Advanced Neutron Instrumentation at FRM-II

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Abstract:

The construction of the new German high flux neutron source FRM-II is finished and FRM-II is waiting for its licence to start nuclear operation. With the beginning of the routine operation 22 instruments will be in action, including 5 irradiation facilities and 17 beam tube instruments, most of them use neutron scattering techniques. Additional instruments are under construction. Some of these instruments are unique, others are expected to be the best of their kind, all instruments are based on innovative techniques.

Introduction

In 1957, the Bavarian state government established the Federal Republic's first nuclear reactor, Forschungsreaktor München (FRM); now, with the new Munich research reactor, FRM-II, is about to provide German scientists and industry with a powerful, scientifically attractive neutron source at the beginning of the new millennium. The concept of a compact, ^{235}U-enriched core allows the provision of high neutron intensity combined with the highest possible levels of safety and environmental compatibility. Being operated and placed in the heart of a university campus its usage is mainly dedicated to basic and applied research and education. However roughly 30% of its experimental capacities are intended to industrial use. Once the licence to start nuclear operation is granted a period of 10 – 12 months is necessary to tune FRM-II up to its full power of 20 MWatt and to achieve routine operation. Routine operation foresees 5 cycles of 52 days each per year.

Moderators, spectrum shifter and beams others than with neutrons

Special moderators optimize the flux density of the neutrons for various uses. At 20 MWatt thermal power an unperturbed thermal neutron flux of 8×10^{14} n/cm^{2}s is expected to build up in the D_2O moderator. In order to minimize the leakage of fast neutrons out of the biological shielding all 12 beam tubes have tangential orientations with respect to the core. A cold source containing about 30 lt. of liquid D_2 is located in the maximum of the thermal flux and feeds three beam tubes, one of them is particular wide and hosts six neutron guides of a cross section up to 6×17 cm^2 leading to the neutron guide hall. Another of these three cold beam tubes will contain a solid D_2 mini source at a temperature of 5 K. By down scattering ultra cold neutrons of typical wavelength of 1000 Å are produced. UCN densities of 10^4 per cm^3 are expected. Further a graphite hot source is placed in the maximum of the thermal flux and shifts the neutron spectrum to shorter wavelength. At the outer corner of the heavy water moderator thermal neutrons are converted to fast neutrons of MeV energy by fission reaction in a plate of about 300 g enriched ^{235}U. One beam tube faces to this converter and provides fast neutrons for tumor therapy and radiography with fast neutrons. One of the two inclined beam holes contains a Cd cladding. n,γ-reaction with the Cd provides an intense γ-radiation which converts by pair creation to positrons and electrons. The positrons are extracted electromagnetically, thermalised and yield an up to now unreached intensity of 10^9 – 10^{10} thermal positrons/cm^{2}s at the sample. One through-going beam tube penetrates the biological shielding from two sides. It will house 1 g of ^{235}U in order to produce fission products. Those will be mass separated and extracted to deliver an intense

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beam of fission products. The UCN source and the fission product beam are particular ambitious projects and will be finalized in the upcoming years. All other beams are ready for being taken into operation.

