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HIGH-BRILLIANCE NEUTRON SOURCE PROJECT

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Abstract

The High-Brilliance Neutron Source (HBS) project aims to design a scalable compact accelerator driven neutron source (CANS) which is competitive and cost-efficient. The concept allows one to optimize the whole facility including accelerator, target, moderators and neutron optics to the demands of individual neutron instruments. Particle type, energy, timing, and pulse structure of the accelerator are fully defined by the requirements of a given neutron instrument. In the following, we present the current status of the HBS project.

INTRODUCTION

The neutron landscape in Europe is in a time of change. On the one hand, the European Spallation Source (ESS) is being constructed as world-leading neutron facility but on the other hand many research reactors used for neutron experiments, like the BER-II reactor in Germany or the ORPHEE-reactor in France, are fading out [1]. The European community for neutron research is therefore facing a mixed outlook towards the availability of neutrons in coming decades. As new reactor sources or spallation sources are costly and therefore difficult to realize, new possibilities for neutron production need to be investigated.

In the HBS project we are developing a scalable compact accelerator driven neutron source (CANS) optimized for scattering and neutron analytics. This type of source produces neutrons using nuclear reactions of protons or deuterons in a suitable target material. At these sources, the whole chain ranging from the accelerator to the target / moderator / shielding assembly and the neutron optics can be optimized according to the needs of the neutron experiments. This approach makes such sources very efficient enabling competitive neutron fluxes at the sample position compared to today's research reactors.

Being a scalable neutron source, the performance level can vary from a low power pulsed neutron source designed for universities and industry with an average power at the target of around 1 kW to a high performance neutron source with ~100 kW average power designed as a full-fledged national facility. We have named the low power CANS NOVA ERA ("Neutrons Obtained Via Accelerator for Education and Research Activities") [2] which is used for basic research, user training and method development, whereas the full-fledged facility compares favorably to nowadays medium flux neutron sources and is operated as a user facility.

In the subsequent text we will describe all basic components of such a source.

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HBS LAYOUT

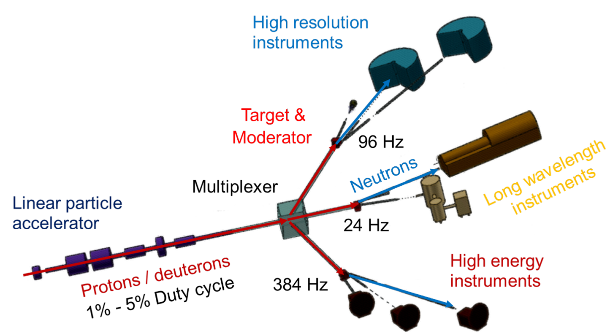

Figure 1: The layout for a high-performance accelerator driven neutron source.

The basic design of a CANS is shown in Figure 1. It consists of a pulsed proton or deuteron accelerator, a multiplexer distributing the protons or deuterons to different target stations each consisting of a target / moderator / shielding assembly and neutron experiments. The neutron experiments with similar requirements for the neutron beam properties are grouped together on the same target station and all upstream elements are optimized to meet these requirements.

This is a general layout which can differ in the specific realization. For example, a low power / low cost CANS like the NOVA ERA will not be equipped with a beam multiplexer and will only maintain one target station.

Accelerator

The protons or deuterons used for the nuclear reaction need to be accelerated to an energy between 10 MeV and 100 MeV. Various types of particle accelerators are available for this purpose, e.g a tandem accelerator, a cyclotron or a

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linear accelerator. A tandem accelerator or a cyclotron are limited to a maximal current and are an option for the low power CANS. For the large scale CANS facility, a linear accelerator with dedicated radio frequency quadrupoles (RFQ) is used which delivers peak beam currents up to 100 mA. The specific current and energy values for both types of CANS facilities are summarized in Table 1.

Table 1: Accelerator Parameters used in the HBS Project

	NOVA ERA	Large scale facility
Accelerator	Tandem	Linac
Particle type	Proton / Deuteron	Proton
Energy	10 MeV	70 MeV
Current	1 mA	100 mA
Frequencies	48 - 384 Hz	384, 96, 24 Hz
Duty cycle	4‰	~ 4.3 ‰
Peak beam power	10 kW	7 MW
Average beam power	0.4 kW	~ 3 · 100 kW

The NOVA ERA accelerator employs a low particle beam energy of 10 MeV with 1 mA beam current where commercially available Tandetrons are available. This design uses just one repetition rate which is optimized to the needs of the instruments.

