THE CONTRIBUTION OF A SMALL TRIGA UNIVERSITY RESEARCH REACTOR TO NUCLEAR RESEARCH ON AN INTERNATIONAL LEVEL

M. Villa, H. Böck and H.W. Weber
Atominstitut der Österreichischen Universitäten
Stadionallee 2, A-1020 Vienna, Austria
Telephone : 0043-1-58801-14171
Fax : 0043-1-58801-14199
E-mail : mvilla@ati.ac.at

1. Introduction

The 250 kW TRIGA Mark-II reactor operates since March 1962 at the Atominstitut Vienna/Austria. Its main tasks are nuclear education and training in the fields of neutron- and solid state physics, nuclear technology, reactor safety, radiochemistry, radiation protection and dosimetry, and low temperature physics and fusion research. Academic research is carried out by students in the above mentioned fields coordinated and supervised by about 70 staff members with the aim of a masters- or PhD degree in one of the above mentioned areas. During the past 15 years about 580 students graduated through the Atominstitut. In addition, the Atominstitut co-operates closely with the nearby located IAEA in research projects, coordinated research programs (CRP) and supplying expert services. Regular training courses are carried out for the IAEA for Safeguard Trainees, fellowship places are offered for scientists from developing countries and staff members carry out expert missions to research centers in Africa, Asia and South America. Special Nuclear Material (SNM) is stored for calibration purposes at the Atominstitut belonging to the IAEA.

The paper focuses especially on the important results in neutron- and solid state physics and the co-operation between the low power TRIGA reactor with high flux neutron sources in Europe such as the Institute Laue-Langevin (ILL) in Grenoble, the Paul Scherrer Institut (PSI) in Villigen, the Rutherford Appleton Laboratory (RAL) in Didcot and the Research Center Jülich. Experiments are set up for test purposes at the TRIGA reactor and then transferred to the powerful neutron sources. Different new perfect silicon channel-cut and interferometer crystals are prepared and then tested at the Bonse-Hart camera, which is a double crystal (or triple axis) diffractometer and at the interferometer set-up. Historically, the first verification of neutron interferometry at a perfect crystal device has been achieved at the 250 kW TRIGA-reactor in Vienna in the year 1974. Also the co-operation with the PSI and the TU Munich in the field of neutron radiography and neutron tomography and VESTA, an experiment for storing cold neutrons with a wavelength of 6.27Å, installed at the pulsed neutron source ISIS at RAL will be mentioned.

The second topic treated in this paper shows the international co-operation in the field of superconductors. This research work is carried out under two European TMR-Network programs.
The third topic in this paper focuses on the co-operation in the field of safeguard. Several projects have been carried out during the past years in co-operation with the IAEA such as establishing a gamma spectrum reference catalogue for CdZnTe detectors and tests of safeguard video cameras under neutron irradiation. Further an integrated safeguard surveillance network composed of a video camera, a gamma monitor and a neutron monitor is under development.

2. The TRIGA Mark-II reactor

The TRIGA Mark-II reactor was installed by General Atomic (San Diego, California, U.S.A.) in the years 1959 through 1962, and went critical for the first time on March 7, 1962. Operation of the reactor since that time has averaged 220 days per year, without any long outages. The TRIGA-reactor is purely a research reactor of the swimming-pool type that is used for training, research and isotope production (**T**raining, **R**esearch, **I**sotope Production, **G**eneral **A**tomic = **TRIGA**). The TRIGA reactor Vienna has a maximum continuous power output of 250 kW (thermal). Since the moderator, zirconium hydride, has the special property of moderating less efficiently at high temperatures, the TRIGA reactor can also be operated in a pulse mode (with a rapid power rise to 250 MW for roughly 40 milliseconds). The power rise is accompanied by an increase in the maximum neutron flux density from $1x10^{13}$ $cm^{-2}s^{-1}$ (at 250 kW) to $1x10^{16}$ $cm^{-2}s^{-1}$ (at 250 MW). In accordance with its purpose as a research reactor, the TRIGA Mark-II is equipped with a number of irradiation devices (Figure 1):

5 reflector irradiation tubes
1 central irradiation tube
1 slow pneumatic transfer system (transfer time 4 seconds)
1 vertical fast pneumatic transfer system (transfer time 0.3 seconds)
1 horizontal fast pneumatic transfer system (transfer time 20 milliseconds)
4 neutron beam holes
1 thermal column
2 neutron radiography facilities

