High Resolution Powder Diffractometer Facility (HRPDF) for Low and Medium Power Research Reactor

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Abstract: The present paper suggests a design of a High Resolution Powder Diffractometer Facility that fits the low and medium power research reactors. The design choice guarantees an acceptable cost of high standard facility. Several components could be home-made. The design then contains detailed information about the components available in the market. It is highly recommended carrying out Monte Carlo simulations of realistic expected luminosity and resolution parameters of the finally designed and approved instrument in advance. Monte Carlo simulations can eventually show which components should be modified in order to achieve the expected resolution and luminosity parameters of the facility.

Keywords: high resolution powder diffractometer, Design, Construction, Low and medium research reactors.

I. Introduction

This study presents a detailed recommendation on the design of a High Resolution Powder Diffractometer Facility (HRPDF) as one of the research facilities that can be constructed at any low or medium research reactor. This work targets the interested scientists, engineers and decision makers so they find in one place the main elements and components of the HRPDF.

The principles of operation of HRPDF are similar to X-ray diffraction [1, 2]. Contrary to X-rays, most scattering of neutrons occurs at the atom nuclei, thus providing information not accessible with X-rays. The neutron furthermore carries a magnetic moment, which makes it an excellent probe for the determination of magnetic properties of matter. In the majority of cases, diffraction is the main mechanism of the interaction of neutrons with matter. This is why powder diffraction experiments are perhaps the most straightforward among all neutron scattering techniques.

The most common information typically extracted from HRPD experiments includes the symmetry of crystal lattices, the dimensions of the unit cells of the crystal structure and, hence, the elemental composition. Additionally, the fractional coordinate and occupation factor of the atom within the unit cell can be extracted with typically very high precision, providing reliable information on the interatomic bond distances, angles and thermal displacements of atoms. Finally, microstructure parameters characterizing the grain size distribution and microstress in the crystal lattice may also be determined. The reader can consult with the available literature on the subject, for example reference [3] on Uranium Oxide study.

In addition, the ability of a neutron to penetrate a material makes it ideal for in-situ experiments using sophisticated sample environments. This allows measurements at low and high temperatures, in electric and magnetic fields, and under varying pressure values.
Examples include study of phase transitions with temperature, geological samples under pressure, magnetoresistive materials, magnetic transitions at ultra-low temperatures, etc. Many important compounds involve light isotopes such as Hydrogen, Helium, Deuterium, Lithium, Carbon, Nitrogen and Oxygen. The neutron's sensitivity to such elements and the difference in scattering between isotopes means neutron powder diffraction plays an important role in determining the structural features of compounds with these elements. Examples include ceramics (oxides), Li batteries, magnetoresistive materials, hydrogen storage materials, superconductors, zeolites, and so on. Magnetic structures can be studied using neutron powder diffraction due to the magnetic interaction between the neutron and local magnetic moments in the compound. Examples include rare earth hard magnets, molecular magnets, correlated electron systems, magneto-elastic coupling, and so on [4].

In the following a design of the neutron powder diffractometer is introduced. Approximate cost of individual components that contributes to the total cost of the facility can also be provided in the references. However, the total cost of constructing a HRPDF is varying from country to country and is impacted by more than one factor such as manpower and labor, local input of shielding and building material such as concrete and steel, and licensing cost…etc. However, the major constituents of the cost come in the form of purchase price of the main components, which is in the range of one million US dollars. As the cost of establishing a HRPDF can be justified by the advantages of having such a facility, the main purpose of this paper is focused on the basic performance based on a very effective simple solution as used in [5], which can be extended and/or supplemented with other components according to alternatives and a choice on the market. As can be seen from the schematic layout in Fig. 1, the diffractometer consists of the main following units; monochromator unit, collimators, sample table and detector system. The monochromator accepts the white neutron beam from a polychromatic neutron source. The monochromatic beam shutter enhances the personnel safety and reduces radiation exposure. The shutter must be custom designed to be appropriate for the radiation burden in the beam and for the mechanical constraints of the instrument installation. Sets of collimators determine divergence of the beam which then has an influence on the diffractometer resolution. The detector records the scattered neutrons through a specific scattering angle. In a modern instrument the neutrons are recorded in Position Sensitive Detectors (PSD). The reader can consult with the available literature on PSD, reference [6] as an example. Shielding plays a crucial role to remove the undesirable neutrons as well as $\gamma$-radiation. The choice of shielding requires special attention in order to achieve an acceptable level of neutron and gamma background.

