. Sanders[3], B. Syme[3], I. Tiseanu[1] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Association EURATOM-MEdC, National Institute for Laser, Plasma and Radiation Physics, Bucharest, Romania
[2]Association EURATOM-MEdC, National Institute for Cryogenics and Isotopic Technologies, Rm. Valcea, Romania
[3]EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[4]Forschungszentrum Jülich GmbH, Association EURATOM-FZ Jülich, Institut für Plasmaphysik,
Trilateral Euregio Cluster, D-52425 Jülich, Germany
[5]Association EURATOM-MHST, Jozef Stefan Institute, Ljubljana, Slovenia
[6]Association EURATOM-ENEA, RFX, Padova, Italy
** See annex of M.L. Watkins et al, “Overview of JET Results ”,*
(Proc. 21st IAEA Fusion Energy Conference, Chengdu, China (2006)).

Preprint of Paper to be submitted for publication in Proceedings of the
25th Symposium on Fusion Technology, Rostock, Germany
(15th September 2008 - 19th September 2008)

ABSTRACT

The main aim of the JET KN3 gamma-ray cameras upgrade is the design of appropriate neutron/gamma-ray filters ("neutron attenuators"). Using the attenuation factor as the main design parameter a set of three neutron attenuators of different shape and attenuation length have been designed for the horizontal and vertical cameras. Pure light water was chosen as the attenuating material for the JET gamma-ray cameras. The operation of the KN3 neutron attenuators is controlled by an electro-pneumatic system. A full-scale prototype of the vertical camera neutron attenuator was constructed and tested. The mechanical behaviour of the attenuator structure subject to the forces and torques produced by the JET disruptions was analysed by means of the finite element analysis method. The radiation performance of the KN3 neutron attenuators as well as the response of the gamma-ray detectors have been addressed by means of neutron and gamma-ray transport calculations.

1. INTRODUCTION

The control of the confinement of fast particles (in particular, the fusion reaction produced alpha particles) in the tokamak plasma is essential for the development of tokamak fusion reactors. One class of diagnostic techniques for the study of the fast particles in tokamak plasmas is based on the detection and analysis of the gamma radiation emitted as the result of the nuclear interactions of fast particles with plasma impurities such as carbon and beryllium [1, 2]. Ideally one should have a gamma radiation diagnostics system capable of providing simultaneous space, time and energy resolution. Such a complex diagnostics system has not yet been developed. At JET two types of diagnostic devices address the various characteristics of the plasma emitted gamma radiation: a Gamma-Ray Camera (GRC) which provides a 2D distribution in a poloidal plane of the gamma-ray emission; a set of collimated gamma-ray spectrometers which provide gamma-ray spectra recorded along two vertical and one quasi-tangential lines of sight.

In the JET tokamak the plasma gamma-ray emission is the result of the interaction of fast ions (fusion reaction products, including alpha particles, NBI ions, ICRH-accelerated ions) with the plasma impurities mentioned above. The JET gamma-ray plasma diagnostics has already provided valuable information on the characteristics of the fast ion population in plasmas [1, 2]. The applicability of this technique to high performance deuterium and deuterium-tritium JET discharges is however strongly dependent on the fulfilment of rather strict requirements for the definition and characterisation of the neutron and gamma radiation fields (e.g., neutron flux on the detector, level of the gamma radiation background). Such requirements can be fulfilled by using so-called neutron/gamma radiation filters (or neutron attenuators) within the gamma-ray diagnostics system. Design solutions for adequate neutron attenuators have been developed for the upgrade of one of the major JET gamma-ray diagnostics, the KN3 gamma-ray cameras [3].