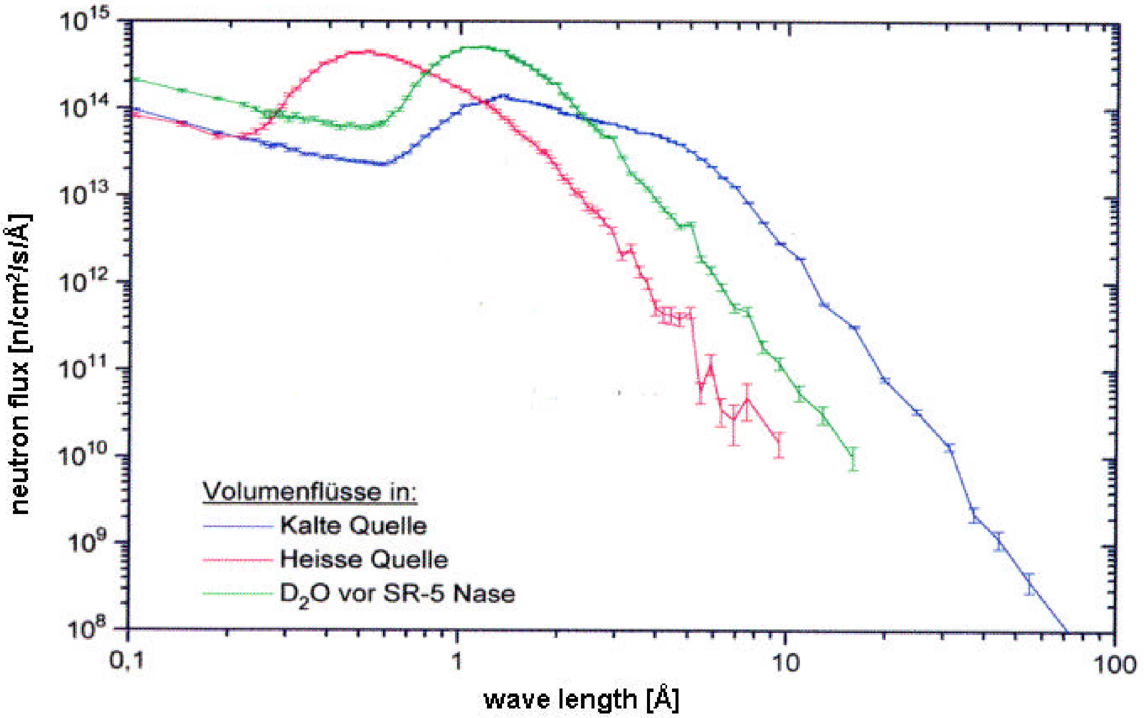

Fig.1: Perturbed spectral fluxes of the different moderators of FRM-II. Shown is the flux at the surface of the cold and hot source, for the thermal flux a reference point in front of a typical beam tube has been taken.

Irradiation facilities

With the emphasis on commercial use, five irradiation facilities will be ready when routine operation begins. The increasing use of radioactive isotopes in science and technology entails great flexibility in output. The various irradiation facilities arranged in the moderator tank have thermal neutron flux densities of between 5×10^{12} $cm^{-2}s^{-1}$ and 4×10^{14} $cm^{-2}s^{-1}$. A substantial advantage of these irradiation positions is the availability of a purely thermal neutron spectrum, in which the parasitic generation of undesirable radionuclides by threshold reactions or the occurrence of extended defect clusters through irradiation with fast neutrons is suppressed to the greatest possible extent.

Possible irradiation periods range from 1/10 second to 52 days of a cycle period for sample sizes from a few µg up to silicon single crystal blocks 20 cm in diameter and 50 cm in length. The rapid, pneumatically operated rabbit system exhibits a conveying time from the irradiation to the measuring position of approximately 300 ms; here, it is possible to perform spectroscopy of short-lived species such as ^{20}F ($T_{1/2}$ = 11 s) and even ^{207m}Pb ($T_{1/2}$ = 0.82 s). A second pneumatic rabbit system allows irradiation periods of between 30 s and 5 h. Long irradiation periods of up to several weeks are possible with the hydraulic capsule irradiation facility. As a result of the high flux density of fast neutrons, the position of the central control rod is the ideal production site for the positron emitter ^{58}Co. A particular example of future cooperation with industry is the production of homogeneously doped silicon; large Si blocks are irradiated in a homogeneous field of thermal neutrons, ^{30}Si being transmuted into ^{31}P.

Table 1:Irradiation facilities at FRM-II

Facility	**Sample Conveying**	**Thermal Flux**	**Irradiation Period**	**Positions**	**Maximum Sample Size**	**Packaging**
High-flux Rabbit Irradiation Installation (HFRP)	pneumatic (CO_2)	$4x10^{14}cm^{-2}s^{-1}$	0,5 ... 2000s	1	$1cm^3$	polyimide
Standard Rabbit Irradiation System RPA	pneumatic (CO_2)	$2x10^{13}cm^{-2}s^{-1}$ $2x10^{14}cm^{-2}s^{-1}$	minutes ... hours	1 x 3	$12cm^3$	polyethylene
Standard Rabbit Irradiation System RPA	pneumatic (CO_2)	$5x10^{12}cm^{-2}s^{-1}$ $1x10^{14}cm^{-2}s^{-1}$	minutes ... hours	1 x 3	$12cm^3$	polyethylene
Capsule Irradiation Facility KBA	hydraulic (pool water)	$4x10^{14}cm^{-2}s^{-1}$	minutes ... hours	2 x 5	$30cm^3$	$AlMg_3$
Silicon Doping Installation SDA	mechanic	$2x10^{13}cm^{-2}s^{-1}$	10 minutes ... 1 day	1	Diameter: 4 – 8 inches	-

