# Experimental Installations and Instruments at the FRM-II

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The new research reactor FRM-II of the Technical University Munich will be the strongest neutron source in Germany when going into operation in 2001/2002. From the beginnings on it was designed as a multipurpose research reactor based on local traditions, recent experience and new ideas. The reactor will be used for neutron scattering and material science, for fundamental physics with cold and ultracold neutrons, for isotope production, fission fragment acceleration, medical tumor treatment and for a manifold of technical and practical applications like computer tomograpy with fast and cold neutrons. According to the wide spectrum of applications the reactor needs a manifold of special installations and instruments, which will be introduced in the present paper.

The reactor will be equipped with a liquid-$D_2$ cold source for high resolution neutron scattering and a solid-$D_2$ UCN source for fundamental physics, with a graphite hot source for high-Q neutron diffraction and a „converter“, which is a U-235 target in the thermal flux maximum to produce fast fission neutrons for medical applications and technical tomography. A series of irradiation plants is designed for production and study of radio-isotopes with half-lives as short as seconds and for phosphor-doping of semiconductor silicon crystals with diameters up to 8 inch. The reactor will be equipped with ten horizontal, one vertical and two inclined beam-tubes, one of the latter ones will take up a most intense, newly developed positron source for solid state physics. Three horizontal beam tubes will look onto the cold source, one of which will take up six neutron guides going into a neutron guide hall 50 x 25 $m^2$. Most of the neutron guides will be coated with super-mirror which allows to build effective beam switches for many end-position experiments. The first generation of about 20 instruments and experimental installations as recommended by the instruments committee will be financed by the Federal and Bavarian ministeries of science and education and are well under construction. These instruments comprise a reflectometer for biological studies, a small-angle scattering instrument for polymer, material and biological research, powder diffractometers for general structure determination and stress and texture studies, a cold and a thermal triple-axis spectrometer as well as time-of-flight instruments for inelastic neutron scattering, a spin-echo and a backscattering spectrometer with ultra-high resolution and special neutron guides for neutron-optical experiments and a source for a fission fragment accelerator experiments.

The present report summarizes the work of, and the discussions with many colleagues and co-workers in the Projektgruppe FRM-II, in the Physics Department of the TUM and in the wide user community. All of them deserve  full acknowledgement.

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## 1. Introduction

The new research reactor FRM-II of the Technical University Munich will be the strongest neutron source in Germany when going into operation in 2001/2002. From the beginnings on it was designed as a multipurpose research reactor based on local traditions, recent experience and new ideas. The reactor will be used for neutron scattering and material science, for fundamental physics with cold and ultracold neutrons, for isotope production, fission product acceleration, medical tumor treatment and for a manifold of technical and practical applications like computer tomography with fast and cold neutrons. According to the wide spectrum of applications the reactor needs a manifold of special installations and instruments, which will be introduced in the present paper.

## 2. Spectrum Shifters and Secondary Sources

Neutrons in science, medicine and technical applications are used in a broad energy range from less than μeV to more than MeV. For optimum intensities within that broad range spectrum shifters and secondary sources are installed in the FRM-II. The reactor will be equipped with a $D_2$ moderated cold source, an ultrcold neutron source with frozen $D_2$, a hot neutron source of graphite and a so-called converter to produce fast fission neutrons. Moreover there will be special beam tube installations for a most intense positron source and a fission fragment source, the fission fragments being extracted and accelerated to high energies to produce heavy and super-heavy elements.

The $D_2$ cold source will be described by Gobrecht / 1 / and the ultra-cold frozen $D_2$ source will be reported on by Schott / 2 / in this conference and therefore will be skipped in the present paper.

