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ICONE – Towards a French HiCANS Neutron Source for materials science and industry

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Abstract. We present the ICONE project which proposes to build a HiCANS source in France. The aim of the ICONE project is to be able to provide the French neutron user community sufficient instrumental capacity to continue performing neutron scattering experiments for their research programs. The baseline goal is to offer performances equivalent to a medium power research reactor or spallation source (such as Orphée or ISIS). We consider that such a machine would fulfil the needs of at least two-thirds of the users which not require ultimate performances but simply beam-time to perform their experiments. We also describe the experimental work ongoing at Saclay around the various technologies necessary to build a HiCANS.

1 Introduction

The decade 2000 was a golden age for neutron scattering in Europe as more than 30000 instruments-days were available across Europe for neutron scatterers. In the future however, the neutron provision is expected to steadily decrease due to the closure of aging facilities and the available beam-days in Europe is currently foreseen to decrease by 40% by the middle of the next decade [1]. If one focusses on the specific situation of France, the situation is far worse. Following the closure of the Orphée reactor in 2019, the number of French neutron scattering instruments, measured in Full Time Equivalent (FTE), dropped from 29 to 9, the current available instruments corresponding to the French share at the ILL and the French shares in the different CRGs around the ILL[†]. Should the Grenoble High Flux reactor shut down, the French access to neutron scattering would be reduced to 2 FTE instruments at ESS[‡] at the beginning of the next decade. France has been at the forefront of neutron science as the second most publishing country, on par with Germany, of scientific publications using neutron scattering techniques. This was made possible because French users had access to a share of 13% of the world neutron scattering instruments[§]. This share is currently foreseen to drop to 1% in the next decade.

Neutron scattering has been identified as a key scientific tool to address current technical and social challenges: Europe is engaged in the construction of the highest performance spallation source, the ESS, the United States are building a second target station around SNS and are upgrading the HFIR reactor at Oak Ridge and the NIST reactor in Washington, China has recently opened two new sources, CSNS and CARR, the United Kingdom is considering the upgrade of the ISIS facility… What could be done so that France remains competitive in this environment and avoids losing its expertise in the field?

Until recently, it was considered that only nuclear research reactors or spallation sources could provide sufficient neutron flux to perform neutron scattering experiments and welcome user programs. However, in the last decade the situation has been reconsidered owing to the progress in several fields: (i) high current proton accelerators, (ii) neutron moderation techniques, (iii) neutron instrumentation.

It is nowadays possible to build and operate proton accelerators with proton currents of the order of 100 mA or even higher [2]. The concept of low dimensional moderators is expected to boost the brilliance of neutrons sources by factors of 3 to 10 [3]. Neutron instrumentation adapted to exploit long neutron pulses has been developed for ESS [4].

Based on these new technical capabilities, the concept of HiCANS, High Current Accelerator-driven Neutron Source has been proposed. The underlying idea is to use low energy proton accelerators (tens of MeV)

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[†] France has access to 25% of 27.7 FTE neutron scattering instruments at the ILL (= 7 FTE instruments) and its shares in the different CRGs correspond to 2 FTE instruments.

[‡] The currently foreseen French share of 14% in ESS would correspond to 2.1 FTE instruments (14% * 15 instruments)

[§] *ICONE, une nouvelle source de diffusion neutronique française (to be published)* and low energy nuclear processes to produce neutrons. The low neutron yield of such processes is compensated by the use of a high proton current, a very strong coupling between the target (which can be very small) and the moderator, and an optimized time structure which allows to use a very large fraction of the produced neutrons. Monte-Carlo simulations show that if all components of such a source are optimized, the performance of such sources for neutron scattering could be on par with medium power nuclear research reactors or spallation sources [5-6].

This has led to the proposition from various institutes to build HiCANS sources to provide neutrons to their user community. We can mention the HBS project in Germany, the ARGITU project in Spain, the SARAF project in Israel, the PC-CANS in Canada or the DARIA project in Russia. In Europe, the institutes working in the field of HiCANS have gathered into ELENA, the European Low Energy accelerator-driven Neutron facilities Association [7]. HiCANS has been considered by the LENS, the League of Advanced European Neutron Sources, as a possible component in the future neutron scattering landscape [1].

France is also considering the HiCANS solution to mitigate the foreseen neutron drought in France. In the following, we describe the ICONE source which aims to provide the French user community with a new facility in the coming decade. We describe the scope of the project and the current technical developments under way.

2 The ICONE project

2.1 Scientific scope

During the last four years, more than 300 different French laboratories have been performing neutron scattering experiments, either within the 2FDN, the Fédération Française de Diffusion Neutronique [8], which is gathering the French laboratories proposing neutron beam time or at the ILL Institut Laue Langevin.