2. DESIGN OF THE NEUTRON ATTENUATORS FOR THE JET GAMMA-RAY CAMERAS

The main objective of an ongoing JET Enhancements (EP2) Gamma-Ray Camera (GRC) diagnostics upgrade is the design, construction and testing of neutrons attenuators for the two sub-systems of the KN3 gamma-ray imaging diagnostics, the horizontal and the vertical cameras (KN3 HC and KN3 VC, respectively). This diagnostic upgrade should make possible gamma-ray imaging measurements in high power deuterium JET pulses, and eventually in deuterium-tritium discharges. Several design versions were developed and evaluated for the JET GRC neutron attenuators during three design phases: conceptual, scheme and detailed design. The main design parameter was the neutron attenuation factor. The following design solutions were finally chosen and developed at the level of detailed design:

- One quasi-crescent shaped neutron attenuator for the horizontal camera
- Two quasi-trapezoid shaped neutron attenuators for the vertical camera, with different attenuation lengths: a short version, to be used together with the horizontal attenuator for deuterium discharges and a long version to be used for high performance deuterium and DT discharges. Both vertical camera attenuator casings (short and long version) have a quasi-trapezoidal shape with internal reinforcements parallel to and between the lines of sight. All three neutron attenuators consist of a metal casing filled with pure light water as attenuating material.

The GRC neutron attenuators are designed to function as neutron filters when in working position in the plane determined by the gamma-ray detectors lines of sight. The locations of the neutron attenuators are shown schematically in Figure 1 together with the detector lines of sight for each of the two KN3 cameras.

The attenuators are placed within the KN3 diagnostics system in the JET Octant 1 between the vacuum port and the camera collimator body (camera radiation shield), both in the case of the horizontal and vertical camera (Figure 1, HC-NA and VC-NA, respectively). To move the horizontal camera neutron attenuator to and from the working position two movements are required: first a 90^o rotation (to the right when looking towards the plasma) and second a 630mm translation as shown in Figure 2. Only a 100mm translation is needed to move the vertical camera neutron attenuator to and from the working position (Figure 3).

The operation of the GRC neutron attenuators is steered and controlled by an electro-pneumatic system driven by electronic and pneumatic components included in two Local Unit Cubicles (in Figure 1, LUC1 and LUC2, respectively). The first one provides also the interface with the JET CODAS computer system.

3. MECHANICAL ANALYSIS OF ATTENUATOR OPERATION

Both horizontal and vertical camera attenuators will operate in the magnetic fields of the JET tokamak. In particular, the vertical attenuators will be placed in the strong poloidal magnetic fields generated by the nearby poloidal and shaping coils. Finite Element Analysis (FEA) was used to evaluate the casings deformation and stresses when subjected to the torques generated by the electromagnetic interactions [4].

The attenuator casings models were constructed in CATIA [5] and then exported to the ANSYS

[6] analysis software. The loads, material properties and boundary conditions are those provided by literature or by the JET Engineering Analysis Group. Figure 4.a shows the loaded model for the Horizontal Camera Neutron Attenuator (HC-NA). A moment of 200Nm was applied on the lateral faces along the longitudinal axis. An internal hydrostatic pressure of 5 bar was applied together with Earth standard gravity. The attenuator ends were fixed. The work environment was set to static analysis.

The model was solved in one step, static solution. The maximum deformation is less than 2mm on X-axis, Figure 4.b; the equivalent von Mises stress is less than 250×10^6 Pa.

A similar ANSYS analysis was done for the vertical camera neutron attenuator and it provided a maximum deformation of only 0.4mm on the Z-axis. The equivalent (von Mises) stress does not exceed 1.7×10^8 Pa. The conclusion of the mechanical behaviour analysis was that the deformations were of negligible magnitude and will not present any cause of concern for the operation of the GRC neutron attenuators.

4. VERTICAL CAMERA NEUTRON ATTENUATOR PROTOTYPE

A full-scale prototype of the KN3 vertical camera neutron attenuator (the short option) was designed, manufactured and tested in operation (electro-mechanical tests only). The prototype system includes the following sub-assemblies (Figures 5 and 6): attenuator casing; steering and control system; support frame and assembly jig.

The neutron attenuating material for the KN3 VC-NA prototype is pure light water. INCONEL 600 was chosen for the prototype casings, the choice being determined by considerations related to the interaction with pure water, the manufacturing process flow (effects of welding, bending) and operational characteristics (mechanical and electrical behaviour).