The large scale facility will use a pulsed proton beam with energies up to 70 MeV and a peak current of 100 mA. The accelerator has to provide a pulsed proton beam for at least three target stations with an average beam power of 100 kW each resulting in an average beam power of 300 kW and a total duty cycle of ~ 4.3‰. With these parameters a normal conducting accelerator is the preferable choice as similar accelerators already exists like the Linac-4/SPL, the FAIR-p-Linac, the ESS or the SNS accelerators. The advantages of the room temperature (RT), normal conducting, linear accelerator are easy access, a simpler and available technology, lower price and higher reliability.

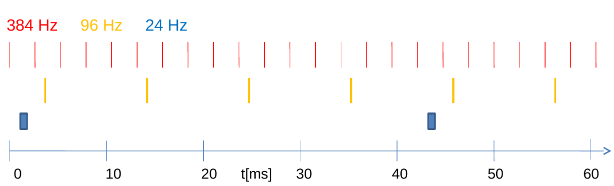

Figure 2: Pulse structure provided by the accelerator for the large scale facility.

Instruments at the different target stations are optimized to use a pulsed proton beam with different frequencies of 24 Hz, 96 Hz and 386 Hz. The pulsing structure needed is shown in Figure 2. The frequencies and duty cycles are chosen in a way that the pulses do not overlap and that the maximal depositable power can be delivered to a dedicated target.

Multiplexer

The three particle beam pulse structures need to be distributed to different target stations. For this reason, a particle beam multiplexer will be used downstream from the linear accelerator. Hereby, a geometric request to the deflection angle from the closed orbit comes from the ion beam dynamics of the setup. In order to avoid divergence and subsequent beam loss, the maximal length of propagation of particles without focusing ion optics is being restricted to ~5 m. This sets a lower limit to the deflection angle provided by a standalone kicker magnet. In order to overcome this limitation, a kicker magnet and septum magnet combination will be employed as it is shown exemplarily in Figure 3.

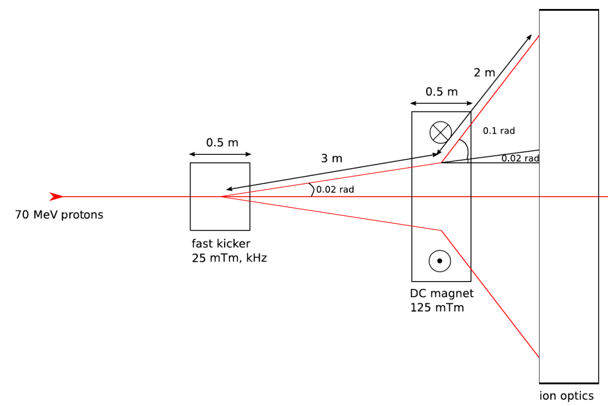

Figure 3: The multiplexer used to separate the different pulse structures.

A fast kicker magnet introduces a 20 mrad kick angle onto the beam's closed orbit which requires an integrated magnetic field strength of 25 mT·m. The field rise time is dominated by the pulse structure shown in Figure 2 and results in less than 800 μs, so that the fast kicker can switch the fields between adjacent pulses. After a well-defined separation of the beam from the closed orbit, a 125 mT·m DC magnet takes over further deflecting the beam. More detailed design studies of the kicker magnet are in progress.

Target / Moderator / Shielding Assembly

The target / moderator / shiedlding assembly is presented in Figure 4 and consists of the target which is surrounded by a thermal moderator like polyethylene (PE) moderating the fast neutrons with MeV energy to thermal energies between 10 meV and 500 meV. A reflector like beryllium, lead or molybdenum increases the thermal neutron flux inside the moderator due to backscattering. Everything is surrounded by the shielding consisting of borated PE and lead.

Extraction channels directing the thermalized neutrons to the experiments are inserted into this assembly. Their location is optimized in such a way that they extract the neutrons from the maximum of the thermal neutron flux inside the moderator. Into these extraction channels cryogenic one-dimensional finger moderators [3] can be inserted further shifting the thermalized neutron spectrum to cold energies between 1 meV and 10 meV.