The aim of the ICONE project is to be able to provide the French neutron user community with sufficient instrument capacities to continue performing standard neutron scattering experiments for their research programs. The baseline goal is to offer performances equivalent to a medium power research reactor or spallation source (such as Orphée or ISIS). We consider that such a device would fulfil the needs of at least two-thirds of the users who do not require ultimate performances but simply beam-time to perform their experiments. This does not preclude the fact that the facility would conduct a high-level scientific program. Statistics show that the quality of the scientific production of facilities is not connected to the power of the source [9].

In parallel, the French users will have access to ESS to perform experiments which require ultimate performances and cannot be performed on ICONE.

The Figure 1 shows a sketch of the ICONE facility. The aim is to offer a suite of instruments covering most of the neutron scattering techniques, mainly diffraction, spectroscopy, SANS, reflectivity and radiography. In order to maximize the efficiency of the source, the instruments will operate in time-of-flight mode as has been adopted on all recent spallation sources. In addition, it is considered to provide different neutrons pulses lengths and time structures by using several target stations, thus being able to fully optimize the need for lower resolution instruments and higher resolution instruments.

2.2 Scientific capabilities

Monte-Carlo modelling of HiCANS has been performed at various institutes across Europe in the past years. The results suggest that the use of a pulsed proton accelerator with an energy of 20 or more MeV and with peak proton currents of 50 mA or more, coupled to an optimized Target – Moderator – Reflector (TMR) system could provide performances on par with reactors [5-6]. The neutron brilliance which can be extracted from the TMR allows to simulate the performances of neutron scattering instruments which would be installed around a HiCANS.

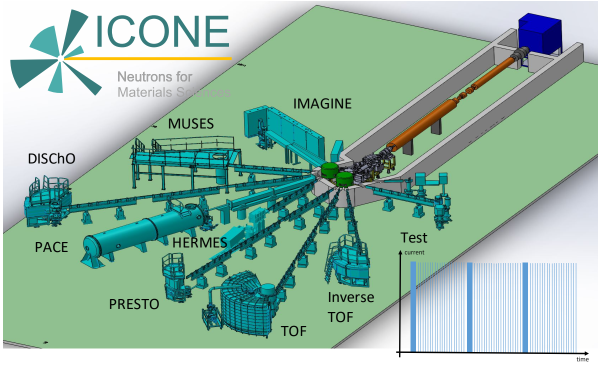

Fig. 1. Sketch of the ICONE facility. The actual facility will require extensive concrete shielding around the accelerator, the target stations.

At the CEA Saclay we consider the reference design described in Table 1. The proton accelerator energy is maintained in the lower energy range (25 MeV) in order to avoid significant activation of the machine. It also reduces the costs of construction and operation. Note that in order to maximize the efficiency of the source, it is necessary to be able to provide different time structures to serve best both high resolution and low resolution instruments. The current configuration which is considered consists of two interlaced time structures (see Fig. 1, bottom –right): (a) 2 ms – 20 Hz and (b) 200 μs – 100 Hz illuminating two different target stations TS1 and TS2. On TS1, the time structure (a) is reminiscent of “long pulse” spallation sources such as ESS and is ideally suited to low wavelength resolution instruments where resolution is traded for flux and bandwidth such as SANS, reflectometry or spin-echo. On TS2, the second time structure (b) is more suited to higher resolution experiments. The repetition rate is increased to maximize the flux at the expense of the wavelength bandwidth. The proposed time structures allow to build very short instruments in the range of 10 to 20 meters with up to 40 m for the longest instruments.

Table 1. The ICONE design parameters.

Accelerated particles	Protons
Protons energy	25 MeV
Peak current	80-100mA
Duty cycle	6% (4% + 2%)
Accelerator	Ion source RFQ 4 vanes (3.6 MeV) Hot DTL (25MeV)
Time structure (2 targets)	2ms – 20 Hz 200μs – 100 Hz
Target	Beryllium
Moderators	Thermal (H2O) Cold (methane) Cold (para-hydrogen)
Instrumentation	5 on Target Station 1 (low res.) 5 on Target Station 2 (high res.)

Using these design parameters, we performed calculations of the flux at the sample position for different techniques by transposing existing instrument designs. The Figure 2 shows the comparison of the flux at the sample position at Orphée (green) and ICONE (yellow). We should underline that one can boost the performances of instruments by going beyond conservative designs and by implementing innovative techniques: focussing techniques for reflectometry [10], focussing SANS for small Q [11], larger area Position Sensitive Detectors for powder diffraction [12], Micro-channel plate detectors for radiography [13] and large solid angle analysis for spin-echo. All these upgrades are either readily available or currently being developed or implemented at various institutes. The conclusion is that it is likely that new instruments on ICONE would probably outperform former instruments around the Orphée reactor. This conclusion is not too surprising as past experience shows that neutron sources have steadily improved the efficiency of their instruments over the decades (sometimes by an order of magnitude per decade) while the source itself remained unchanged. The ILL is a perfect illustration of this process.