The movement of the prototype to and from its working position is driven by a steering and control system based on pneumatic linear drives whose block-diagram is presented in Figure 6. It contains three sub-systems:

- LUC-1 (Local Unit Cubicle 1) consisting of a Programmable Logic Controller (PLC), operator unit and power supply. The PLC receives electrical signals from the pneumatic-electric converter from Local Unit Cubicle 2 (LUC 2) and sends electrical signals to the directional control valves from LUC-2. The programmable logic controller has an Ethernet port that provides connection with a central control.
- LUC-2 (Local Unit Cubicle 2) consists of directional control valves, flow control valves, pressurized air supply and pneumatic-electrical converters.
- PS (Pneumatic Sub-system) consists of pneumatic actuators, pneumatic limit switches and blocking devices.

The operation of the prototype is monitored by means of a local programmable logic controller interfaced with a central control system (possibly the JET CODAS computer system).

All manufactured components went through a dimensionality check and a series of hydrostatic pressure, penetrating liquid and helium leak tests were applied to the attenuator casing. The results have shown that all components met the specified requirements.

5. RADIATION (NEUTRON AND PHOTON) ANALYSIS OF ATTENUATOR OPERATION

The main purpose of the neutron/photon calculations was the evaluation of the neutronics performance of the neutron attenuators designed and constructed for the JET KN3 diagnostics system. A secondary purpose of these calculations was the estimation of the influence of the KN3 neutron attenuators on the JET machine neutron and gamma-ray fields. In the work reported in [4] the main emphasis was given on the estimation of the in-scattering of neutrons from the neutron attenuator in the parking position into the KN3 neutron detectors. The number of the neutron induced gammas and the attenuation factors for neutrons and gammas in the short version neutron attenuator of the KN3 vertical camera were estimated as a next step. The estimations were performed on the basis of Monte Carlo calculations using the MCNP5 code [8]. Due to the extreme degradation of the flux from the plasma to the KN3 detector position the main emphasis of the work has been to develop variance reduction techniques for the specific case of the KN3 profile monitor. The following results were obtained from the combined output of these techniques: the neutron attenuation factor was 0.01; the ratio of the neutrons scattered into the detectors with respect to transmitted neutrons was 0.1 for the central and 1.0 for the edge channel; the number of induced gammas of energy 2.2MeV reaching the detectors, per transmitted neutron, was 0.1 for the vertical and 0.6 for the edge channel.

The neutron fluence distribution within the vertical camera neutron attenuator was also obtained. In Figures 7 (a and b) the neutron flux through a vertical cross section through the middle of the neutron attenuator are plotted: red represents high neutron flux, blue represents low flux regions. Fast and thermal neutron flux are plotted separately. Regarding the operation of the neutron attenuator it can be observed that the intensity of the fast flux is high only in the surrounding of the attenuator or on its lowest side. The majority of the fast neutrons is scattered down shortly after entering the attenuator from below. The thermal flux behaves differently its intensity being highest at some 6 cm above the lower edge of the attenuator and decreases towards its upper edge. The thermal neutron intensity is low outside the attenuator. The neutron flux shape is not symmetrical with respect to the centre channel of the vertical camera. This is due to the wedge shape of the upper vertical vacuum port, which results in a higher integrated flux towards the low field side.

The influence of different CsI(Tl) gamma-ray detector geometries for an optimum detector response in the case of KN-3 gamma-ray imaging was analysed by means of the Integrated TIGER Series (ITS) Monte Carlo electron/photon radiation transport code [8]. The calculations were done for channel 15 (central channel) of the KN3 vertical camera and they provided an evaluation of the global detector response. The response function of the CsI(Tl) detector, useful for spectra unfolding, was also calculated for the 1-10MeV energy range using 256 energetic channels (Figure 8).

CONCLUSIONS

A set of three neutron attenuators of different shape and attenuation length has been designed for the JET KN3 horizontal and vertical gamma-ray cameras. The design parameter was the neutron attenuation factor. Pure light water was chosen as the attenuating material. The operation of the

KN3 neutron attenuators is controlled by an electro-pneumatic system that is connected to the JET CODAS computer system. A full-scale prototype of the vertical camera neutron attenuator was constructed and tested. The electro-mechanical performance of the prototype complies with the design specifications. The mechanical behaviour of the attenuator structure subjected to the forces and torques produced by the JET disruptions was analysed by means of the finite element analysis method. The analysis has shown that there was no cause for concern regarding the effect of the transient electromagnetic filed of the tokamak machine. The radiation performance of the KN3 neutron attenuators as well as the response of the gamma-ray detectors have been analysed by means of neutron and gamma-ray transport calculations. The calculations have provided a neutron attenuation factor of 10^{-2} for the short version of the vertical camera neutron attenuator.