FIG. 1. Schematic layout of neutron diffractometer installed at steady state source.
II. Main Components of the HRPD

The facility should be designed and constructed in such a way that it can meet its objectives and goals. Therefore, the instruments and tools should be carefully identified with the proper specifications such that they support each other and work in unison to give the best performance. The HRPD instrument should consist of the listed below three main components. These components should be competent with each other, and should contain every single essential part.

II.A. Neutron Beam Related Components:

The beam transferring components should safeguard delivering sufficient, clean and focused neutron beam from the source. In addition, these components should make sure that the working environment is radiological safe. The main components are:

1. Beam shutter: The beam shutter should guarantee acceptable dose rate level at the reactor hall when the neutron beams are not in use. This is a very important criterion at the stage of designing the HRPDF in an open pool research reactor where the neutron beam is carried out from the reactor pool to the experimental hall.

2. Neutron filter: The neutron beam filter should reduce as much as possible the contribution of fast neutrons and gamma background spectra at the beam port of the HRPD. Therefore, the material used in the manufacturing process should be carefully selected in order to deliver clean thermal neutron beam.

3. Neutron collimators: Collimation has strong impact on the resolution and intensity of the measurement. The collimators set the divergence in the horizontal and vertical directions to produce clean, coherent, and sufficiently intense beam. In order to obtain high instrumental resolution, it is necessary to use a radial collimator, which is to focus the diffraction pattern. See for example the simulation of collimation in [28] presented in Fig. 3.
4. Beam line shielding: shielding in diffraction experiments plays critical role in safety of the environment and quality of the experiment. There are more than one source of background radiation and noise such as scattering of the thermal beam, large divergence of fast neutrons and \(\gamma\)-rays at the beam port and the incoherent scattering of thermal neutrons at the experimental station. More than one option in shape and material can be used to construct the shielding walls and blocks, for example the C and H shape bricks as shown in Fig. 4.

![FIG. 4. Sketch of C and H shape shielding bricks.](image)

5. Neutron monochromator unit including the slit systems: The basic function of the monochromator is to diffract the neutron beam at a particular wavelength into a particular angle through the successive beam apertures from the core to the beam port. As the angle-dispersive methods at constant wavelength are used to measure the powder diffraction pattern, a single wavelength is selected from the white beam using a single-crystal monochromator such as Cu, Be, Ge or Si. The latter two crystals are the best since they have high resolution for the perfect crystals.

![FIG. 5. Self-explanatory monochromator made of Ge crystal.](image)

The monochromator should be placed in a house of a proper material in order to protect it from damage in case of a structural failure in the main beam line. The material type and thickness of the housing should be able to withstand the ambient vacuum pressures and to transmit the neutron beam with the desired wavelengths. Generally speaking, the materials and components of the HRPDF should be of grades and types according to the specifications in reference [12]. Collimation slits serve to determine the angular resolution. They must cover the desired range of dimensions with proper accuracy.

6. Sample positioning: This term refers to the accurate alignment of the sample with the collimated beam and with the detector system. The alignment can be achieved using various methods such as optical, mechanical or using neutron curve scan. The alignment requires table that can be moved on x-, y- and z-axis.
7. Detector system: For neutron detection a low background and high thermal neutron sensitivity, combined with a good localization of the detection event is essential. $^3$He based detectors with a proper sensitive area can cover the diffracted beam under almost all measurement conditions.

8. Shielding: The main function of the shield is to protect against the unwanted radiation, protect against damage and against fields such as thermal and electromagnetic radiation. Therefore, there is a need for thick shielding walls, or/and exclusion zone around the facility building and the instruments such as the neutron source and detectors.

Generally speaking, shielding has to be designed to satisfy the aforementioned functions. Because the fission process produces high energy neutrons, the primary shielding of the source is rather thick. In addition and in order to absorb the unwanted radiation, a massive monochromator shielding for example should be designed. Therefore, the monochromator shielding with easy maneuvering blocks should be used. The shielding can be home-made of a mixture of polyurethane and boron carbide. However, it should be noted that shielding can significantly reduce the active solid angle and is difficult to design and manufacture, and hence should be carefully handled.