The **hot source** is in some details similar to the one at the ILL in Grenoble. It consists of a solid graphite cylinder of 20 cm diameter and 30 cm height, which is heated by the core radiation (about 40 cm distance between the two axes). The hot graphite block is thermally insulated by graphite felt altogether being encapsulated in a double-wall zircaloy container. The heat conductivity of the graphite felt, and thus the temperature of the solid graphite moderator, depend on the type of the gas in the graphite felt. The FRM-II hot source has been licensed for both modes of operation: vacuum operation with an expected temperature of 2800 K and neon operation ( < 0.5 bar) with an expected temperature of 2400 K. The temperature in the moderator can be measured by a graphite thermal noise thermometer, the temperatures in the insulating felt by a series of thermocouples. A mock-up experiment with electrical heating of a representative model structure confirmed the expected temperatures. The pressure control of the helium gas ( 3 bar) within the two zircaloy vessels is an important safety feature to detect leaks in the inner as well as in the outer vessel. The zircaloy vessels are built according to German rules of „basicly safe" containers. The hot neutrons can be extracted by a horizontal beam tube (SR-9) and will be mainly used for neutron diffraction with high Q transfer to study anharmonic Debye-Waller factors, high Q structure factors of liquid and amorphous materials and some details of magnetic form factors. More technical details can be found in / 3 /.

The so-called **converter** is an effficient source of fast fission neutrons. This thermal-to-fast-fission-neutron converter consists of an U-235 target near the nose of beam tube SR-10, from where fast fission neutrons can be extracted without any or with only a minimum number of collisions with moderator atoms. The U-235 target contains 350 grams of U-235 and is fabricated similar to a fuel plate of the central fuel element. The thermal power of the target in a thermal flux of $5 \times 10^{13}$ n/cm²s is about 80 kW and has to be dissipated by $H_2O$ from the reactor pool in a separate cooling circuit, which has to fulfill nuclear safety standards. The spectrum of the radiation, primarily a mixture of fast neutrons and hard γ - rays, can be modified by filters like 120 cm long silicon or iron cylinders according to the demands of the application. A prototype of such a source exists since more than a decade at the „Atom-Ei" in Garching and is mainly used for medical therapy of tumors, which are not deeper than 2 – 4 cm in the human body. The radio-biological efficiency of fast neutrons is nearly one order of magnitude larger than that of γ - rays. With a beam intensity at the beam tube exit of about $10^9$ n/cm²s a dose of 5 Gray/minute can be applied onto a field as large as 28 cm x 28 cm at the new reactor. This installation was developed in cooperation with the medical faculty of the Technical University of Munich. When the beam is not needed for therapy it can be used for radiography and tomography of technical objects as described in chapter 7. More technical details can be found in / 4 /.

Positrons are an important tool in solid state physics: By studying the angular correlation of annihiation radiation the momentum distribution of electrons in solids and by studying the positron halflife details of crystal defects can be investigated. A new type of a **positron source** as proposed and demonstrated by Schreckenbach and co-workers / 5 / will be installed in the FRM-II. The positrons will be produced in a tungsten foil by pair production as induced by $\gamma$ - rays. The $\gamma$ - rays are generated by neutron capture in Cd. The nose of a beam tube will be coated therefore by a 1 mm thick Cd foil, the tungsten structure for generation and moderation of the positrons will be inside the beam tube as well as the extraction optics and the guide fields. The positron source will be ideally installed in an inclined beam tube (SR-11) as the charged positrons can easily be deflected into a comfortable horizontal direction. The effect of the strongly absorbing Cd target on the reactivity of the core and the neutron field around the neighboured beam tubes had to be studied very carefully.