ACKNOWLEDGEMENTS

This work was supported by the European Commission under Contracts of Association between EURATOM and the MEdC, UKAEA and MHST Associations. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1]. V.G. Kiptily, F.E. Cecil and S.S. Medley, Gamma ray diagnostics of high temperature magnetically confined fusion plasmas, Plasma Phys. Control. Fusion, **48** (2006) R59–R82.

[2]. V.G. Kiptily, D. Borba, F.E. Cecil, M. Cecconello, D. Darrow, P.C. de Vries, V. Goloborod'ko, K. Hill, T. Johnson, A. Murari, F. Nabais, S.D. Pinches, M. Reich, S.E. Sharapov, V. Yavorskij, I.N. Chugunov, D.B. Gin, G. Gorini, A.E. Shevelev, V. Zoita, Fast ion JET diagnostics: confinement and losses, AIP, 988 (2008) **283**.

[3]. S. Soare, V. Zoita, T. Craciunescu, M. Curuia, V. Kiptily, I. Lengar, A. Murari, P. Prior, M. Anghel, G. Bonheure, M. Constantin, E. David, T. Edlington, D. Falie, S. Griph, F. Le Guern, Y. Krivchenkov, M. Loughlin, A. Pantea, S. Popovichev, V. Riccardo, B. Syme, V. Thompson, I. Tiseanu, Upgrade of the JET Gamma-Ray Camera, AIP 988 (2008) 299.

[4]. S. Soare, M. Curuia, V. Kiptily, A. Murari, P. Prior, V. Zoita, M. Anghel, G. Bonheure, M. Constantin, E. David, T. Edlington, S. Griph, F. Le Guern, Y. Krivchenkov, S. Popovichev, V. Riccardo, B. Syme, V. Thompson, Design of the upgraded JET Gamma-Ray Cameras, J. Optoelectronics Advanced Mat., **10** (2008) 2088 – 2091.

[5]. CATIA product of Dassault Systemes, 92150 Suresnes, France.

[6]. ANSYS product of ANSYS Inc., Canonsburg, PA 15317, USA.

[7]. J. F. Briesmeister, Ed., "MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C", LA-13709-M (April 2000).

[8]. J.A. Halbleib, R.P. Kensek, T.A. Mehlhorn, G.D. Valdez, S.M. Seitzer, M.J. Berger, ITS version 3 – The integrated TIGER series of Coupled Electron/Photon Monte Carlo Transport Code, Sandia National Laboratories.

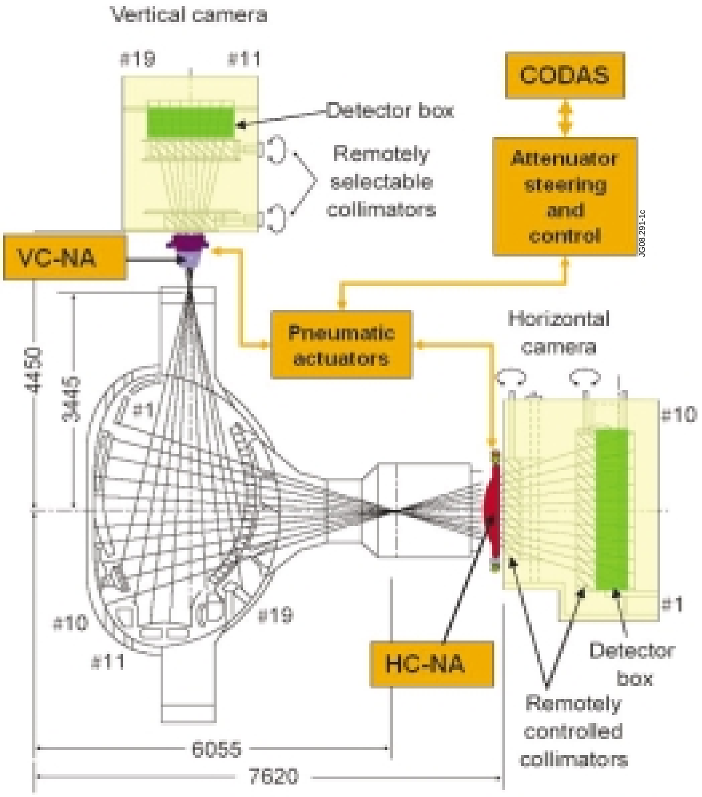


Figure 1: The JET KN3 gamma-ray camera neutron attenuator assembly (HC-NA: horizontal camera neutron attenuator; VC-NA: vertical camera neutron attenuators)