9. Electronics and softwares: In experimental sciences, good experimental data provide good results of the experiment. Neutron powder diffraction technique can be used for various experimental objectives. For example, experiments on crystallography can provide information on crystal and magnetic structures of materials, thermal and electromagnetic properties, mechanical properties…etc. These requirements justify spending some extra money and efforts to carefully selecting the appropriate electronics and softwares in order to achieve the objectives of the experiment. Among many other things, a compatible and friendly user softwares and proper electronics to tackle the data such as acquisition and analysis should be used.

II.B. Sample Environment Depending on the Planned Experiments:

Sample Environment term is used to point out to equipment used in accurately controlling the experimental parameters such as temperature, pressure and magnetic fields, cryostats, furnaces,… etc. These are essential and common in scattering experiments in order to fix the sample and keep its conditions such that. The below sample environment equipment are necessary for the current design:

1. Goniometer heads
2. Eulerian cradle
3. Powder sample containers
4. Cryogenic device
5. Furnace apparatus
6. Tension/compression rig

II.C. Accessories Including Monte Carlo Simulations:

Powder measured diffraction patterns contain instrumental as well as sample contributions. Monte Carlo simulation of the interaction of neutrons with atoms is a powerful tool allows following the history of the individual neutron from its creation until detection, and hence, taking the instrumental as well as the sample contributions into account. The simulation should take in to account the effect of the main components such as the moderator on the flux, neutron guide, neutron detectors, collimators … etc. It is not the purpose of this report to carry out simulations. However, the necessary simulations using one of the neutron tracing softwares such McStas [25] should be carried at the proper time of implementing the design.

III. Recommended Systems, Equipment and Material for the Main Components of the HRPD

The recommended diffractometer consists of a monochromator unit and two large goniometer circles. The smaller one provides sufficient space for placing the various sample environments. The detector bank is mounted in a molded neutron shielding made from boron carbide ($\text{B}_4\text{C}$) powder in epoxy resin [8]. The detection bank contains thirty five $^3$He point counters with corresponding 10' Soller collimators [9]. They are all individually adjustable and set at angular intervals of 4.00° in 2θ. The bank moves on air pads, which provides together with the stepping motor smooth positioning of this heavy loaded bank. Diffraction patterns can be collected in the angular range from 2 to 148 degrees in 2θ with step down to 0.02° and step delay controlled by
strict time or neutron flow read by monitor. As an option, a two-dimensional PSD or an array of several one-dimensional PSDs can be used. Depending on the construction of the monochromator unit, several individual wavelengths of the secondary beam can be selected for measurement. Concerning the monochromator unit, as an example, a simple vertically changeable monochromator system can be used. Another choice of doubly focusing monochromator system can be used. This option can be useful for several individual neutron wavelengths [8]. In the following, description of the material and equipment is presented:

1. Shielding Walls

Shielding walls can be constructed from C and H shape polyethylene bricks containing 3-5% of \( \text{B}^{10} \). One wall requires several bricks of C of standard dimensions (25, 8, 12) cm put together in four layers and then inserted into a frame.

2. Radiation Shielding Solid Lead Bricks

For radiation, solid lead bricks of \( \text{PbSb}_3 \) can be used to make shielding walls. It is highly recommended using two layers of bricks around the neutron collimator inside the concrete shielding before the monochromator. \( \text{B}_4\text{C} \) sheets can be used as an alternative shielding material [10]. Cadmium (Cd), plates can be costumed for apertures, diaphragms, slit blades and shutters [11]. It is recommended to cover the concrete beam housing by one centimeter thick Boron-carbide sheets. Table 1 presents the nuclear density, capture cross section, scattering cross section, attenuation cross and fraction absorption after 10 cm, respectively, for various shielding materials for fast, 2 MeV neutrons.

### Table 1. Nuclear density, capture cross section, scattering cross section, attenuation cross and fraction absorption after 10 cm, respectively, for various shielding materials for fast, 2 MeV neutrons