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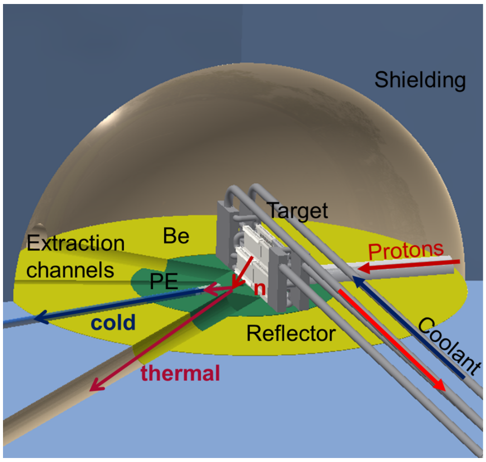

Figure 4: The target / moderator / shielding assembly.

The advantage of the compact design is the possibility to place the first optical elements like neutron guides, filters and choppers close to the target / moderator. Therefore, a large neutron phase space volume can be transferred to the instruments increasing the brilliance. Less neutrons are produced with the nuclear reaction in comparison to spallation or fission, but with this compact design this is compensated by the improved coupling of the moderator and extraction system making the source competitive to modern research reactors.

As the whole target / moderator / shielding assembly is optimized to the needs of the instrument and especially as each instrument can have its own optimized cryogenic source, this approach initiates a paradigm change: "Each instrument has its own source".

Neutron Production

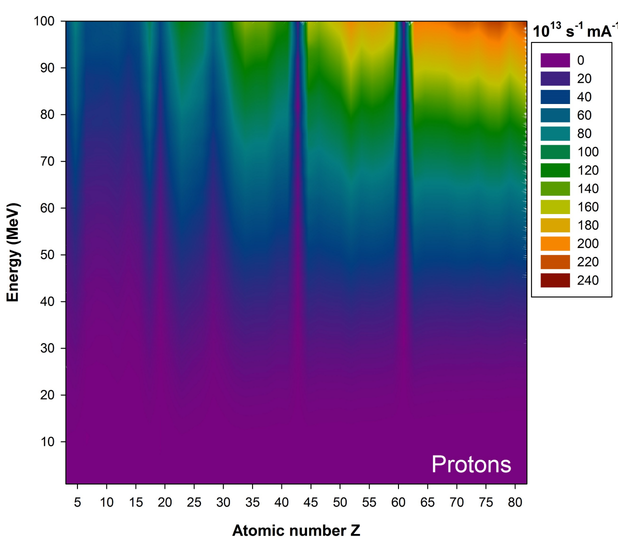

Figure 5: The proton induced neutron yield depending on the primary particle energy for the first 85 elements.

The neutrons are produced by nuclear reaction in a suitable target material. The neutron yield depends on the cross section, the primary particle energy and the stopping power of the target material. Therefore, different target materials are preferable depending on the energy. In Figure 5 the neutron yield for protons at various energies for the first 85 elements is presented.

For energies below 30 MeV, low Z materials are preferable like beryllium or lithium. For energies above 50 MeV, high Z materials like tungsten or tantalum are preferable regarding the neutron yield. As the power depends directly on the energy, a low power CANS like the NOVA ERA will therefore use a beryllium target and the large scale facility will utilize a high Z material like tantalum.

Table 2: Average neutron yield for different power levels, energies and target materials calculated using the TENDL 2017 database [4].

power [kW]	energy [MeV]	target	neutron yield [s^{-1}]
0.4	10	beryllium	$3 \cdot 10^{11}$
1	16	beryllium	$1 \cdot 10^{12}$
10	30	beryllium	$2 \cdot 10^{13}$
100	70	tantalum	$5 \cdot 10^{14}$

The expected average neutron yields are summarized in Table 2 for different power levels, energies and target materials.

Target

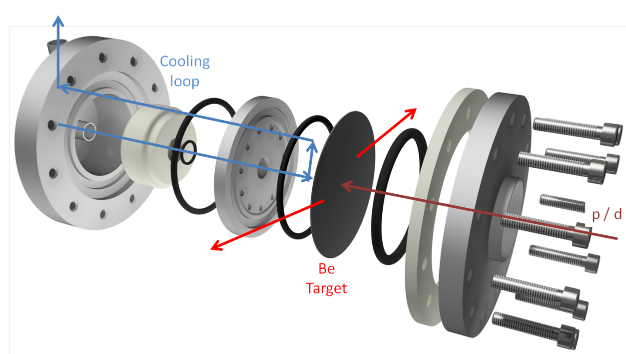

Figure 6: Target design for a NOVA ERA source at a power level of 0.4 kW.

