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NORRØNT AS

Proposal for the development of a compact neutron source

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Preface

This proposal gives an overview of the investment needed for the realization of proof of principle and further development of a compact neutron source based on the research into Rydberg Matter by Prof. L. Holmlid and his collaborators. The energy technology based on this research is being developed by Norrønt AS.

The research into Rydberg Matter by Prof. L. Holmlid has resulted in a method to produce neutrons via muon-catalyzed fusion of hydrogen isotopes. The projected optimized intensity of this neutron source is between 10^{14} to 10^{16} neutrons per second which is 2 to 4 orders of magnitude larger than state-of-the-art neutron generators.

This neutron intensity in a relatively small volume is comparable to research reactor sources based on fission of uranium, but the amount of radiation and radioactive waste produced will be negligible compared to fission sources. This makes this source a perfect candidate for the replacement of these research reactors in the future where each neutron spectrometer can have its own neutron source.

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Contents

1. Introduction

The development of small neutron sources was started directly after the discovery of the neutron by Chadwick in 1932. He used a polonium source that emitted alpha radiation that was converted to neutrons by means of Beryllium.

Since then it has been discovered that neutrons can be created using several methods, the most used is by means of a nuclear reactor based on a chain reaction of neutron induced fission. Another method is by colliding charged particles on a target, creating fast neutrons by either a fission or a fusion reaction. Yet another method is based on radio-nuclides where the decay process produces neutrons. Finally a method can be used so that by means of a gas discharge the collisions are made to be able to fuse hydrogen isotopes.

All these methods have disadvantages. Either being the large infrastructure needed to safely operate the source (for instance in case of a nuclear reactor or proton beam) or being the small neutron intensity produced (for instance in case of radio-nuclides or gas discharge).

These disadvantages are absent in case of the proposed neutron source discussed here. The amount of radioactive waste is negligible with respect to a nuclear reactor and the neutron intensity of the compact sized source can be as large as the that of a nuclear reactor. This is elucidated in the below figure 1.1. The picture is taken from [32] and the projected performance of the neutron source proposed here is added as a red dot.

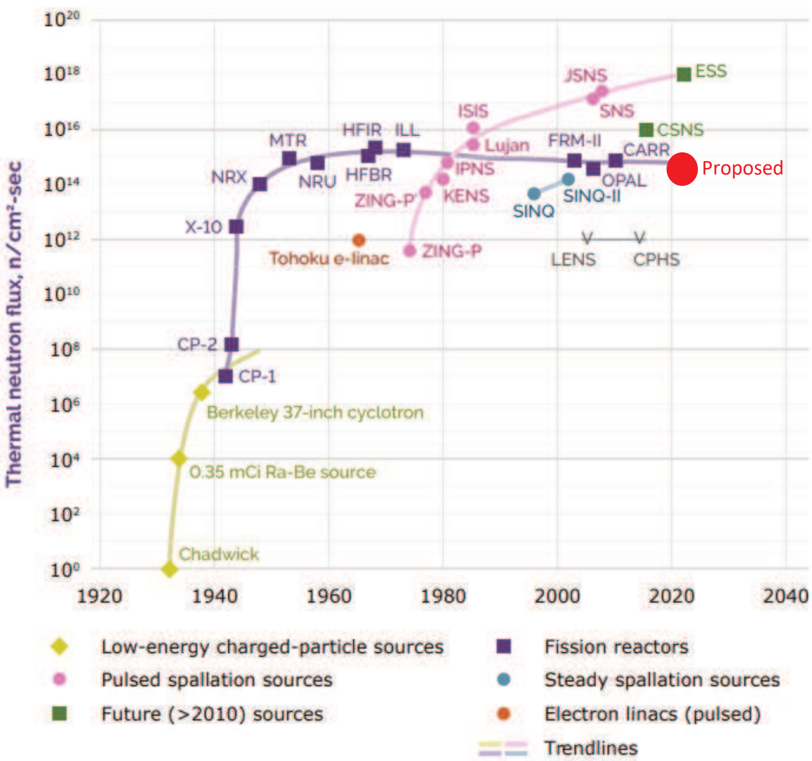

Figure 1.1: *The evolution of effective neutron source fluxes as a function of calendar year, from the discovery of the neutron in 1932 to the time horizon of this report. HFIR, ILL, ISIS, SINQ, SNS, JSNS and FRM-II (MLZ) are still operational and CSNS and ESS are under construction*