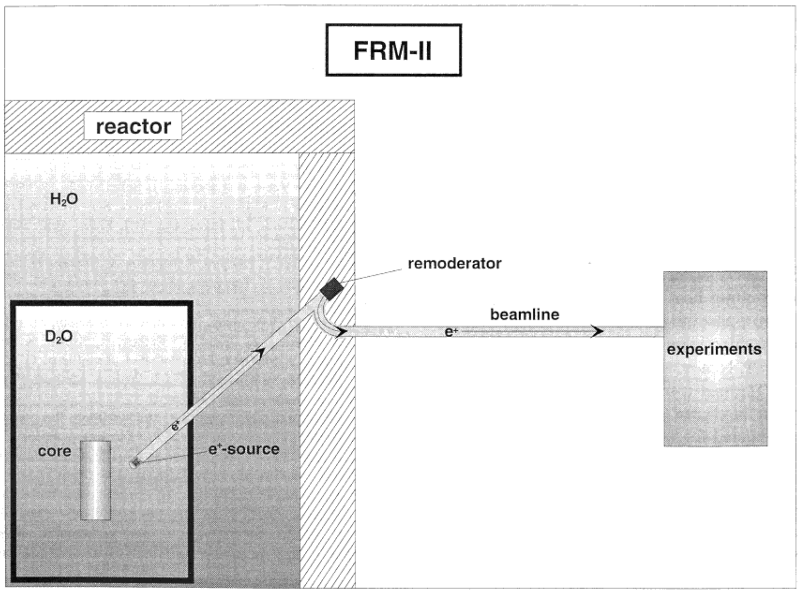


Fig. 1: Scheme of the positron source at FRM-II

A very ambitious and challenging project at the FRM-II is that of a **fission product accelerator**. Fission products are very neutron-rich and the cross-section for production of heavy elements in collision of high energy fission products with other target nuclei is larger than that for any other reaction. A U-235 target of 1 – 2 grams contained in a small graphite cylinder is positioned in the middle of a double-ended beam tube. The target can be manipulated from one end of the beam tube and the fission products are extracted throuhg the other end of the beam tube. After filtering in mass-separators the fission products will be accelerated in an external experimental hall, where a variety of experiments on nuclear and atomic properties of heavy and super-heavy reaction products can be studied / 6 /.

**3. Beam Tubes**

The reactor pool of the FRM-II has big holes for two inclined beam tubes and ten horizontal beam tubes, one of which is a through-going, double-ended beam tube (Fig. 2). A so-called „compensator tube“ with an elastic bellow is fixed at one end inside the beam hole and at the other end at the moderator tank. At the same flange of the moderator tank is also fixed the beam tube nose, which is only about 1 m long. The beam holes with a typical diameter of about 1 m at the outer side of the pool are filled with heavy plugs with the beam channels. Normally two channels 12 cm high and 8 cm wide are worked into these plugs. Both channels are oriented to the end of the beam tube nose with an angle of about 8 ° in between in the horizontal plane. The beam tube plug has a rotor with a horizontal axis, which closes the two beam channels when turned by 90° (Fig. 3). Neutron guides, collimators or diaphragmas can be mounted in the channels of the rotor according to the experimentalists demands. The beam tubes are closed by big steel plates with neutron windows of aluminum 2 mm thick. The beam tubes are filled with helium gas of 1.2 bar. A special machine was built to install the plugs and to mount the deep-laying beam tube noses, which are expected to be replaced every 7 -10 years because of radiation damage. The big dimensions of the beam holes give a high flexibility in the use of the beam tubes. More than one neutron beam can be extraced from one hole (in case of beam tube SR-4 a special plug is being planned to extract even three neutron beams, one of which will be an UCN beam / 2 /). The beam tubes are also big enough for installation of a horizontal cold source or multi-beam guide tube systems. The fission product accelerator experiment will be installed in beam tube SR-6. One of the inclined beam tubes will take up the positron source, the other is designed for extraction of a monochromatic neutron beam for a special neutron diffractometer. The inclination angle of 42° of the inclined beam tubes originates from a characteristic Bragg angle of pyrolithic graphite, which is often used as a monochromator. Beam tubes SR-1, SR-2 and SR-4 are looking onto the cold source, beam tube Sr-9 is oriented onto the hot source. An additional beam tube is integrated into the vertical cold source, from where, with a special neutron guide, very cold neutrons can be extracted and used on the upper floor of the reactor building. The neutron flux at the beam tube noses is between 2.5 x $10^{14}$ and 5 x $10^{14}$ n/cm²s for different tubes.