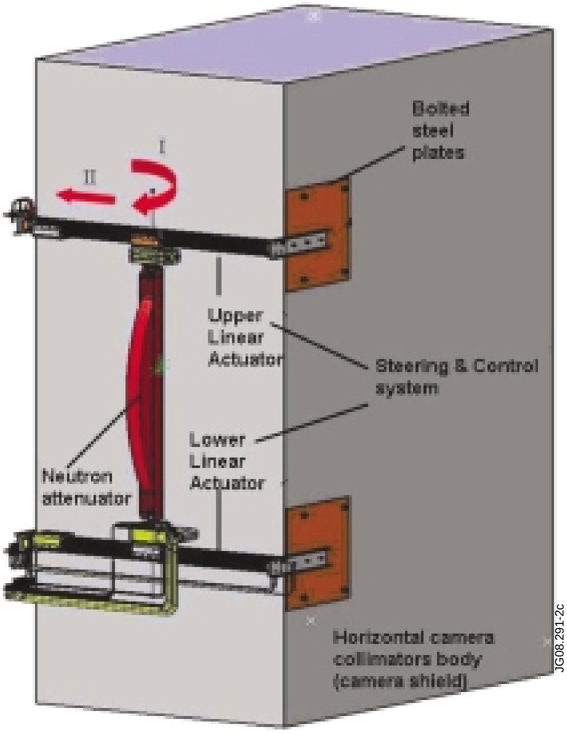


Figure 2: Horizontal camera neutron attenuator in working position (I and II: attenuator movements)

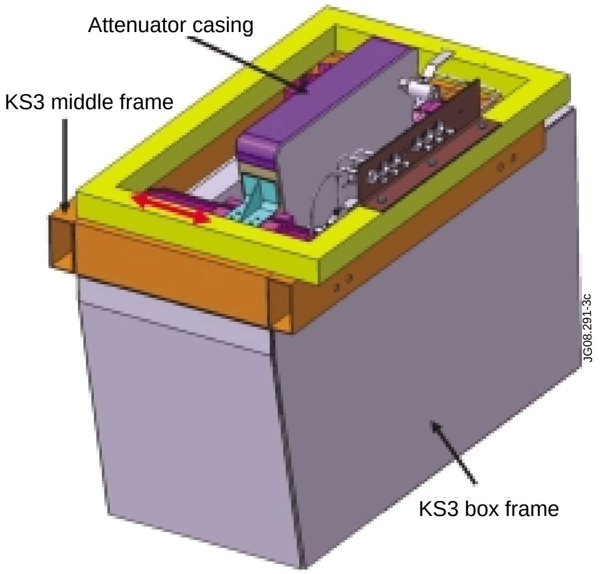


Figure 3: Vertical camera neutron attenuator in working position. Double red arrow: attenuator movement; KS3: H alpha diagnostics.