2. Principle

2.1. Rydberg Matter

The technique is based on the research performed by Prof. L. Holmlid during the last 25+ years. He investigated the properties of Rydberg Matter (for an independent overview see [1]). This is a condensed form of matter consisting of Rydberg Atoms or Rydberg Molecules. These particles have 1 (or more) electron(s) in an excited state, but not ionized [2,3]. Therefore the size of these particles increases considerably, they have long range interactions and become entangled. In this way a macroscopic quantum system is created which has many new properties.

Normally, Rydberg Atoms or Molecules are created by laser excitation of gas atoms or molecules. Then, by cooling down it is possible to condense them into a supra-liquid form. However, this can only be realized with special cooling techniques at low temperatures. Prof. Holmlid found out that by using a suitable catalyzer it is possible to create the condensed state during the desorption from the catalysts surface [4].

In this way it is also possible to use hydrogen isotopes to create Rydberg Matter. It can condense to form metallic hydrogen [5] with a bonding distance of 150 pm. It was soon found out that this substance created very fast particles when excited by means of a laser pulse (Nd:YAG pumped dye laser; 5 ns 60 mJ pulses; wavelength of 564 nm; power density of approximately 10^{15} W m^{-2}) [6], [7], [8]. Then it was realized that this might be a source of compact fusion fuel [9], [10], [11], which was indeed observed after increasing the laser power to about 1 J per pulse [12], [13],[14],[15],[16].

In search for the reason for the high energy particles released by the hydrogen Rydberg matter it was found that a second form of hydrogen Rydberg Matter exists that has a very high density with an atomic distance down to 2.3 – 3.7 pm. This is now known as Ultra-dense hydrogen H(0) which is expected to be a superfluid and superconductive quantum material [17],[18],[19]. The transition from normal hydrogen Rydberg Matter to this ultra-dense form seems to be oscillatory from which a picture was formed of the structure of ultra-dense hydrogen [20],[21],[22] as shown in figure 2.1.

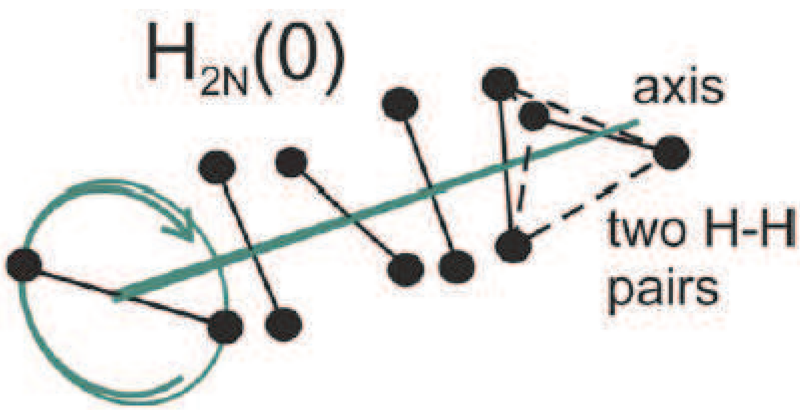

Figure 2.1: *Sketch of ultra-dense hydrogen Rydberg Matter.*

2.2. *Nuclear particles*

Depending on the precise experimental parameters like laser power, pulse duration and repetition frequency together with hydrogen isotopes used and target symmetry the production of several nuclear particle species are observed [23]. When the Rydberg Matter is excited by a laser pulse several hydrogen atoms merge under the production of mesons (kaons that can decay within a few 10's of ns and pions). Most of the mesons decay into muons within approximately 100 ns. The kaons and pions formed initially have relatively low kinetic energy, while the muons can receive an energy of at least 10 MeV [23, 24]. Recently [25], it was found that small $H_N(0)$ clusters with 3 to 4 atoms (as shown by the dotted lines in figure 2.1) are responsible for the meson-ejecting nuclear process.