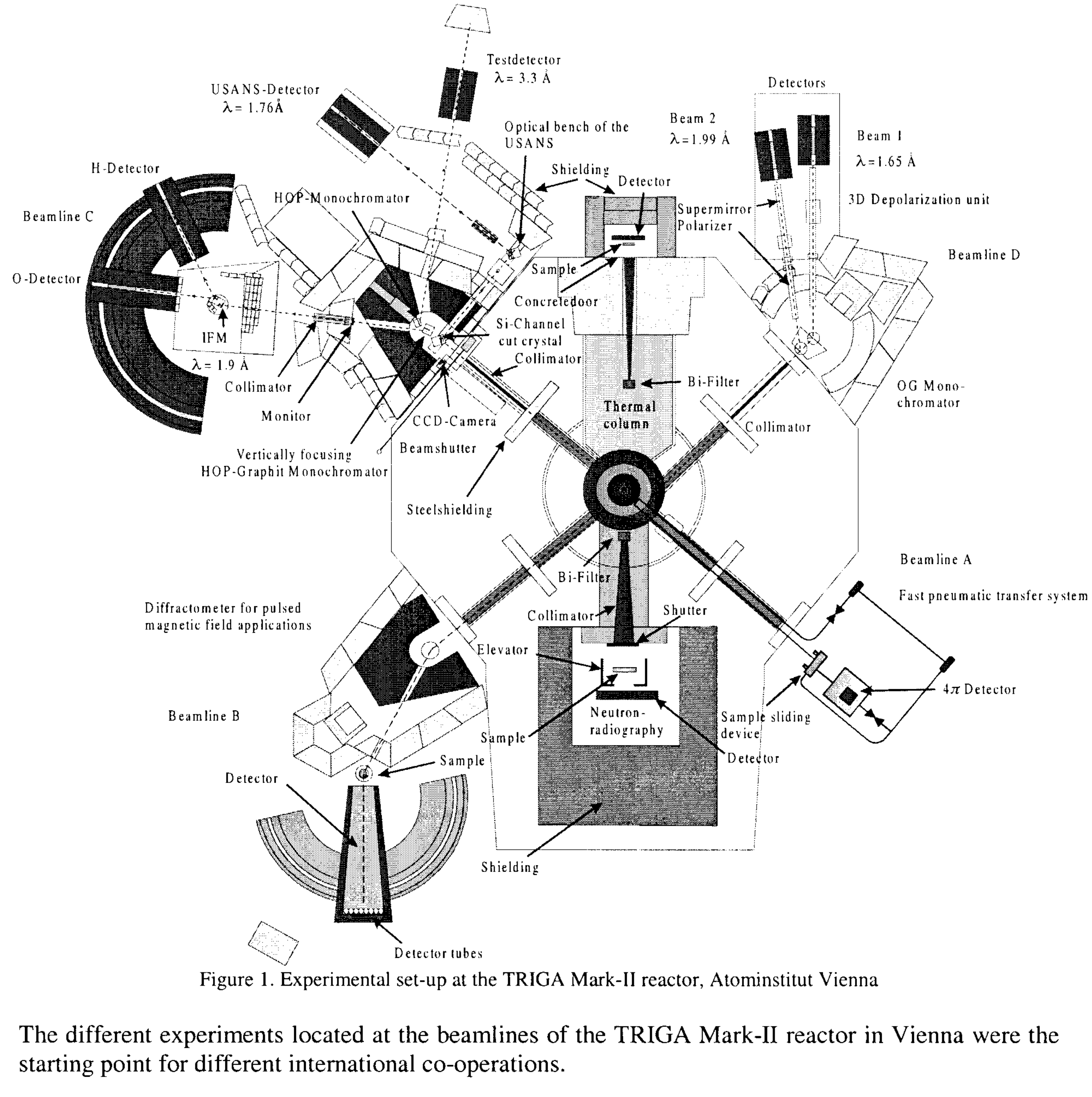

Figure 1. Experimental set-up at the TRIGA Mark-II reactor, Atominstitut Vienna

The different experiments located at the beamlines of the TRIGA Mark-II reactor in Vienna were the starting point for different international co-operations.