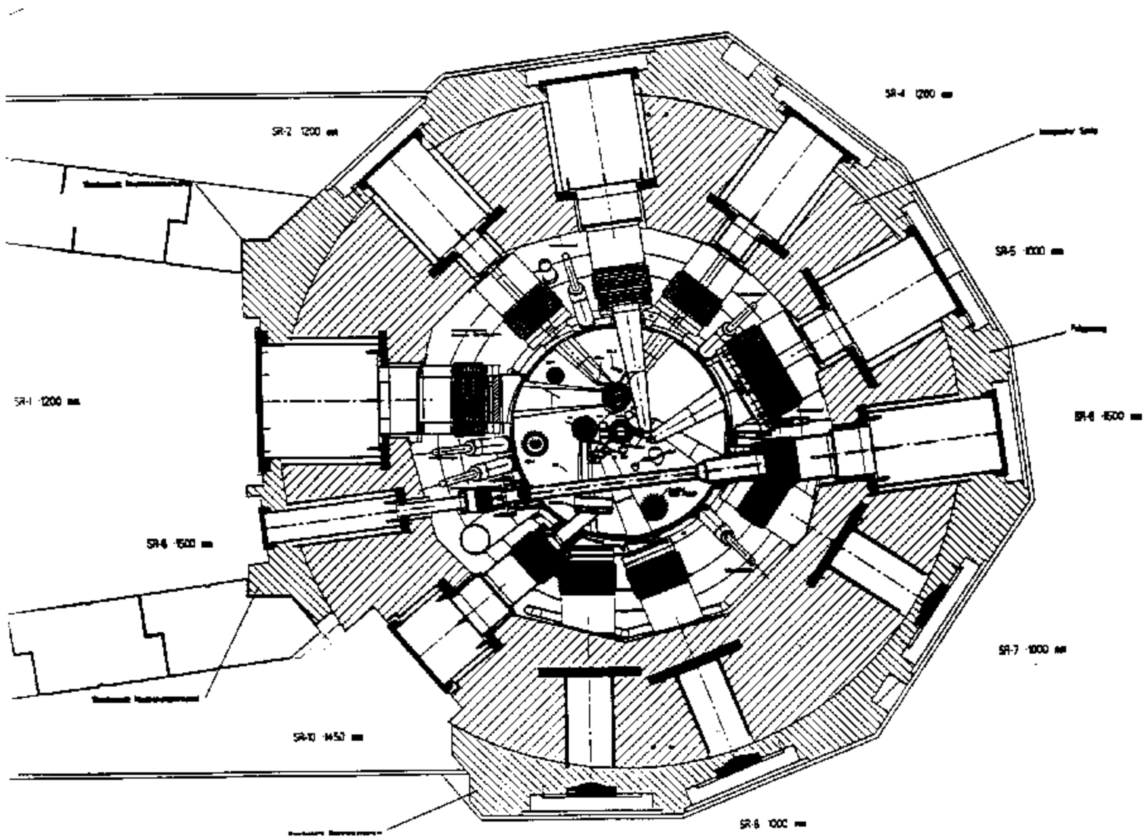

Fig.2: Horizontal cut through FRM-II at a height of 1500 mm

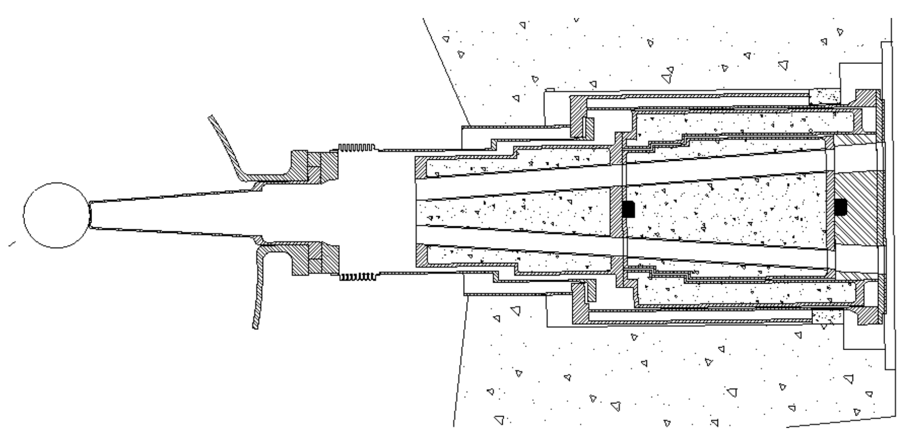

Fig.3: Principal design of a beam tube plug with 2 neutron channels and a rotating shutter

**4. Neutron Guides**

Neutron guides are nowadays the most important devices for beam transport and beam handling. Large experimental areas can be opened and supplied with neutrons, extremely good TOF resolution can be obtained by using a guide as a long flight path, the background radiation from the reactor core can be suppressed by curving a guide and polarized neutron beams can be produced by special mirror coatings. Guides with normally rectangular cross-section are manufactured from very flat or precisely curved glass plates which are coated by natural nickel or Ni-58 with critical glancing angles of about 0.1° per Angstroem. With so-called super-mirrors as developed during the last decade the maximum glancing angles can be enlarged by a factor 2 – 4 compared to natural nickel. With the larger glancing angle one gets higher beam intensities (with larger divergence!), which is very important especially for thermal neutrons. Moreover the length of direct sight of a curved guide can be made shorter using super-mirror coatings. This means that the background radiation which is emitted within that length of a guide can be kept nearer to the reactor and farer from the experiments in a guide hall. For the guide tube