2.3. *Neutrons*

The production of neutrons is based on the muon-catalyzed fusion and muon-capture process in hydrogen [26]. Muon-catalyzed fusion was discovered in 1956 by Luis Alvarez and is by now a well known process. It boils down to production in a deuterium-tritium mixture of more than 100 fusion reactions with the release of some 17.6 MeV per fusion, depending on the precise reaction. For most of those reactions a neutron is released. For a production rate of 10^{15} muons per laser pulse [27], this could yield a neutron source strength of 10^{17} neutrons/pulse with a laser repetition rate of 10 Hz. This corresponds to the number of neutrons per second produced by the ILL research reactor. When a deuterium-deuterium reaction is considered the muon can catalyze about 7 reactions so that this number reduces by a factor 10-14, yielding a source strength between 10^{15} and 10^{16} neutrons/pulse, still 2 to 4 orders of magnitude larger than existing compact neutron sources [33], [34], [35].

3. Existing Techniques

In the laboratory, the production Rydberg Matter [28] and of ultra-dense hydrogen [29,30] are well-established techniques and have been reproduced by several groups (Holmlid in Sweden, Olofson in Iceland and Zeiner-Gundersen in Norway). A review of its properties is given in [31]. Hence, here the focus is on the production of mesons and their decay into muons to deliver the muon-source with the help of a pulsed laser. The effective transformation from muons to neutrons determines also the performance of the neutron source and specially the neutron detectors are taken into account. These should be able to determine the source strength effectively. Finally the shielding is addressed, as with the high neutrons strength projected, this will be a major challenge.

3.1. Muon source

The muon source is produced by pulsing a high power laser onto ultra-dense hydrogen containing surface or close to that surface. This method is disclosed in [36]. Norrønt AS was able to reproduce this source. The schematics are shown in figure 3.1.