<table>
<thead>
<tr>
<th>Material</th>
<th>Nuclear Density (Nuclei/cm(^3)) (\times 10^{22})</th>
<th>(2 MeV) (\sigma_c) (cm(^2)) (\times 10^7)</th>
<th>(2 MeV) (\sigma_s) (cm(^2)) (\times 10^3)</th>
<th>(2 MeV) (\sigma_a) (cm(^3)) (\times 10^3)</th>
<th>Fraction attenuated after 10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{H}_2\text{O})</td>
<td>3.346</td>
<td>8.36</td>
<td>0.1673</td>
<td>111.1</td>
<td>~ 52%</td>
</tr>
<tr>
<td>(\text{Li}^6)</td>
<td>5.33</td>
<td>5.33</td>
<td>0.1066</td>
<td>2.052</td>
<td>~ 54%</td>
</tr>
<tr>
<td>(\text{Li}^7)</td>
<td>4.59</td>
<td>1.97</td>
<td>0.0597</td>
<td>3.216</td>
<td>~ 41%</td>
</tr>
<tr>
<td>(\text{B}^{10})</td>
<td>1.391</td>
<td>1.11</td>
<td>0.01391</td>
<td>6.955</td>
<td>~ 84%</td>
</tr>
<tr>
<td>(\text{Cd}^{114})</td>
<td>4.565</td>
<td>5.21</td>
<td>0.002</td>
<td>2.803</td>
<td>~ 49%</td>
</tr>
</tbody>
</table>

3. Neutron Detection System

Neutrons cannot be detected directly. Indirect detection involves the interaction of the released neutrons with the material releasing charged particles and inducing ionization current. Therefore, material with high absorption neutron cross can be used for neutron detection. \(\text{BF}_3\) and \(^3\text{He}\) are the main gas detectors because of their high absorption cross section. For HRPDF, more than one alternative can be used:

1. The use of a multidetector system [12] or
2. The use of one or two pieces of two-dimensional PSD covering a reasonable range of scattering angles. In both cases, it is recommended to purchase the whole system.

A rather easier and cheaper way for building the detector system is to use two pieces of 2d-PSD, each situated to a massive shielding as shown in reference [13]. Fig. 6 presents one detector shield and one 2D detector, 2d-PSD (20 cm x 20 cm active area) made in Frank Laboratory of Neutron Physics, JINR, Dubna, and the NPI Řež made.

4. Aluminum Construction Profiles

A complete range of modular system products - made by the German-based item Industrietechnik und Maschinenbau GmbH, are available in the market [14]. This system is based on precise anodized aluminum profiles with longitudinal grooves and holes for mounting the connecting elements and extensive accessories; surface is corrosion- and abrasion resistant.

The concept of the system allows considerable flexibility, high precision and strength, and fast convertibility and opportunity to re-use various elements of the system. The profiles with the air pad systems can be effectively used for the detector system support as well as for easy movement of the detection unit in the scattering plane around the sample.
Calculation of the Electric Quadrupole Moment of and in Shell Model and Cluster Model

5. Cryostats for Neutron Scattering [16, 17, 18, 19]

For short-duration experiments (one day or less), the simplest cryostat system is a small continuous flow. This type of cryostat is connected to storage Dewar for the length of the experiment. This type of systems is designed for operation down to ~5 K, with short excursions to lower temperatures down to 2 K. The sample is placed in the vacuum space of the cryostat. The system can be easily built with an aluminum vacuum shroud suitable for use with neutrons.

This short-duration system can also be of a liquid helium cooled type with a built in reservoir for the cryogens. It is typically built with a sample tube with static exchange so the user can stay away from systems with flowing liquid helium in the beam path. Another cooling option is to build a closed cycle refrigerator system, which is suitable for operation down to ~4 K. In this unit the sample is located in the vacuum space of the cryostat and must be warmed up in order to change the sample. Note that the system uses a large cryocooler rated to have one Watt of cooling power at 4.2 K. It is worth noting that other models of cryocooler are available in the market, which are lighter-weight and lower-priced but these come with less cooling powers.

For long periods of experimental time, closed cycle refrigerator system for operation down to ~4 K can be used. This type is a top loading system so the sample can be changed while the cryostat remains cold.

The PTSHI-950T cooling system is similar to the SHI-950T [16] such that it is a top-loading closed cycle refrigerator system, but it is configured for continuous operation below 2 K.

The sample is in static exchange gas and has a separate helium gas circuit, which provides the sub-2 K cooling.

6. Neutron Monochromator Assembly [12]

The monochromator system is ~ (13.03, 19.05) squared centimeter and consists of nine silicon blades, which are mechanically bent in the horizontal plane. The monochromator is mounted with the [110] plane vertical axis so that all of reflections of the [110] zone are accessible. Several of these reflections are useful for neutron diffraction. The [115] 1.478Å, [113] 2.316 Å and [335] 1.171 Å reflections can all be accessed by simple rotations of the monochromator, assuming fixed 90° take-off angle. The [331] 1.762 Å and [551] 1.075 Å reflections can be accessed by “flipping” the monochromator and mounting it with the top and bottom swap. The monochromator goniometer should consist of a translation, rotation and tilt stepper motor.