3. The CRG-C experiment S-18 at ILL, Grenoble

In the year 1974 perfect crystal neutron interferometry has been introduced by test measurements at a 250 kW TRIGA Mark-II reactor in Vienna [1,2]. It provides widely separated coherent beams and reasonable intensities due to the nondispersive action of the reflecting crystal plates and the possibility to use rather large beam cross sections. The perfect crystal interferometer technique has been developed before for X-rays [3] and profits from the availability of large perfect silicon crystals. In a joint undertaking between the Atominstitut in Vienna and the University Dortmund and according to an invitation of H. Maier-Leibnitz, the director of the ILL at that time, a prototype interferometer was installed at the high flux reactor at Grenoble [4]. After the shutdown of the 58 MW High Flux Reactor (HFR) in Grenoble (replacement of reactor vessel), and the restart of the HFR in January 1995 the whole set-up of the S-18 instrument was replaced and adapted to new technologies.

In parallel to the interferometer set-up a perfect crystal Bonse-Hart [5] small angle scattering camera has been installed [6], which takes advantage of a new tail suppression method [7]. This double crystal diffractometer (DCD) is an integral part of the instrument. Also polarized neutrons can be adapted by magnetic prism deflection within the air gaps of two prism shaped permanent magnets placed between the monochromator and the interferometer. In 1998, the combined interferometer and ultra small angle neutron scattering (USANS) instrument S18 at the HFR at the ILL started operation.

Due to the installation of the new supermirror guides at the HFR at the ILL, the intensity at the instrument position has been increased by a factor of five and the signal to background conditions have been improved considerably. The neutron interferometer set-up S18 has been upgraded to a triple axes instrument and an advanced Bonse-Hart ultra small angle scattering camera has been added. Both instruments use a highly vibration isolated optical bench and a common data acquisition system.

Since the first test measurements in 1998 several experiments in the field of neutron interferometry, ultra small angle scattering and polarized neutrons have been performed. Small and ultra small angle neutron scattering investigations on fusion relevant SiC/SiC_f ceramic composite materials (this work has been carried out within the association EURATOM-ÖAW, ADV1.1.1 - Advanced materials, SiC/SiC_f ceramic composites - Thermodynamical properties and material characterization)[8], Permanent magnetic field-prism polarizer for perfect crystal neutron interferometers [9] and Diffraction enhanced imaging (DEI) has been tested.

4. Neutron radiography and neutron tomography with PSI, Switzerland and TU Munich

Neutron radiography provides a very efficient tool in the field of non-destructive testing as well as for many applications in fundamental research. A neutron beam penetrating a specimen is attenuated by the sample material and detected by a two-dimensional imaging device. The image contains information about materials and structure inside the sample because neutrons are attenuated according to the basic law of radiation attenuation. Nevertheless, there are many aspects of structure, both quantitative and qualitative, that are not accessible from two-dimensional transmission images and, therefore, there is interest in three-dimensional neutron imaging. At the Atominstitut der Österreichischen Universitäten neutron radiographic examinations have been carried out for more than 35 years. Presently, two neutron radiography facilities are located at the 250 kW TRIGA Mark-II reactor. Main data of these facilities are shown in Table 1.

	STATION 1	STATION 2
FLUX DENSITY ($cm^{-2}s^{-1}$)	$3x10^5$	$1.3x10^5$
L/D-RATIO	50	125
BEAM DIAMETER (cm)	40	8
Cd - RATIO	3	20

Table 1. Main characteristics of the neutron radiography facilities at the Atominstitut

At one of these facilities a neutron tomography facility has been installed (Figure 2). The neutron flux at this beam position is $1.3x10^5$ neutrons/(cm^2s) and the beam diameter is 8 cm. For a three-dimensional tomographic reconstruction of the sample interior, transmission images of the object

taken from different view angles are required. Therefore, a rotary table driven by a step motor connected to a computerized motion control system has been installed at the sample position.
In parallel a suitable CCD-camera based imaging device [10] has been designed. It can be controlled by a computer in order to synchronize the software of the detector and of the rotary table with the aim of an automation of measurements. Reasonable exposure times can get as low as 20 s per image. This means that a complete tomography of a sample can easily be performed within one working day. Calculation of the 3D voxel array is made by using the filtered backprojection algorithm.