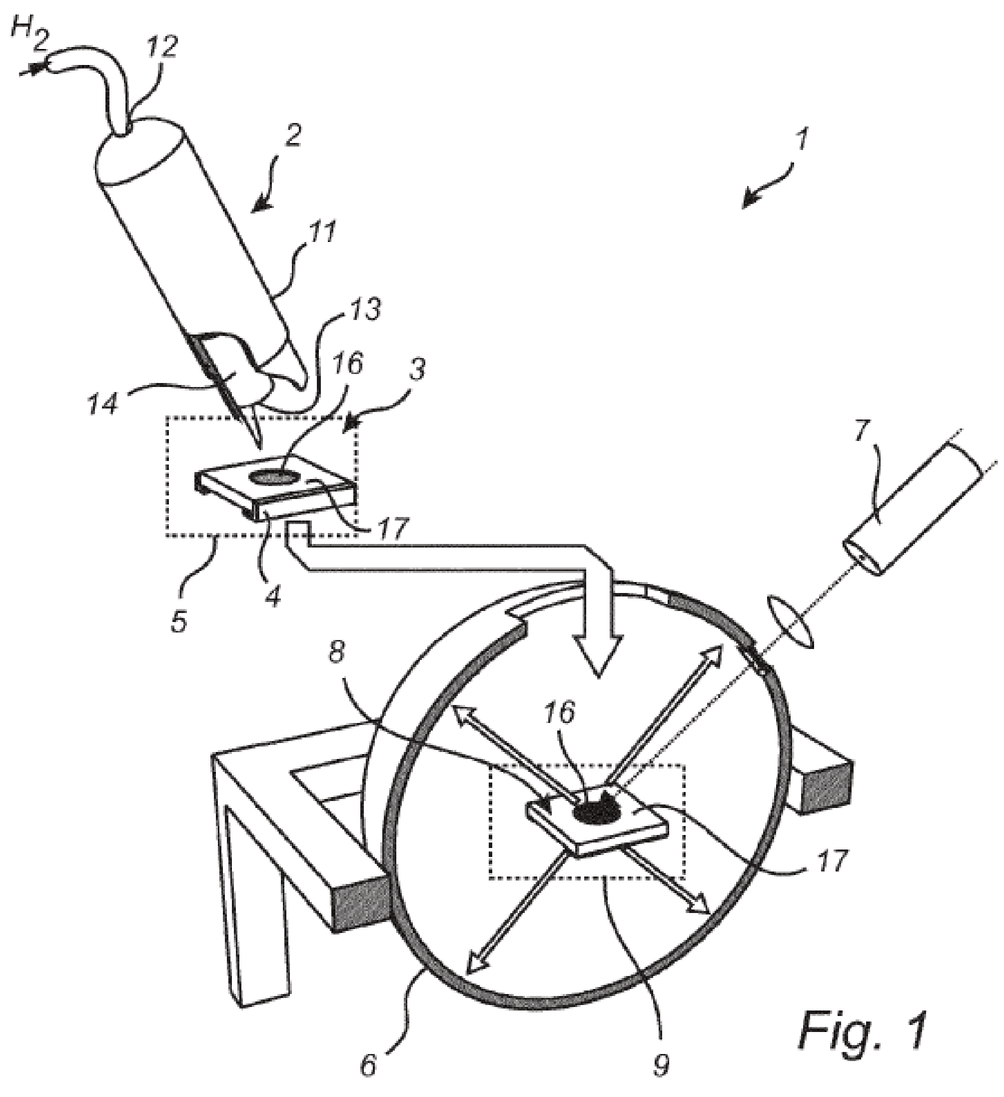

Figure 3.1: *Sketch of muon-source, copied form [36].*

Gaseous hydrogen is fed into a hydrogen feeder (2) passing into a vacuum chamber (6) where hydrogen is transformed into Rydberg Matter (16) by transmission though a suitable catalyzer (13). It drops down in container (17) where it is stored and can be transformed into ultra-dense hydrogen by means of an intense light pulse from laser (7). The light enters the vacuum chamber by means of a suitable window. The laser focusing on or close to the container surface where the Rydberg Matter resides is not shown.

3.2. Laser

The laser is a Nd:YAG laser with an energy of <200 mJ per each 5 ns long pulse at 10 Hz. The laser is operated at 532 nm. The laser beam is focused close to the container surface with an f = 400 mm spherical lens. The intensity in the beam waist of (nominally) 30 mm diameter is relatively low, ≤ 4×10^{12} W cm^{-2} as calculated for a Gaussian beam. In front of the focusing lens, a glass plate in a precision rotation mount is used to shift the laser beam slightly in the horizontal direction. The total shift possible with this beam shift construction is close to 0.7 mm, and the shift between two consecutive measured points on the surface is close to 50 mm.

3.3. Muon-Neutron converter

Muons can interact with nuclei by nuclear capture processes. The most process is when a muon reacts with a proton

$$\mu^- + p \rightarrow n + v_\mu$$

where a neutron and a muon neutrino are produced. This reaction suffers from a low capture rate and the fact that the muon is lost. The current muon-neutron converter based on this reaction. It consist of a tube of hydrogen gas under 200 bar pressure. The length is 1 m and the radius 10 cm. This enables the interaction of the muons with the hydrogen molecules inside the gas. The length of the tube and the high pressure is needed to increase the interaction chance with the muons and hence the neutron intensity. An apparent disadvantage of this converter is its size, reducing a-priori the neutron brightness, which is the most important parameter for a neutron source.

3.4. Neutron detectors

As a neutron detector two types were used. A standard neutron detector as used for equivalent dose rate measurements and a large surface detector sandwiched between two poly ethylene plates for the thermalization of fast neutrons.

3.5. Shielding

Charged particle are readily absorbed in materials and depending on the type of particles a sheet of paper (electrons) or aluminum sheets (muons, protons) can easily be shielded. For neutrons in general more effort is needed. The conversion from neutron flux to dose rate depends on the energy of the neutron. For fast neutrons (high energy of about 10 MeV) the conversion factor is about 2 $\mu Sv.hr^{-1}/(cm^{-2}s^{-1})$. For slower neutron the conversion factor is lower. The limit for a radiation hazard for the general public is 1 $\mu Sv.hr^{-1}$. Hence, at a typical distance of 30 cm from the source, the maximum source strength should be more than 10^5 n/s to necessitate shielding. Hence, for the existing source strength shielding is irrelevant.