The Popovici monochromator is a doubly bent perfect single focusing silicon crystal [20] is composed of nine slabs of perfect single crystal Silicon cut from a single wafer with nominal dimensions of (1.45, 0.053,19.05) cm.

For a 90° take-off angle, the reflections and wavelengths accessible for the monochromator are: [113] 2.316 Å, [115] 1.478 Å, [335] 1.171 Å, [117] 1.075 Å, [331] 1.762 Å, [551] 1.075 Å. The most intense reflection is from the [115] plane although the other reflections are also useable for diffraction experiments.
7. Sample Goniometer

A two-theta rotation, tilt and translation motions needed for aligning the monochromator in the white beam should be provided.

In order to perform neutron powder diffraction experiments in special environment chambers (cryorefrigerators, cryostats, furnaces, etc.) as well as to reduce environmental background, it is necessary to suppress the scattering from vacuum and heat shield walls that are external to the sample itself. The Radial Oscillating Collimator (ROC), which must be well shielded, is used to accomplish this task [12,21]. The ROC has thirty-six of (145,86,0.13) mm stainless steel blades separated by an angle of 1.25° and coated with neutron absorbing paint. They are radially oriented and can effectively prevent scattered neutrons at a distance larger than two centimeters from the sample position from reaching the detector. The front and back faces of the ROC are covered with 0.6 mm thick Cadmium metal shielding bonded to thin aluminum plates.

8. Linear Position Sensitive Neutron Detector Assembly

It is recommended using eleven position sensitive neutron proportional counters containing Helium and Argon gas. The detector tubes are clamped onto plane array that is mounted in the detector shield. Appropriate decoding electronics, software, interconnecting cables, and high voltage bias should be supplied. Also, a Position Encoding Module (PEM) to determine event position in linear position sensitive proportional counters must be installed [12,22]. An appropriate Neutron Diffractometer Control System (NDCS), for example, from Instrumentation Associates in reference [12], should be integrated in the system.

9. Power Module: PWR

A wide NIM bin that supplies preamplifier power to the detector array should be provided from [12], as a possible provider. The PWR module supplies clean +/- 6 V from 2 DB-9 connectors mounted at the back of the module. One PWR module can supply power for up to 15 detector elements (30 preamplifiers). The PWR module also contains a detector preamplifier that can be used to exercise PEMs. Two BNC connectors at the back of the module and two BNC connectors on the front of the module are connected to the internal preamplifier. A single input BNC connector at the front panel is a pulser to test input signals.

10. Position Encoding Module (PEM)

The Position Encoding Module (PEM) described in [12] was developed specifically to determine event position in fully equipped linear position sensitive proportional counters. It is a wide NIM device that accepts signals from the detector preamplifier, digitizes them and calculates the event position from the ratio of the signal amplitudes. It maintains pulse height and event position histogram in its internal memory and delivers the information to the instrument host computer via USB bus on command. One PEM is used to service the signal from a single detector element. Appropriate softwares with the source codes can be provided. The PEMs provide the event positions as “position spectra” and these must be related to the instrument geometry and detector calibration in order to convert them to angular histograms and to combine the data from all PEMs and detector elements.

11. Detector Shield

The large size and high efficiency of the linear PSD array requires an effective shield. The shield can be composed of high density polyethylene, borated polyethylene and lined with cadmium metal. Fig. 7 presents sketch diagram of 15-element detector shield. It is composed of high density polyethylene, borated polyethylene and is lined with cadmium metal [12].

The detector array can be moved within the shield assembly to two different distances from sample position: typically 1.6 m is used as the sample-detector separation for the highest resolution with 24” (61 cm) long detector elements. At this distance, the detector spans 20° two-theta. The detector can also be placed at 1.05 m from the sample, spanning 30° two-theta at somewhat lower resolution. Data acquisition at the 1.05 m detector distance is nominally 2.6 times faster than that at the 1.6 m detector distance using the three mm sample holder. The detector array is mounted on rails inside the shield assembly and has two preset locations set by mechanical stops. At the top of the shield there is a slot for the insertion of a precision comb mask for detector calibration. The detector can be serviced without the need to remove the array from the shield.
A scintillator-CCD neutron camera should be provided to facilitate alignment of the sample with the neutron beam. Generally, neutron camera/beam visualization used to visualize the monochromatic beam, exit slit and sample position greatly increases the efficiency of adjusting the diffractometer for different experimental conditions. The neutron camera can be used with a small LCD TV-type display or with a frame-grabber module that can provide images to the host instrument computer for enhancement or record keeping.