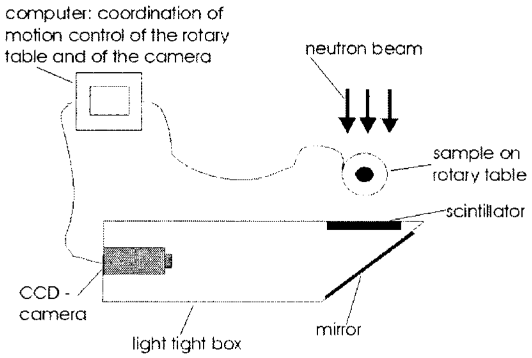

Figure 2. Neutron tomography facility

First reconstructions have been made at TU Munich and in parallel at Paul Scherrer Institute. Figure 3 shows the neutron tomography of a diode, as an example of a neutron tomography made at the Atominstitut. Part of this work has been financed by the EURATOM-ÖAW association, UT4 - Underlying Technology Project. Neutron Inspection of Fusion - Relevant Materials, Neutron Micro - Radiography.

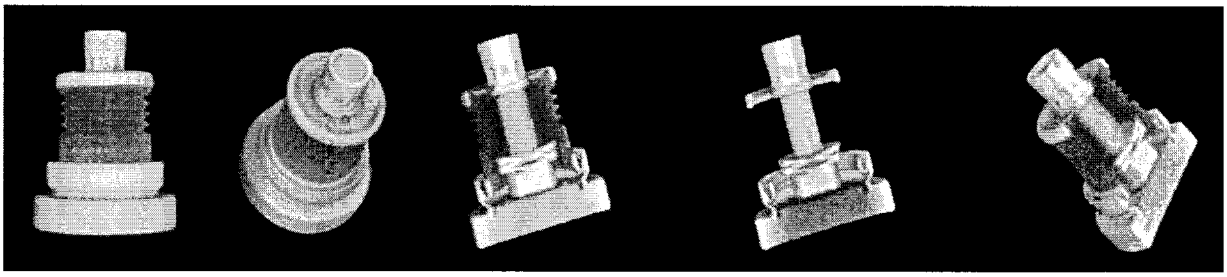

Figure 3. Neutron tomography of a diode

5. VESTA (Viennese nEutron Storage Apparatus) at Rutherford Appleton Lab (RAL)

VESTA is an experiment for storing cold neutrons with a wavelength of 6.27 Å, installed at the pulsed neutron spalation source ISIS. A highly monochromatic neutron beam is trapped by Bragg-reflections between two precisely parallel silicon crystal plates in backscattering geometry (Figure 4). The first set-up was tested in 1989 [11] and since that time the system was optimized till 1999. Although primarily designed as a neutron optical device, VESTA could also be used for measuring fundamental properties of the neutron and quantum physics effects. Due to the high number of reflections of neutrons inside the device (several thousand) and the long flight path that results (several kilometers), it has the potential to become a powerful tool for testing neutron guide tubes and mirror materials. corresponds to a flight path of 2.66 km inside VESTA, or to 2500 consecutive Bragg-reflections After [12].

Currently, a new storage device, "VESTA Type 2", is under construction. In this case the energy shift for neutron entry and exit will be achieved by using a pulsed HF-spin flipper and a static NMR magnet.

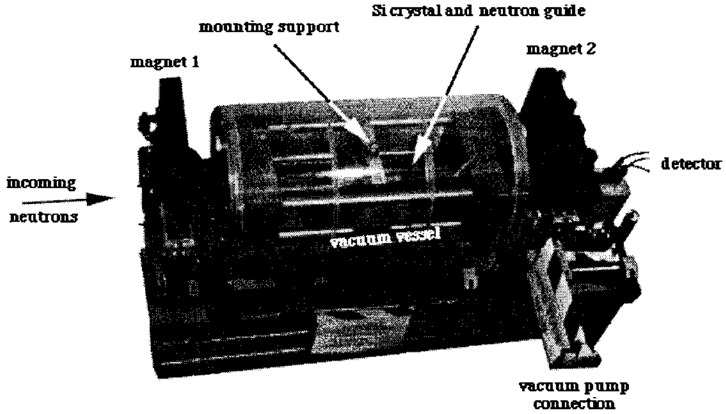

Figure 4. Experimental set-up of VESTA

It can be expected that by removing the pulsed magnets of the existing device and by reducing other sources of vibration, the storage time and efficiency can be further improved. VESTA is part of the TMR Network "Perfect Crystal Neutron Optics", contract ERB-FMRX-CT96-0057.