4. Developments

The current status of the Norrønt AS neutron source is proof-of-principle where the source strength is estimated to be of the order of 30-100 kBq. The energy and spatial distribution of the emitted neutron radiation is largely unknown. However, for an optimal design the precise production mechanism must be known. Further, the source strength is unstable and quite unpredictable. These issues are the ones that needs to be solved before an effective design for a commercial neutron source can be addressed. This calls for research in the fundamental properties of the source (optimization of muon production and the research path) and the development of stable methods to control the source strength (the instrumental development). Finally, because the neutron source needs to meet customer expectations, these needs to be incorporated into the development (the market awareness).

4.1. Optimization of muon production

As the neutrons are produced from the muons, first their production must be optimized and the muon-source needs to be stable and predictable.

Ultra-dense hydrogen production
The ultra-dense hydrogen production by means of the catalyzer and its storage needs to be optimized to enhance initial yield and to keep losses to a minimum.

Laser
The trigger for the production of muons from the ultra-dense hydrogen is a laser pulse of a certain energy and energy density. Although the laser itself is of the shelf technology, its focusing on the target needs to be automated and controlled in a robust way. A technique for this must be applied. Further, the optimal pulse shape, density and repetition frequency needs to be established.

Detection mechanisms
To be able to control the muon production fast, reproducible and accurate detectors must be constructed to keep track of the source performance and enable source control.

4.2. Research path

Energy distribution
Neutron interaction with materials (be it samples, beam collimators, shielding, moderation, etc.) strongly depends on the energy of the neutron. Hence, for a good design it is imperative to know the energy distribution of the produced neutrons.

Directional distribution
A major drawback of standard neutron sources is that they radiate neutrons in all directions (so-called 4π sources). This severely reduces the neutron intensity when the distance to the source becomes larger. If a neutron source would have a preferred direction this could increase the effectiveness by two or three orders of magnitude. To mitigate this most neutron sources are equipped with neutron guides, that are able to confine the neutron beam by reflection to a mirror surface to a certain area while receding from the source. Unfortunately with normal materials the neutrons can only be reflected under shallow angles of 1-2 degrees at most. It could be possible that ultra-dense hydrogen would be able to reflect neutrons under a much higher angle so that a directional source can be constructed by optimizing the target design.

Timing distribution
As the neutron are created after the laser pulse, the neutron source has the potential of being operated as a pulsed neutron source, enhancing the effective intensity with respect to a continuous source by two or three orders of magnitude. The reason for this effective enhancement is that with the time-of-flight technique one is able to determine the neutrons velocity so that it is not needed to monochromatize the neutron beam. However, to have a good resolution the exact neutron pulse intensity distribution must be known.

4.3. Instrumental development

Muon-Neutron converter
The initial particles that are created and that can be effectively transformed into neutrons is a muon. When the muon interacts with a hydrogen isotope in a target material, neutrons can be produced. The production can be significantly enhanced when the muon is used as a catalyzer, hence when it is not lost during the nuclear reaction. An examples is for instance given by the following reaction

$$\mu^- + d_2 \rightarrow \quad {}^3He^{2+} + n + \mu^-$$

This reaction has to compete with other non-muon conserving reactions so that the total multiplication rate is a factor of 7 [26]. Another possibility is [27]

$$\mu^- + dt \rightarrow \quad {}^4He^{2+} + n + \mu^-$$

with a multiplication rate of 100. Therefor the target must be designed to optimize the neutron yield. One can use liquid hydrogen (isotopes) as it has a favorable neutron production channel by muon catalyzed fusion and can have a much higher density than gas. The precise geometry and the cryogenic equipment needs to be designed and optimized. An additional advantage of liquid hydrogen is that the neutrons are effectively moderated to become thermal neutrons with an energy favorable for most neutron scattering spectrometers.