system at beam tube SR-1 of the FRM-II we have tried to keep the direct sight of length for all guides as short as possible. Some of the guides with a total width of 50 mm will therefore be subdivided into two channels 24 mm wide by a thin vertical wall.

The complete system is made up from six guides. The two innermost guides have a cross-section of 170 mm x 50 mm, the outermost two guides 120 mm x 60 mm and the other two 170 mm x 60 mm. The guides start at a distance of 2 m from the cold source. The first 7 m of the guides are made from unborated glass, the rest from borated glass. The angles to the centre line of the whole system are +-1°, +-6.6° and +-8.75°. A shutter common to all 6 guides is placed directly at the exit windows of beam tube SR-1 inside the guide tunnel, which is about 14 m long. The guides inside the tunnel are mounted in evacuated housings, most of the guides in the neutron guide hall will be mounted without vacuum housings and will be evacuated directly. The primary cross-sections of the guides will be split up into partial beams, which are obtained by horizontal or vertical subdivision. Individual beams with the instruments installed at their „end positions“ are obtained by „switches“ and beam benders as shown in Fig. 4. The complete system of guides and instruments both in the experimental hall of the reactor building and in the neutron guide hall outside (about 50 m x 25 m area for experiments) is shown in Fig. 5A and Fig. 5B.