6. High critical current superconductors for technical applications

Superconductors for technical applications are required to carry very high currents without losses in the presence of magnetic fields. Decades of research have led to highly satisfactory results for metallic alloys and compounds at 4.2 K. With the advent of high temperature superconducting compounds, an enormous step forward was expected, since the cryogenics involved are much less sophisticated and expensive. However, in view of the complicated nature of these compounds, e.g. the anisotropy of their physical properties and the generally weak flux pinning structures, the achievement of high currents at elevated temperatures turned out to be extremely difficult. Nevertheless, a few compounds are emerging at present, which could meet these requirements, if appropriately tailored and characterized, such as YBCO monoliths for bearings and levitation as well as BiSSCO tapes and coated conductors for cables. These issues are vigorously addressed in the United States and Japan. The present consortium will respond to this challenge, carry out highly innovative research objectives, expects to achieve major steps towards technical applications through this co-operative effort, and provides the European Union with well trained manpower that will be urgently needed when the envisaged applications are realized in practice. The Vienna group, in particular, is involved in the optimization of the defect structure for flux pinning in all technologically relevant high temperature superconductors. One of the most successful ways to enhance the critical current densities at the boiling temperature of liquid nitrogen consists of artificially introducing extended defects by radiation techniques[13] Fast neutrons, e.g., produce spherical collision cascades, which act as efficient flux pinning centres in high temperature superconductors with a more "three-dimensional" magnetic micro-structure, such as YBCO, whereas extended columnar defects (thermal neutron induced fission tracks in materials with small additions of ^{235}U) are most efficient in more "two-dimensional" superconductors, such as BiSCCO tapes [14]. As a consequence of these defect modifications, the critical current densities can be enhanced by orders of magnitude. The research work in this field is part of the TMR Network "Supercurrent", contract ERBFMRXCT98-0189.

7. Radiation effects on fusion reactor materials

The radiation response of various superconducting magnet components [15] is investigated by exposing them to a mixed neutron and gamma radiation environment. Special emphasis is placed on the ITER [16] magnet insulation systems. ITER relevant data are generated for their mechanical properties under various static and dynamic load conditions prior to and following irradiation. Selected superconductors are investigated as well with regard to the radiation-induced changes of the critical current densities. The research reactor of the institute, which represents a well characterized radiation source, is employed and supplementary irradiation experiments in a pure gamma environment are made at a partner institute within the Euratom associations. Based on the results of previous research programmes [17] and considering the extensive materials development and testing programmes which are presently under way in the framework of the ITER programme, we address the following subjects, which are all related to radiation effects in fusion magnet materials. Firstly, radiation effects on superconducting magnet components are assessed. The material of primary concern for the lifetime performance of the magnet is certainly the insulation of the magnet windings. Following extensive scaling experiments [18,19] to assess suitable sample geometries for the small irradiation volumes in the reactor, we proceed with testing newly developed fibre reinforced plastics and assess their mechanical properties in tension as well as in the interlaminar shear mode both under static and dynamic loading conditions [20]. A special effort is made to investigate fatigue effects under tension and shear of these materials following irradiation at ambient temperature. The materials are provided by the US, Japanese and European manufacturers involved in the fabrication of the ITER test coils. Secondly, radiation effects on superconducting materials selected for ITER are investigated with the equipment available at the institute, the main parameter being in this case the change of the critical current density. Finally, new developments, e.g. the implementation of superconducting current leads, based on high temperature superconductors, and their radiation response, are investigated as well (EURATOM contract ERB 5005 CT 99 0115, TW0-T404-2/01).

8. Cooperation with the International Atomic Energy Agency Vienna

8.1 CdZnTe Detectors:

Safeguards inspectors use increasingly miniature CdZnTe detectors for practical applications in the fields of verification of nuclear material. These detectors have many advantages compared to previously used HPGe detectors as they are all solid state, do not need any cooling and their resolution is between Na(I) and HPGe. The preparation and planning of applications requires good knowledge of the characteristics and spectral performance of these detectors. While numerical data can be used to characterize detector performance, many users prefer the use of graphical images of gamma spectra for planning of applications. The great success of previous gamma spectra catalogue for NaI and HPGe detectors has shown this. In this project a spectral data catalogue for room temperature semiconductor detectors has been initiated, a catalogue which is not only for users and application planners but also for researchers modeling gamma spectra and developing spectrum processing software. In the current project totally 26 nuclides have been measured with 3 different CnZnTe detector types and the resulting gamma spectra have been catalogued and are available through the IAEA [21,22].