The target design depends on the power it has to withstand, the type and energy of the primary particle and the target material. The target material defines the stopping power and the thermomechanical properties. The energy dependency is related to the stopping range of the primary particles in the target material as the thickness of the target has to be smaller then the stopping range. This will produce most neutrons ($\geq 99\%$) but prevent deposition of hydrogen atoms into the target material ($\leq 0.1\%$) avoiding hydrogen accumulation

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and blistering [5]. With these complex dependencies, each parameter requires its own target design.

The target design for the NOWA ERA source at an average power level of 0.4 kW and a proton energy of 10 MeV is shown in Figure 6. The target is composed of a 0.7 mm thick beryllium window clamped in an aluminum housing [2] and cooled by a water jet. The mechanical simulations with the ANSYS toolkit show that the temperature inside the target is around 50°C and the yield strength around 80 MPa well below the yield strength of beryllium.

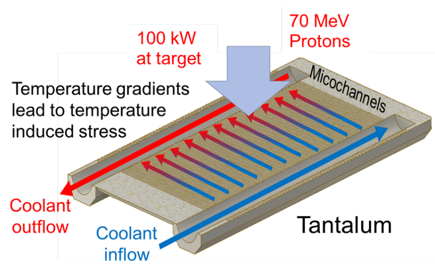

Figure 7: Target design for a large scale facility source at a power level of 100 kW.

The target design for the large scale facility at a power level of 100 kW and a tantalum target is more sophisticated. The power density deposition with a target area of 100 cm^2 is 1 kW/cm^2 and cannot be cooled by conventional cooling. In order to cool such a power density it is necessary to use μ-channels which can remove up to 3.5 kW/cm^2 [6]. The target concept using a direct μ-channel cooling of the tantalum target is shown in Figure 7. With a complex fin-like μ-channel structure, it is possible to remove the heat very efficiently and achieve temperatures inside the target which are below 100°C and a temperature induced stress of around 80 MPa well below the yield strength of tantalum (300 MPa) as calculated using the ANSYS toolkit.

Moderators

The fast energy neutrons in the MeV range need first to be moderated to thermal energies between 10 meV and 500 meV which will be done by a PE moderator with a diameter of about 10 cm surrounding the target.

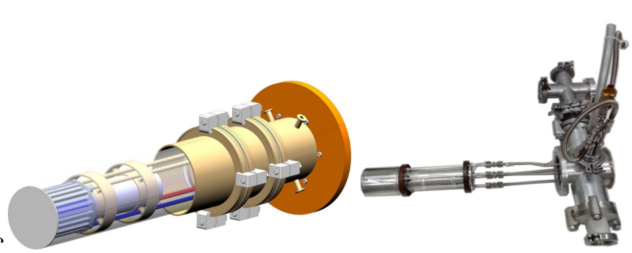

Figure 8: The design and construction of a one-dimensional finger moderator.

Depending on the instrument, a cryogenic moderator shifting the neutron spectrum to energies between 1 meV and 10 meV is needed. For this purpose a one-dimensional finger moderator as shown in Figure 8 is inserted into the extraction channel positioned at the thermal maximum in the PE moderator. The cryogenic moderator is filled with a suitable material like solid methane, mesitylene or liquid hydrogen with a specific ortho/para ratio at cryogenic temperatures.

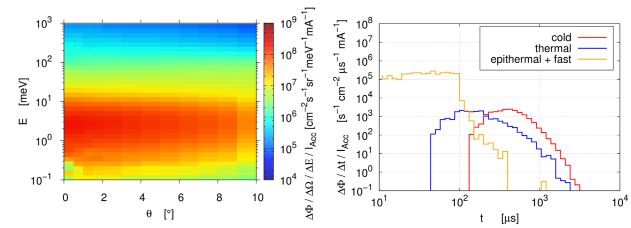

Figure 9: Left: Brilliance as a function of wavelength and divergence for a cryogenic moderator filled with methane [2]. Right: Time structure of this moderator [2].

The dimensions and the moderator material of the cryogenic one-dimensional moderator are optimized to the requirements of the instrument. MCNP6 simulations were used to determine and optimize the neutron phase space volume leaving the extraction channel which is shown in Figure 9. The neutron bandwidth, the pulse width and the divergence is matched to the requirements of the instruments. With this approach, each instruments has its own source.