12. High Temperature Furnace

The central portion of the furnace should consist of a tube (stainless steel: melting point 1510 °C, boiling point 2750 °C for lower temperature operation, alumina: melting point 2072 °C, boiling point 2977 °C for higher temperatures [18]) into which the sample is lowered (with appropriate heat shields on the sample down-rod). The diffractometer design requires that the central tube be filled with a static gas (typically Argon) but a minor modification to the design will allow for continuous controllable gas flow, with the gas introduced below the sample and vented at the top [12]. A high vacuum pumping station is required for both the furnace and low-temperature sample environment. Two heaters surround the central tube, one above and one below the sample location. These are potted super Kanthal (or similar) elements that can be operated above 1000 °C [23]. A type K thermocouple (sensor containing Chromel and Alumel conductors that meets the output requirements as stated in reference [7]) is mounted on the surface of each heater closest to the sample, while two additional thermocouples are mounted to the top and bottom of the sample can. A heat shield surrounding the heaters and one or more additional heat shields (depending on the operating demands) can be at larger diameters inside the vacuum space. The shell of the furnace is made of aluminum. In general, samples are changed without breaking the vacuum, so the lifetime of the elements in the vacuum space should be quite long. The furnace controller is fully integrated into the control system, but can also be operated in stand-alone mode to produce the calibration data.

13. Cryorefrigerator System

A low temperature sample environment cooling system based on an Advanced Research Systems (ARS) with integrated software should be provided [12]. The system should control the temperature between room temperature and 10 K°. It should be designed to mount on the sample-table X-Y translation at the proper height for neutron diffraction data acquisition. Samples are placed in an aluminum can, sealed with indium O-rings and mounted to the end of the cold-head cold-finger. Two exchange-gas sample cans should be available. The cans are normally filled with compressed helium gas before the indium O-rings.

14. Furnace System

A top loading furnace designed to operate between room temperature and (conservatively) 800°C, is recommended. This furnace has a center zone that opens from top to allow sample insertion and removal without breaking the vacuum around the heater elements. The center
A microprocessor controlled stepper motor drivers appropriate for the monochromator goniometer and ROC motions is recommended. These stepper motor controllers should communicate with the user instrument control computer via software.

16. Vacuum System

A microprocessor controlled diaphragm backing pump, turbomolecular pump integrated vacuum station with vacuum gauges, vacuum valves, connecting tubes and fittings should be supplied for pump-out of the cryorefrigerator and furnace peripherals.

IV. Conclusion:

The present paper suggests a suitable design of a high resolution powder diffractometer facility that can be built at any low or medium multipurpose research [26]. The design is simple, low cost, and can use the available instruments and tools in the market. Nevertheless, the facility can only be operated efficiently when ancillary equipment are provided. In this context, it is worth mentioning that the complete neutron diffractometer is supplemented by a variety of additional components that should be included to obtain the functionality of the instrument. None of these elements are “optional” in the sense that they should be included for a proper functioning of the instrument. Examples of the ancillary equipment are:

Neutron Beam Monitor and Support Electronics: A low efficiency neutron detector, placed directly in the beam line upstream of the specimen position, is usually used to control the duration of neutron scattering experiments.

Interchangeable Monochromatic Beam Slits and Slit Holder: A set of interchangeable monochromatic beam slits is used to limit the beam so that only the sample is exposed.

Recirculating chillers with good cooling capacities covering range from 0.3 kW up to 20 kW, for example. The FL11006 Recirculating Cooler [24] can be provided.

Finally, Monte Carlo simulation is inevitable for the design and construction of a HRPDF to be complete. However, for each neutron source there are particularities should be taken in to account, see for example the Jordan Research and Training Reactor [27]. Therefore, the simulation has been left to a later stage of the decision. A possible layout of the HRPDF can follow the facility arrangement of the North Carolina State University presented in Fig. 8. Because Also, the reader can note that the introduced parts and components are essential for each HRPDF, which is the main theme of this report, and the design can accommodate and satisfy the researcher needs for various applied sciences, and can be easily developed to satisfy the future needs of the researchers in any field of research.

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Calculation of the Electric Quadrupole Moment of and in Shell Model and Cluster Model

FIG. 8. Layout of North Carolina State University HRPD

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