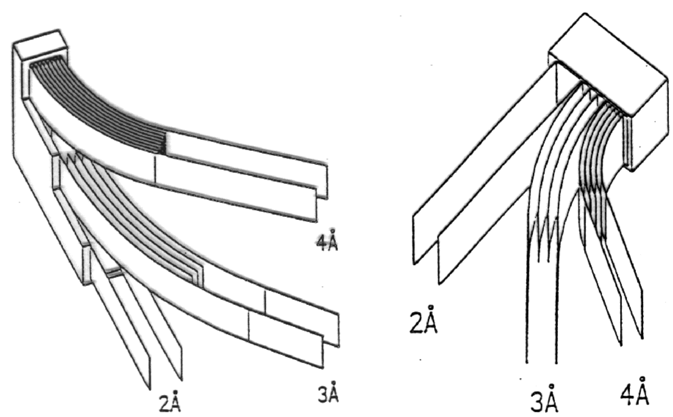


Fig. 4: Two types of beam splitters

**5. Instruments for Neutron Scattering and Fundamental Research**

As can be seen from Fig. 5A and Fig. 5B about 30 instruments for neutron scattering and fundamental physics can be installed in the experimental areas in the reactor building and in the neutron guide hall. 16 installations have been decided for first-day-operation. About 10 instruments are planned to be either transferred from other research reactors in Germany lateron or still have to be designed and financed. A complete list with already decided and planned instrument is given in Table 1. The instruments are being built from interested groups of German universities and research centers and are financed either by the Bavarian or Federal ministery of research and education. The instruments will be operated in a user-mode. This means, that the pioneering groups, who build the instruments, will get about 30% of the beam time, the rest being allocated according to requests from individual groups and scrutiny by subcommittees of the scientific council.

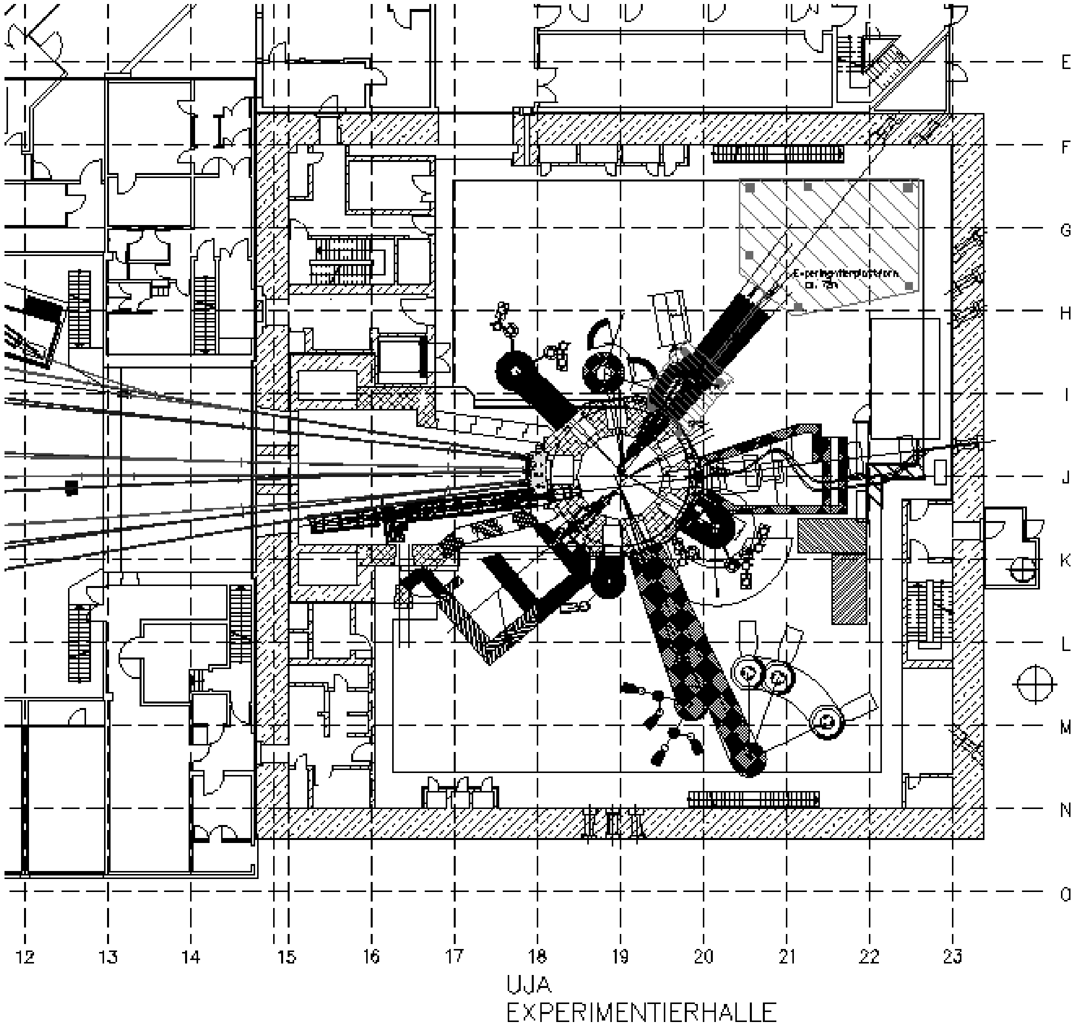


Fig. 5A: Lay-out of the experimental hall in the ground floor of the reactor building of FRM-II