Neutron detectors
As initially the neutrons source will be of limited intensity the use of effective neutron detectors will greatly enhance the performance of the final spectrometer. Further, it is evident that to prove the performance of the neutron source well tested and calibrated neutron detectors are needed.

Shielding
Although the current neutron source has an intensity that does not need shielding, as soon as the targets are met, shielding becomes imperative. Therefore, during the design of the complete source, all aspects of radiation safety should be kept in mind. This not only entails the shielding of the source when in operation, but also the possible effect of long term neutron irradiation on the components and the dismantling properties of the source.

4.4. Market awareness

Matching expectation and possibilities
There is a worldwide cooperation for the development of small neutron sources [36] and a very active community of neutron researchers [37]. The possibilities of the current development must be brought to the attention of this community as they represent future clients. By interaction with

this community also the customers expectations can be inventoried and maybe also directed. This can be done by one-to-one visits and conference contributions.

Competition comparison

As the neutron source is under development one can compare the performance of the current development with other small neutron source manufacturers and find out what the market position of the current development is.

5. Economics

An overview of the investment and testing costs will be discussed in the next section. Here we present the possible returns based on information presented in report [32] considering the availability of neutron scattering facilities in Europe for the coming 20 years.

5.1. European Market

According to the report [32] currently there are 175 neutron spectrometers available resulting in approximately 35000 instrument days per year. According to the same report the operational cost of the neutron sources to provide these instrument with neutrons are 11 kEuro per instrument day per year, summing in total to 375 MEuro/year. These are 6% of the investment cost [32] so that the investment cost were 5600 MEuro. With a typical lifetime of these neutron sources of 40 years this is an investment of 440 MEuro/year. The total costs of operating the neutron sources in Europe mounts to about 800 MEuro/year.
The report [32] raises concern about the age of the existing neutron sources and estimates a decay to 20000 instrument days per year in the coming 20 years, i.e. a total market for the coming 20 years in Europe of 8000 MEuro, i.e. 400 MEuro/year.
This estimate is based on the expected closure of existing sources and the planned new sources. Market growth by reduced investment and operational costs of possible alternative sources is not included.

5.2. Equipment cost

A typical small neutron source has 2-4 instruments, so to replace the instrument days of a small neutron source by existing technology will cost 10-20 MEuro/year. Over 5 years the total amount is 50-100 MEuro. This only considers the costs of the neutron source.
When the equipment has a guaranteed lifetime of 5 years and the operational costs of the source will be 1 MEuro/year, the breakeven point for the cost of the replacement source is 45-95 MEuro, depending on the number of instruments. If only 1 instrument is needed the breakeven point is reached for 20 MEuro.
When the benefits are shared, the cost of the equipment can be between 10 and 50 MEuro depending on the number of instruments used. The construction costs should probably not exceed 25 % of that to be profitable. On the other hand, the profit should be no more than a factor of 2 of the construction costs, otherwise more parties will get involved.
The above estimate is based on a typical performance of the neutron source equal to that of the main reactor or accelerator sources. Otherwise the equipment costs must be reduced by an appropriate factor equal to the square root of the performance ratio (based on neutron statistics). Hence a factor of 100 lower source strength should be 10 times reduced in price. This is shown as the black line in figure 6.1.