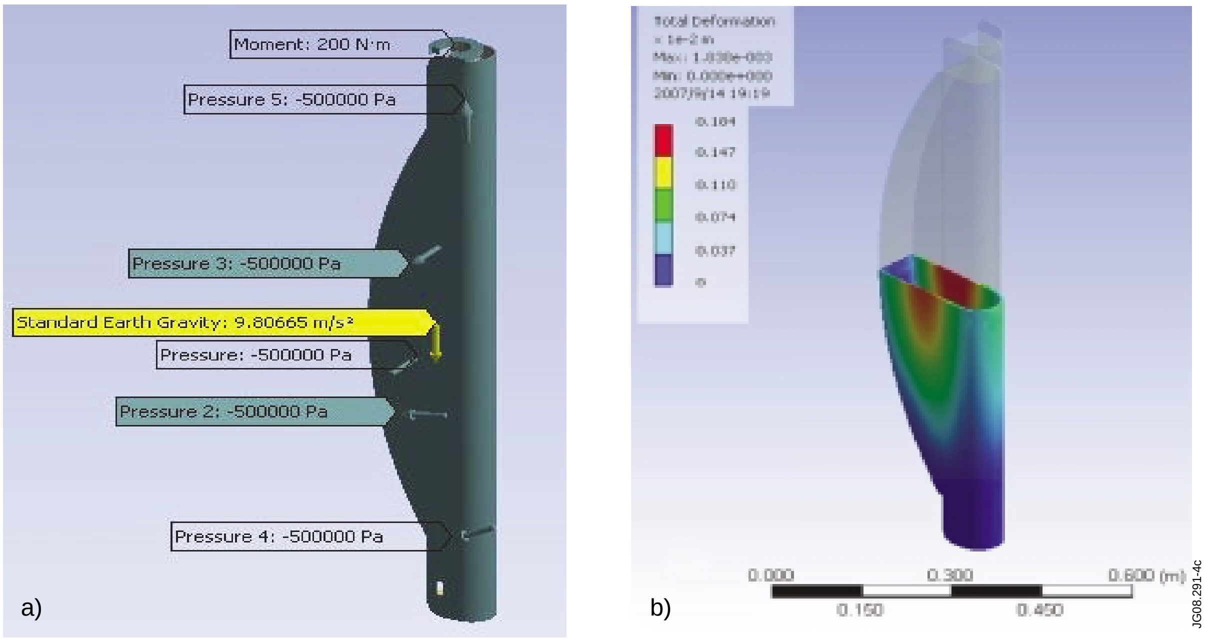


Figure 4: a) Horizontal camera neutron attenuator loaded model: applied moment, internal hidrostatic pressure and gravity; b) Half-model showing the maximum deformation.

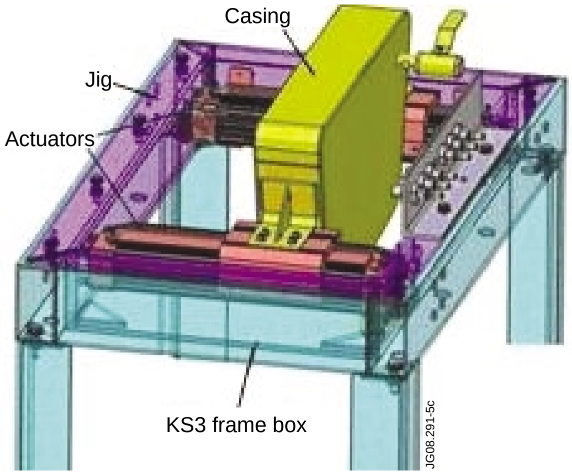


Figure 5: Neutron attenuator prototype assembly. KS3: H alpha diagnostics.