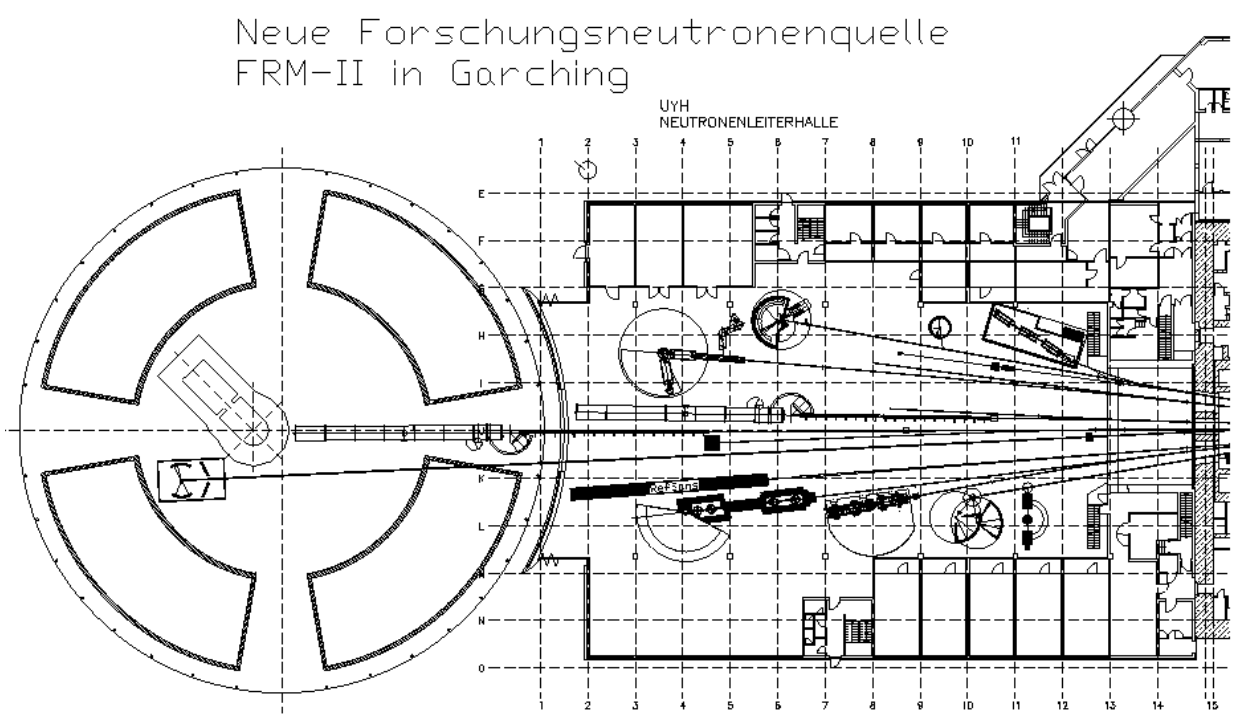


Fig. 5B: Lay-out of neutron guides and instruments in the neutron guide hall of FRM-II

## Instruments at FRM-II

| Decided (Planned) | Responsible |
|---|---|

### Small Angle Scattering and Reflectometry

| | |
|---|---|
| Standard SANS KWS-II | |
| Standard SANS KWS-I | FZ Jülich |
| (Focussing SANS) | FZ Jülich |
| Reflectometer for Biomaterials | GKSS Geesthacht |
| (Reflectometer for Material Science) | MPI Stuttgart |