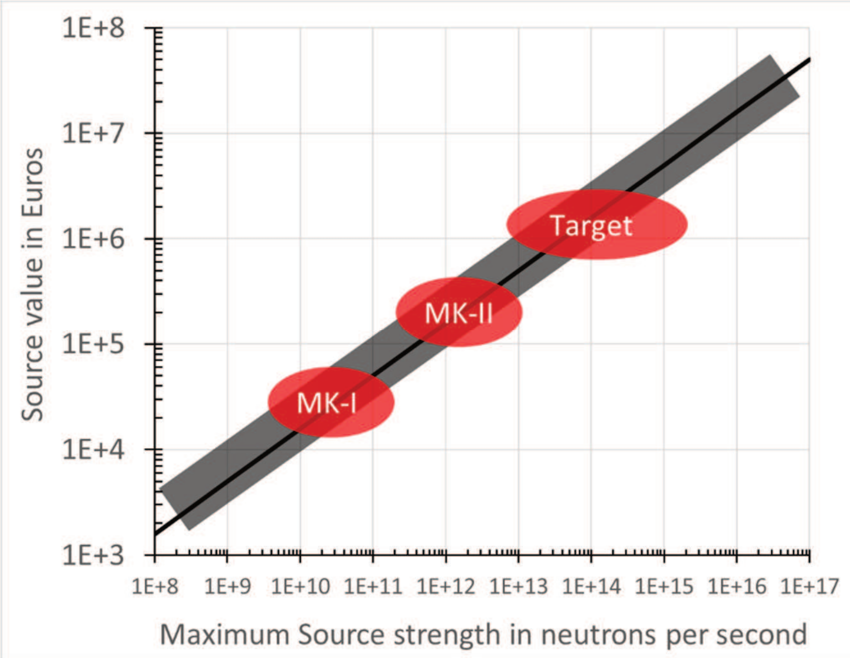

Figure 6.1: *Estimated resellers costs of equipment depending on the source capacity. MK-I should be attainable without more investment costs than the current proposal. MK-II could be realized after optimization of MK-I and the Target is the currently maximum envisioned compact neutron source.*

5.3. Production size and growth in Europe

The projected loss in instrument days per year is about 1000 per year for the coming years [32]. When this can be compensated by the new sources it would result in a market of 5 sources per year for the coming 5 years and then an increase to 10 sources per year in the next 5 years and 15 sources per year in the third 5 years after which it is stabilized. This is based on the expected live time of the source (guarantee). Hence, the estimated turnover starts with 50 MEuro/year and grows after 15 years to 150 MEuro/year. This turnover can be guaranteed by using a lease construction. So the product is the assurance that neutrons are produced during 5 years and so on.

It is assumed that the existing market in Europe remains stable and no other mitigating measures will be taken. Considering the benefits of the neutron source these are not unreasonable assumptions.

Finally, it should be noted that the equipment will increase the market considerably as it will enable the use of the source in universities, security and industry all over the world. In such a case another potential increase can be provided by supply not only the source but also the neutron spectrometers.

6. Scope of work

The current proposal aims to define the scope of work and resources needed to reach the conceptual design stage of the MK-I neutron source. Therefor the activities described in section 4 need to be performed. Before this research path can be executed, the muon source must be optimized for neutron production and the equipment must be made available (although maybe not their final design) and finally the possible radiation safety issues must be addressed. These can be addressed, because of the MK-I neutron source intensity definition. So the scope of work consists of

Muon source optimization
As the neutrons are produced from the muons, first their production must be optimized and the muon-source needs to be stable and predictable. Therefor the ultra-dense hydrogen production, the excitation mechanism and the detection mechanisms will be optimized.

Radiation hazards
The identification of radiation hazards (based on MK-I type of neutron source), both during operation of the neutron source and non-operation and dismantling. These radiation hazards need to be compared to the acceptable hazards for occupation related activities and for the general public. If these hazards are significant then measured must be defined and designed to make sure that no relevant remaining hazards remain.

Prototype MK-I
A prototype for the neutron source MK-I must be built to enable the evaluation of the source performance and the research path tests.

Energy distribution tests
Experiment(s) to test the neutron energy distribution must be designed and executed.

Direction distribution tests
Experiment(s) to test the neutron direction distribution must be designed and executed.

Pulse time-structure tests
Experiment(s) to test the time-structure of the neutron pulse must be designed and executed.

Market awareness
Potential customers visits, market survey by questionnaires, conference contributions.

7. Investment and time schedule

On overview of the complete investment and testing costs in man-hours and expenses are shown in table 7.1. The realization is divided into four phases: detailed design, construction, testing and closure. After the detailed design phase a go/no go mile stone is reached when it can be decided to continue the project or not. After one year of testing it can be decided to close the project or to continue depending on the obtained results.