Instrumentation at beam tubes

Neutrons are ideally suited to investigate the microscopic or atomic origin of modern functional materials. As a consequence most of the instrumentation at beam tubes or in the neutron guide hall are dedicated to material science. They are applicable to a large variety of materials and work pieces, ranging from metals to biomolecules, from engines to fuel cells.

Tumour therapy

The biological effect of high-energy radiation is based on the irreparable damage of the chromosome in living cells. Neutrons display an outstanding efficiency in this respect compared to conventional X-ray or gamma-treatment: both cords of the chromosome helix have to be cut in order to stop the self-repairing mechanism of a cell, and neutrons with their relatively high energy transfer to living matter are most effective for this purpose.

Neutron therapy is also advantageous in case of those tumours, where the supply of oxygen is highly reduced. Under hypoxic conditions neutrons are more efficient with regard to tumour cell kill than the X-rays used in conventional radiation therapy. Recurrent tumours in particular appear to be hypoxic.

In cooperation with the FRM, the department of radiation therapy of the Technische Universität München has been managing for several years a fast-neutron irradiation facility used for tumour therapy and basic research. There are very promising results for various types of near-surfaces tumours, especially in the region of the head and neck and for certain breast tumours, in cases of tumours with high resistance against X-ray-treatment, such as malignant melanomas, neutrons often

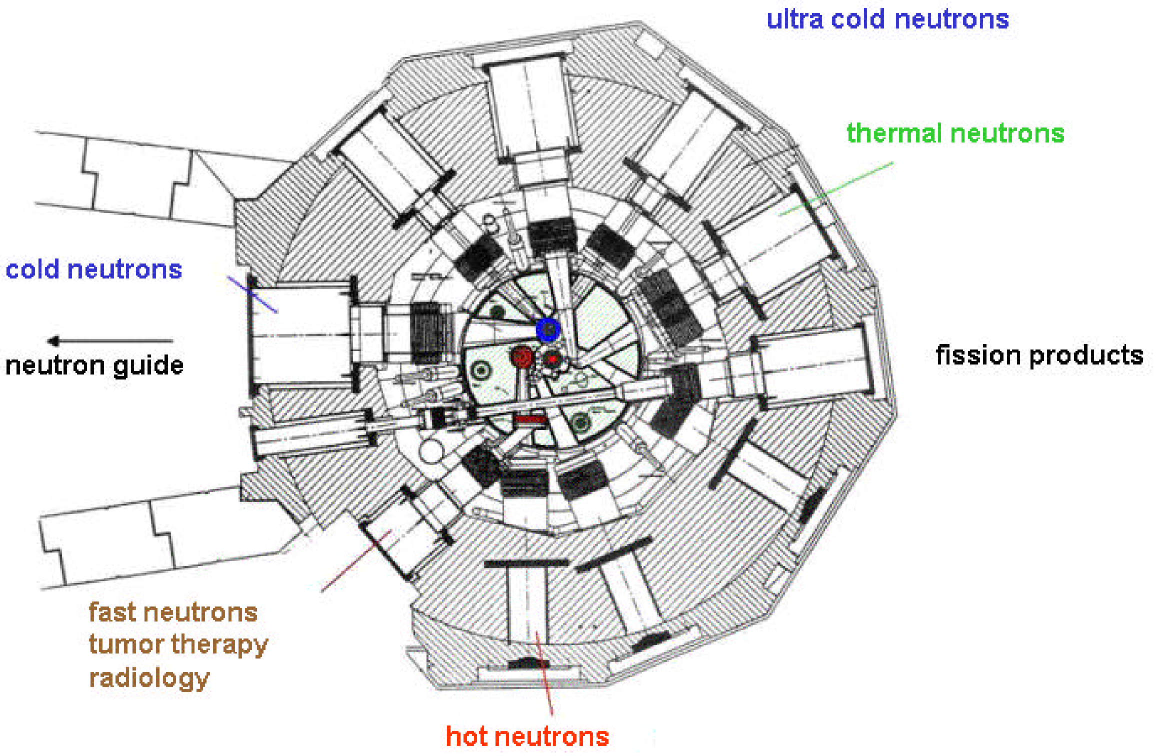

Fig.2: Cut through the compact core, moderator, biological shielding and vertical beam tubes.