### Diffractometers

| | |
|---|---|
| Powder Diffractometer | TU Darmstadt |
| Strain and Texture Diffractometer | HMI + Clausthal |
| Single Crystal Diffractometer Thermal Neutrons | TU/LMU München |
| Single Crystal Diffractometer Hot Neutrons | RWTH Aachen |
| (Diffuse Scattering Diffractometer) | FZ Jülich |

### Spectrometers

| | |
|---|---|
| Triple-Axis-Spectrometer Cold Neutrons | TU Dresden |
| Triple-Axis-Spectrometer Thermal Neutrons | Uni Göttingen+TUM |
| Backscattering Spectrometer | FZ Jülich |
| TOF - TOF - Spectrometer | TU München |
| Crystal - TOF - Spectrometer | Uni Kiel |
| (TOF Spectrometer Thermal Neutrons) | FZ Jülich |
| Resonance Spin Echo Spectrometer | TU München |
| (Triple Axis Resonance Spin Echo Spectrometer) | MPI Stuttgart |
| (Spin Echo Spectrometer) | FZ Jülich |

### Fundamental Physics

| | |
|---|---|
| Cold Neutrons for Particle Physics | Uni Heidelberg |
| Cold Neutrons for Optical Experiments | TU München |
| (Ultra Cold Neutron Source) | TU München |

### Special Devices

| | |
|---|---|
| Positron Source | BWU/TU München |
| (Fission Fragment Accelerator) | LMU/TU München |

## 6. Irradiation Service

Based on experience and traditions at the old research reactor and needs at the new reactor a series of irradiation devices are in planning and under construction for the new FRM-II. The installations are good for irradiation times from seconds to many weeks and longer, neutron fluxes from 5 x $10^{12}$ n/cm²s to 4 x $10^{14}$ n/cm²s and sample volumes between cubic millimeters and some liters. Samples are contained either in polyethylene capsules or aluminum cans and are transported via pneumatic or hydraulic tube systems into the neutron field inside the moderator tank. A very important installation will be a device for neutron transmutation doping of semiconductor silicon crystals with phosphor. Crystals with diameters from 4 to 8 inches and a length of 50 cm can be irradiated under rotation with axial flux profile smoothening to a homogeneity better 5%. All irradiations will be performed in the upper floor of the reactor building with easy access to a hot cell and strict separation from the research activities in the ground floor of the reactor building and the neutron guide hall.

## 7. Neutron Radiography and Tomography

With increasing demand for rigorous quality control of high tech products radiography and computer tomography with neutrons have obtained new importance. By new high resolution position sensitive detectors, fast computers and highly developed software for tomography and visualization – part of which can be transferred from medical applications – the neutron technique has also got new perspectives and impetus. A paper showing the state of the art was recently published by Schillinger et al. / 7 /. Based on the characteristic energy dependence of the cross-sections of neutrons for hydrogen and technical materials like iron, aluminum or other metals we are planning to install two radiography/tomography stations: One with cold neutrons at beam tube SR-4, looking onto the cold source, and another one with „second-hand-use“ of the fast beam behind the medical irradiation plant. The cold beam will be useful to detect small amounts of hydrogen containing material in metals, the contrast from which can be changed by wavelength change across the Bragg cut-off in the cross-section. The fast neutrons with a cross-section for hydrogen similar to that for metals can be used for examination of technical objects with higher content of hydrogeneous materials.

## 8. References


/1/ K. Gobrecht, IGORR-7
/2/ W. Schott, IGORR-7
/3/ E. Gutsmiedl, Jahrestagung Kerntechnik ´99, INFORUM Verlag, Bonn
/4/ W. Waschkowski, FRM-II Internal Report
/5/ C. Hugenschmidt et al., Applied Surface Science 149 (1999) 7 – 10
/6/ O. Kester et al., NIM B 139 (1998) 28 – 36
/7/ B. Schillinger et al., NIM A 424 (1999) 58 – 65


The Internet address of the FRM-II project is www.frm-2.tu-muenchen.de