Item	**Detailed Design**		**Construction**		**Testing**		**Closure**	
	hours	Costs	hours	Costs	hours	Costs	hours	Costs
Muon source optimization	1000	28	2000	250	1000	50	120	20
Radiation hazards	120	4	40	50	40	20	8	10
Prototype MK-I	500	10	240	100	220	50	8	10
Energy distribution tests	80	2	60	50	100	10	16	2
Direction distribution tests	80	2	60	50	100	10	16	2
Pulse time-structure tests	80	2	60	50	100	10	16	2
Market awareness	40	2	40	10	240	40	16	4
Total	**1900**	**50**	**2500**	**560**	**1800**	**190**	**200**	**50**

Table 7.1: *Overview of the investment and testing costs in man-hours and costs in kEuro ex. VAT.*

7.1. Detailed design and construction

During the detailed design phase the definitive set up is defined and needs and requirements for the equipment and test are established. During the construction phase the equipment is purchased or manufactured if not available in the market, further the components are put together. The testing phase is needed to test the instrument and to fine tune all the parameters to obtain the optimal performance of the instrument and to perform the research path tests. The hours indicate the man-hours needed for the specific tasks. The expenses are for tasks that need to be out-sourced or for actual equipment. The total investment for the detailed design, construction phase and 1 year of testing is estimated to be 6200 man-hours and 800 kEuro ex. VAT.

7.2. Testing

The yearly testing costs are 1800 man-hours and 190 kEuro ex. VAT.

7.3. Closure

After the experiment had been finished the results must be made available to the stake holders and the instrument dismantled. The costs for dismantling are estimated to be 10-20% of the construction costs. The man-hours are needed for reporting.

7.4. Total investment

For the complete proposal at least 6400 man-hours and 850 kEuro ex. VAT are needed.

7.5. Time schedule

An overview of the time schedule is shown in figure 7.2. The time schedule is split into four phases: detailed design, construction, testing and closure. The time-schedule has been made keeping in mind the needed man-hours and turnaround time of purchase and construction. The realization of the set-up will take two years and the minimal testing time is one year.

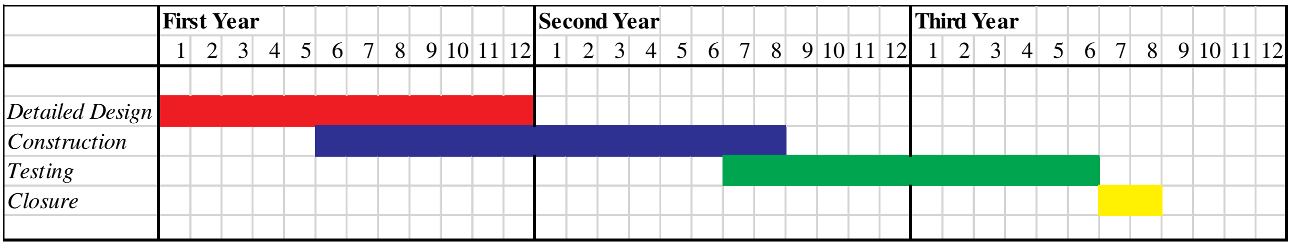

Figure 7.2: *Time schedule for realization of the proposal.*

8. Conclusions

The total investments costs of 6400 man-hours and 850 kEuro ex. VAT are considerable, but negligible compared to other investments in neutron sources of the projected strength.

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Summary

The potential market for new neutron sources can reach 150 MEuro per year in the coming 15 years in Europe alone. This proposal gives an overview of the 6400 man-hours and 850 kEuro ex. VAT investment needed for the realization of a proof of principle and further development of a compact neutron source with a maximum intensity between 10^{14} to 10^{16} neutrons per second based on the research into Rydberg Matter by Prof. L. Holmlid and his collaborators. This neutron source will be many orders stronger than its direct competitors and will have a moderate cost price between 750 kEuro and 1.5 MEuro, depending on its performance. This proposal defines the scope of work and resources needed to reach the conceptual design stage of a MK-I neutron source with a strength of 10^{10} - 10^{11} n/s.