show spectacular success. Until now, more than 700 patients were treated with fast neutrons at the FRM. In general this treatment is very well tolerated. For many patients a cessation of tumour growth has been achieved. Clinical application has proved that especially patients with highly differentiated salivary tumours benefit from neutron treatment.

The experience gained from the present neutron therapy at the FRM proved invaluable when it came to the design of the new facility at the FRM-II. Precise beam-handling, a large beam area, variation of the neutron energy and significantly higher intensity will now improve the therapeutic possibilities and will also furthermore promote research in this field.

Material science with positrons

The availability of thermal positrons with intensities in the order of $10^9 – 10^{10}$ p/cm^{2}s will enable new types of experiments. By position life-time measurements it is expected to detect the defect structure of surface layers of metals and polymers. A positron microbeam should enable a positron microscope in order to reveal plastic deformations in the vicinity of micro cracks or electrical transport damage of conductor tracks on microchips. Positron induced Auger electron spectroscopy allows to detect the electronic structure of the upper most monolayer of solids. Contrarily to the well established Auger spectroscopy by electron beams this new method detects its signal free of background.

Neutron radiography and tomography.

The installation for radiography and tomography with fast and thermal/cold neutrons allows non-destructive investigation of many different samples to address scientific and industrial problems. Such problems include the determination of hydrogen-containing substances (oils, plastics) in (large) metallic objects, the detection of cracks and the general determination of the distribution of linear attenuation coefficients in unknown samples. Practical applications include elemental analysis of large volume samples, filling level measurements, corrosion testing for aerospace systems and defect analysis in composite materials.

Two radiography/tomography installations are built for applied research and industrial use at FRM-**II**. The two installations use different neutron spectra and are designed for illumination with thermal and fast (fission) neutrons. Due to the differing neutron cross-sections for nuclei in the two energy ranges, the results from the two installations are complementary. With a collimation ratio of L/D = 325 and L/D = 650 and intensities of approx. 1.2 x 10^8 and 3 x 10^7 $cm^{-2}s^{-1}$, the thermal/cold neutron installation will be outstanding, while the fast neutron installation with its fission spectrum and an intensity of approx 2 x 10^8 and 7 x 10^7 $cm^{-2}s^{-1}$ at L/D = 100 and L/D = 200 will also be excellent.

In conjunction with Garchings's existing gamma tomography installation, the new installations will provide excellent facilities for the non-destructive determination of matter distributions in objects of the most varied size and composition.

Table 2:Tumor treatment, positrons and radiography/tomography at FRM-**II**

Name	**Type**	**Remarks, special features**
Medapp	cancer irradiation	fast neutrons with MeV energy, large irradiation field of 20 x 30 cm^2, tumour therapy on clinical level
Positron	Positron Source	intense beam of thermalized positrons, can be switched to 6 different experiments like positron lifetime measurement, Auger spectroscopy, defect microscope etc.
Antares	Tomography	cold and thermal neutrons, large (high resolution image plate) and fast (CCD camera) area detectors for kinetic measurements
Nectar	Tomography	fast neutrons (converter facility) optimized for large or hydrogen containing objects

Elastic neutron scattering

Measuring elastically scattered neutrons under small and large scattering angles reveals the position of atoms and molecules. At FRM-**II** this is done in a wide range of applications: reflectometry to determine lateral and perpendicular structures of surfaces from sub- Angström to 1000 Angström, powder diffraction to determine the position of atoms in new upcoming materials like high-T_c-supraconductors, single crystal diffraction with thermal and hot neutrons for the structural analysis of ceramics, catalysts or proteins. One diffractometer is dedicated to texture and internal stress analysis. Several of these diffractometers can operate with polarized neutrons, i.e. are best suited to detect magnetic structures. All these diffractometers use new technologies like large area image plate detectors, super mirror guides with focussing optics or ^{3}He spin filters for wave length independent spin definition and analysis. Table 3 summarises the diffractometers which will be available with the start of routine operation.