8.2 Safeguards:

Being the closest research reactor to the IAEA headquarters various departments of this organization uses extensively the TRIGA facility mainly in the fields of Nuclear Safeguards. For example various Special Nuclear Material (SNM) samples are stored at the Atominstitut to be used frequently for calibration purposes for safeguard instruments to be later applied in nuclear power plants. Two WWER 440 fuel assemblies are stored for this purpose in the fresh fuel storage facility. A Load Cell is available to calibrate a sensitive balance to be used to weight spent fuel elements under water in the spent fuel pond to detect any removal or exchange of individual fuel rods in fuel assemblies. Video cameras used for surveillance of sensitive areas in NPP are tested for their radiation resistance to neutron exposure.

8.3 Training:

Every two years a four weeks training course is carried within the Safeguards Traineeship Program of the IAEA to train future Safeguards Inspectors from developing countries to fulfil the application criteria for Safeguard Inspectors. In the past 15 years approximately 80 trainees have passed through these courses at the Atominstitut. Finally it has to mentioned that the Atominstitut readily accepts

IAEA fellows from developing countries to be trained in various nuclear fields for periods from one month to one year. During the last 15 years more than 100 fellows have received their training in the Atominstitut and continue the cooperation with the Atominstitut also after their return to their home institute.

9. References

[1] **H. Rauch, W. Treimer, U. Bonse**; Phys.Lett. 47A (1974) 369

[2] **W. Bauspiess, U. Bonse, H. Rauch, W. Treimer**; Z.Physik 271 (1974) 177

[3] **U. Bonse, M. Hart**; Appl.Phys.Lett. 6 (1965) 155

[4] **W. Bauspiess, U. Bonse, H. Rauch**; Nucl.Instr.Meth. 157 (1978) 281

[5] **U. Bonse, M. Hart**; Appl.Phys.Lett. 7 (1965) 238

[6] **G. Kroupa, G. Bruckner, O. Bolik, M. Zawisky, M. Hainbuchner, G. Badurek, R. J. Buchelt, A. Schricker and H. Rauch**; Nucl.Instr.Meth. A 440 (2000), 604

[7] **M. Agamalian, D. G Wignall, R. Triolo**; J.Appl.Cryst. 30 (1997) 345

[8] **M. Hainbuchner, M. Villa, G. Kroupa, G. Bruckner, M. Baron, H. Amenitsch, E. Seidl, H. Rauch**; J. Appl. Crystr. 33, (2000) 851

[9] **G. Badurek, R.J. Buchelt, G. Kroupa, M. Baron, M. Villa**; Physica B 283 (2000) 389

[10] **S. Körner, E. Lehmann, P. Vontobel**; Nucl.Instr.Meth. A 454 (2000), 158

[11] **M. Schuster, H. Rauch, E. Seidl, E. Jericha and C.J. Carlile**; Phys. Lett. A 144, (1990) 297

[12] **E. Jericha, D.E. Schwab, M.R. Jäkel, C.J. Carlile, and H. Rauch**; Physica B 283 ,(2000) 414

[13] **M.C. Frischherz, M.A. Kirk, J. Farmer, L.R. Greenwood, H.W. Weber**; Physica C232, 309 (1994)

[14] **S. Tönies, H.W. Weber, D. Milliken, Y.C. Guo, S.X. Dou, A. Gandini, R. Sawh, Y. Ren, R. Weinstein**; Physica C 341-348, (2000) 1427

[15] **H.W. Weber**: in "Handbook of Applied Superconductivity", B. Seeber; Editor, IOP Publishing (1998), Vol. 1, Chapter C5, pp. 593-600

[16] **www.iter.org**

[17] **H. Schönbacher, B. Szeless, M. Tavlet, K. Humer, H.W. Weber**; CERN-Report 96-05, 4. July 1996

[18] **P. Rosenkranz, K. Humer, H.W. Weber**; Cryogenics 40, (2000) 155

[19] **P. Rosenkranz, K. Humer, H.W. Weber, D.H. Pahr, F.G. Rammerstorfer**; Cryogenics (in press)

[20] **K. Humer, P. Rosenkranz, H.W. Weber, P.E. Fabian**, J.A. Rice;J. Nucl. Mat. 283-287, (2000) 973

[21] **E. Gryshchuk**; Atominstitut internal report 993023b (1999)

[22] **Hubert Zwickelstorfer**; Atominstitut internal report 20309 (2000)