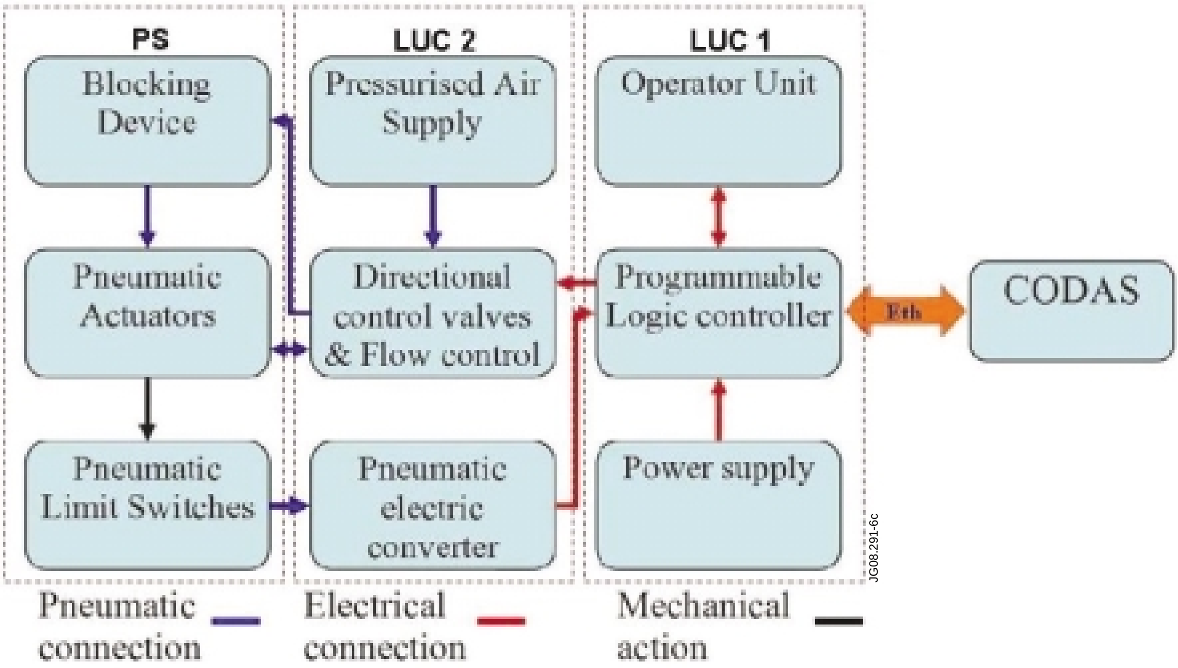
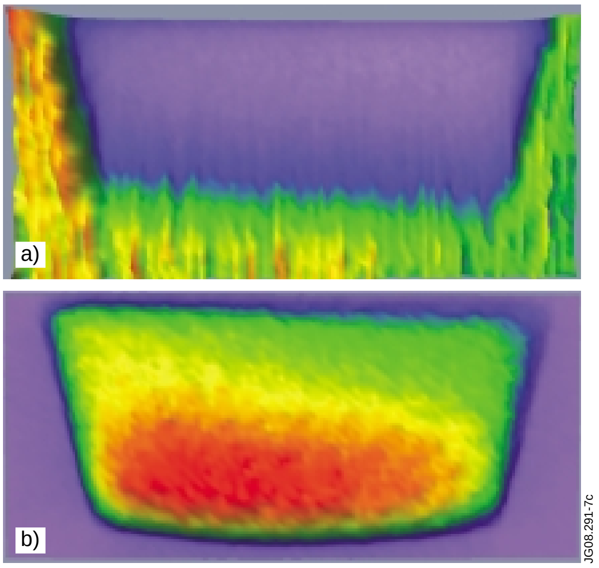


Figure 6: Block-diagram of the steering and control system for the KN3 neutron attenuator prototype: PS – Pneumatic Sub-System; LUC Local Unit Cubicle; Eth: Ethernet connection; CODAS – COntrol & Data Acquisition Systems.



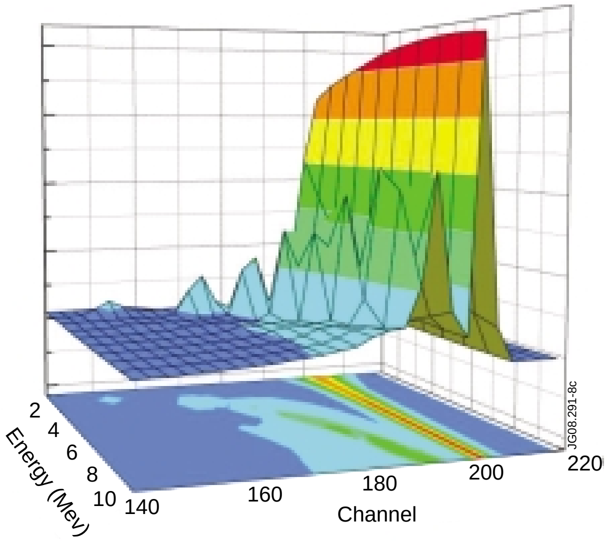


Figure 7: Neutron flux distribution in the Vertical Camera Neutron Attenuator (VC-NA-S). Vertical cross section through the middle of the attenuator. The intensity of the flux is presented in rainbow colours. Red: high flux; blue: low flux a) fast flux (above 2.5MeV), b) thermal flux (below 5.5eV)

Figure 8: Response function of the KN3 channel 15 CsI(Tl) detector.