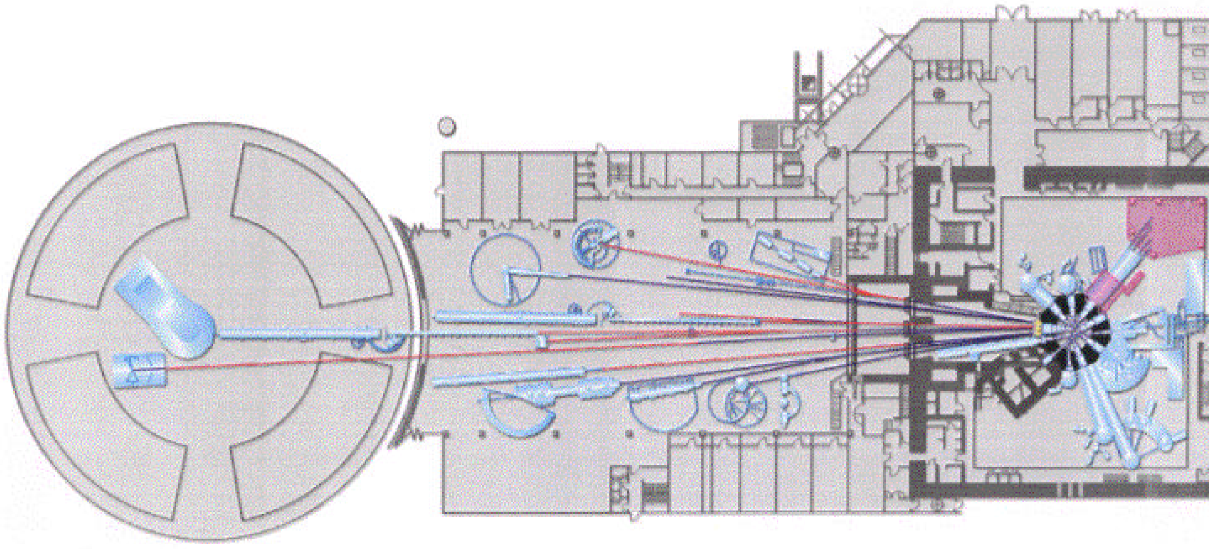

Fig.3: First generation instrumentation at FRM-II. From left to right: the old FRM, neutron guide hall and experimental hall with the compact core and biological shielding.

Table 3: Diffractometers and reflectometers at FRM-II

Name	**Type**	**Remarks, special features**
Spodi	Powder diffractometer	thermal neutrons, optimized for high resolution experiments. 80 linear position sensitive detectors, small angle scattering option
Resi	Single crystal diffractometer	thermal neutrons, optimized for low background, uses large area image plate detector, structure analysis and diffuse scattering
Heidi	Single crystal diffractometer	hot neutrons, large momentum transfer for structural analysis
Stress-Spec	Materials diffractometer	high thermal flux, dedicated to stress and texture measurements, small probe volume smaller than 1 mm^3 inside the sample volume
MatSci-R	Reflectometer	cold neutrons (guide hall). horizontal or vertical sample position, optimized for material science
Refsans	Reflectometer	cold neutrons (guide hall), time of flight mode, liquid samples, SANS detector, kinetic experiments
Mira	Reflectometer	very long wave-length neutrons (guide hall), flexible instrument for developments of new neutron techniques and reflectometry with long wave length neutrons

Inelastic neutron scattering

To know how the atoms move is of crucial importance in order to understand their functional properties. For example supraconductivity, i.e. the coupling of electrons to Cooper pairs which move through the lattice without any resistance is mediated by internal vibrations. Or the properties of viscous liquids are determined by the diffusive motion of its constituents.