Instruments

Table 3: Analytically Calculated Instrument Parameters for a NOVA ERA Source [2,7]

	Resolution [Å^{-1}]	Bandwidth [Å]	Flux [s^{-1}cm^{-2}]
	Large scale structures		
Reflectometer	0.34	2 - 9.5	$5 \cdot 10^4$
SANS	0.48	2 - 10.3	$7 \cdot 10^4$
	0.44	2 - 8.3	$2 \cdot 10^4$
	0.36	2 - 8.3	$4 \cdot 10^3$
	0.31	2 - 7.4	$1.5 \cdot 10^3$
	Diffractometers		
Powder	0.006	1.1 - 2.0	$4.3 \cdot 10^3$
	Analytics		
Imaging	0.5 mm, 0.3 Å	1 - 7	$2.5 \cdot 10^3$
PDGNAA, NDP	-	-	$1.4 \cdot 10^7$

The instruments built at a pulsed CANS are designed in a time-of-flight (TOF) setup and can be mainly distinguish by the bandwidth they can use and the resolution they need. The bandwidth and the resolution can be defined by choppers which in most cases results in a loss in neutron flux at the sample position. A more efficient approach is to match the repetition rate of the neutron beam to the instrument length in such a way that the maximal useful phase space volume is filled. For a large scale facility we distinguish at least

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three different repetition rates, eg. 24 Hz, 96 Hz and 384 Hz. Instruments using these repetition rates are grouped together and built at the same target station.

Table 4: Analytically Calculated Instrument Parameters for a Large Scale Facility

	Resolution [Å^{-1}]	Bandwidth [Å]	Flux [s^{-1}cm^{-2}]
Large scale structures operating at 24 - 48 Hz			
Reflectometer	0.2	1.2 - 5.7	$1.3 \cdot 10^8$
SANS	0.31	3 - 8.4	$2.4 \cdot 10^7$
	0.27	3 - 7.7	$5.3 \cdot 10^6$
	0.23	3 - 7	$1.5 \cdot 10^6$
	0.2	3 - 6.4	$6 \cdot 10^5$
Diffractometers operating at 96 Hz			
Powder	0.003	1.3 - 2.6	$6 \cdot 10^6$
Spectrometers operating at 100 - 400 Hz [8]			
Backscattering	1	1.84	$2.5 \cdot 10^7$
Cold ToF	2	5	$1.3 \cdot 10^5$
Thermal ToF	5	45	$1 \cdot 10^5$
Analytics operating at 24 - 96 Hz			
Imaging	0.5 mm, 0.2 Å	1 - 7	$4.4 \cdot 10^6$
PDGNAA, NDP	-	-	$2.5 \cdot 10^{10}$

At the highest repetition rate of 384 Hz, short length secondary spectrometers for inelastic neutron scattering experiments will be built. As the flight path is short, the phase space volume can be filled with a high repetition rate so that the flux is maximized. The target station with the intermediate repetition rate of 96 Hz will provide neutrons for high resolution thermal diffractometers with a larger bandwidth. At the low repetition rate of 24 Hz, instruments with a large bandwidth of cold neutrons with a relaxed resolution will be built like a reflectometer so that these instruments have no resolution problem with long pulses.

Analytic instruments like a prompt and delayed gamma neutron activation analysis (PDGNAA), neutron depth profiling (NDP) or an imaging station will be built at the target station with the low or intermediate repetition rate. The resulting resolution can resolve Bragg-edges for the imaging experiment and the PDGNAA can be operated in ToF-mode giving depth resolved information.

The expected neutron fluxes at the sample position for a NOVA ERA source where all instruments are built at a single target station are presented in Table 3. The neutron fluxes with for the large scale facility with three different target stations and adjusted proton pulse frequencies are presented in Table 4.

TIMELINE

The current aim of the HBS project is to develop and realize the large scale CANS facility. For this, a conceptual design report will be written and published. It will give an overview about the project and describes all relevant parts. As many different technological challenges are present in the HBS project ranging from accelerator system, neutron targets, moderators up to the instruments, it is necessary to investigate the components individually. A dedicated technical design report will be prepared within the next years.

The project aims to realize a prototype facility to be constructed within the next five years to prove that the concept is working and the full-fledged facility can be constructed within the next decades.

CONCLUSION

The HBS project develops a scalable accelerator driven neutron source optimized for neutron experiments. It ranges from a low power CANS named NOVA ERA which can be built at universities and industry and perform basic experiments to a high power CANS which has competitive fluxes at the sample position to nowadays neutron experiments.

CANS come at a much smaller price tag then research reactors or spallation sources, avoid the problem with nuclear licensing and the nuclear fuel cycle, and allow one to construct instruments fitting to the particular problem at hand, e.g. smaller samples.

The approach of the scalable accelerator driven neutron source enables one to develop a network of large and small neutron sources throughout Europe improving the access to neutrons.

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