Measuring the energy gain or loss of scattered neutrons reveals the time and spatial scale of these internal motions. Analyzing the scattering angle and the energy gain or loss of the scattered neutrons goes on the expense of measuring intensity. FRM-II with the high flux for cold neutrons is best suited for this kind of instrumentation. A set of 6 instruments each of them with a particular compromise between intensity at the detector, time and spatial resolution and eventually spin analysis are set up. Smallest energy transfers and thereby longest time scales of ~ 30 ns are measured by the spin echo spectrometer. Backscattering technique provides much more intensity in the detector with only slightly reduced energy or time resolution when compared to spin echo. Time-of-flight spectroscopy with cold neutrons guarantees large dynamical ranges by a background suppression in the order of $10^5 – 10^6$. Triple axis spectrometry with cold, thermal and polarized neutrons allows highest flexibility in the 4-dimensional space-time frame. All these instruments profit from new technologies. Intensity at the spectrometers is optimized by focussing neutron guides using supermirror techniques up to a glanzing angle 4 times that of natural Ni. Background by fast neutrons is suppressed by single curved or S-shaped guides. Highest polarized intensity is achieved by using polarized guides and spin analysis will be done by ^{3}He filters. For the first time higher order contaminations in triple-axis spectroscopy will be suppressed by a fast tuning selector down to wavelength of 1 Å. The chopper disks of the time-of-flight spectrometer use magnetic bearings and are made of carbon fiber, thereby allowing rpms far beyond those possible with metallic disks. Table 4 lists the instruments available for inelastic neutron scattering.

Table 4: Instruments for inelastic neutron scattering available at FRM-II

Name	***Type***	***Remarks, special features***
Reseda	Resonance-spin echo spectrometer	cold neutrons (guide hall), very high resolution with resonance-spin echo technique. Two analyser arms
RSSM	Back scattering spectrometer	cold neutrons (guide hall), optimized for high flux (phase space focussing) and high energy resolution
TofTof	Time of flight spectrometer	cold neutrons (guide hall), optimized for high flux and low background, large detector area
Panda	Three axis spectrometer	cold (polarised) neutrons, optimized for high resolution and magnetic scattering experiments
Puma	Three axis spectrometer	thermal (polarized) neutrons, optimized for high intensity at the sample position. Velocity selector to suppress higher order contamination of incoming beam, multi-analyser option
NRSE-TAS	Three axis spectrometer	thermal (polarized) neutrons, high resolution by resonance-spin echo addition Spin-echo focussing for dispersive modes

Instruments in progress

Further instruments are in progress and will be achieved in a rhythm of about one instrument per year. For nuclear physics a beamline using polarized and focussing supermirrors will be in operation late 2004. A diffractometer for biological structures and an intense small angle camera allowing spin analysis are in the concept phase. Similar holds for a Prompt Gamma Analysis (PGA). International collaborations pursue the two major projects for particle and nuclear physics, the Munich Accelerator of Fission Fragments (MAFF) facility and the source of Ultra Cold Neutrons (UCN). Altogether FRM-II can host 30 – 35 instruments, almost all of them at intense end positions of beam holes or neutron guides.

Summary

The Munich research reactor FRM-II will be the most powerful neutron source in Germany. Optimization of the source on one hand and the instrumentation on the other is intended to provide the possibility of cutting-edge neutron research. As a high-intensity neutron source, FRM-II is one of Germany’s contributions to international scientific cooperation and competition.

All beam tube facilities remote from the core, e.g. diffractometers and spectrometers are installed and will be operated by user groups. These user groups come from the universities, the Max Planck Society, the Helmholtz Society and the Leibnitz Society. The financial and personnel resources have been provided from FRM-II project funds, national funding and research group budgets. This approach of involving potential users in installation and operation, in particular ensures the general integration of FRM-II into the overall scientific landscape.

Bearing in mind the twin aspects of commitment to cutting-edge research and the need to develop young scientific talent in the field of neutron research, beam time for scientific use will be allocated according to the following principles:

- Measurement time for research intended for publication will be made available free of charge
- Visiting scientists who wish to perform experiments at FRM-II will be allocated measurement time on the basis of an application examined by a committee of experts. All applicants will enjoy equal rights.
- In general the local contact should participate as an author in publications which emerge from experiments done at FRM-II. In any case FRM-II has to be mentioned in prominent form.

References

Technical details of the neutron source FRM-II and its instrumentation are available on the web pages of FRM-II: www.frm2.de

Further a booklet “Experimental facilities at FRM-II” is available upon request from

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