Hence, we are confident that the ICONE source would satisfy the needs of a vast community of users.

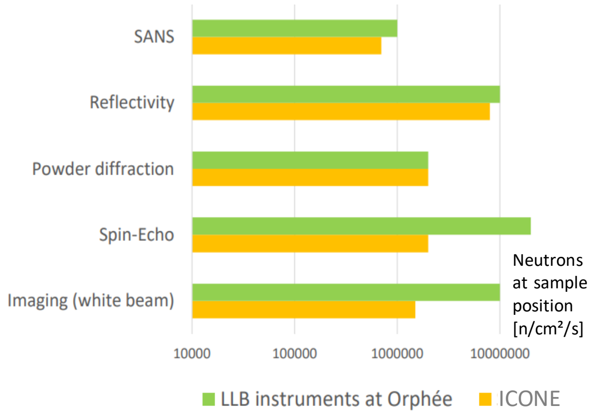

Fig. 2. Comparison of the performances of various types of neutron instruments: (green) typical instruments around Orphée, (yellow) similar instruments around ICONE.

Table 2. Foreseen instrumental suite and projection of the number of experiments, which could be done on the facility.

Instrument	***Typical run duration***	***Nb. Run / year***
SANS 1 (soft matter)	2.5 days	64
SANS 2 (hard matter)	5 days	32
Diffractometer 1	5 days	32
Diffractometer 2	2.5 days	64
Diffractometer 3	5 days	32
Reflectometry	5 days	32
Radiography	5 days	32
Direct ToF spectroscopy	5 days	32
Inverse ToF spectroscopy	15 days	10
Backscattering spectroscopy	10 days	16
Spin-Echo spectroscopy	15 days	10
TOTAL		**356**

Table 2 proposes a typical instrumental suite, which would meet the needs of the major part of the French user community. Assuming typical run durations extrapolated from earlier experience at Orphée-LLB, we estimate that it should potentially be possible to perform more than 300 experimental runs per year. This should lead to about 100-150 scientific publications per year.

2.3 Development plan

Owing to the fact that there are no HiCANS currently in operation, the construction of a demonstrator machine is a necessity to validate the technical concepts and the actual performances. This strategy is explicitly proposed by LENS [1].

HiCANS machines are especially suited to the construction of demonstrators as such machines are very modular. The proton energy can be upgraded over the lifetime of the machine by adding DTL modules. Provided that there is enough reserve power, the number of illuminated targets can be increased by distributing the proton beam on several targets. The target and moderator monoliths are rather modest in size and can be designed to be rather easily modified.

Hence, we propose to decompose the project ICONE into two phases: PRELUDE-ICONE which would be a demonstrator using an accelerator with an energy of about 10 MeV to produce sufficient neutrons. A single target would be illuminated and a limited number of instruments would be built (e.g. one diffractometer, SANS, reflectometer and radiography station). Such a limited scope machine would nevertheless allow to demonstrate all key technologies in actual operation and validate the operation and performances of typical neutron scattering instruments. The construction of a full-fledge user facility (25-30 MeV, 10 instruments) could be started with virtually no pending technological risks. Besides, the final machine ICONE could reuse most of the equipment of the demonstrator machine.

3 State of the art of the technologies

Over the period 2018-2022, the IRAMIS and IRFU Institutes at the CEA were supported by a SESAME programme of the region Île-de-France to develop the *IPHI – Neutron* platform. The goal was to setup a testbed for several technologies essential to the construction of HiCANS. This included in particular the operation of a proton accelerator at a high proton current (of the order of 100 mA), the construction of a target able to cope with a total incident proton power of 50 kW and the demonstration of the operation of a neutron scattering instrument around a CANS.

3.1 Accelerator

The *IPHI-Neutron* platform is built around the Injecteur de Proton à Haute Intensité (IPHI) accelerator. This accelerator was built to demonstrate the capability of operating a proton accelerator at a current up to 100 mA with a high current Electron Cyclotron Resonance (ECR) ion source and a 4-vanes Radio-Frequency Quadrupole (RFQ). The IPHI technology has been subsequently used for the design and the construction of the ion source of the IFMIF Prototype Accelerator (LIPAc), currently under commissioning at Rokkasho, Japan [14], and of the ESS RFQ, currently under commissioning at Lund, Sweden [15].

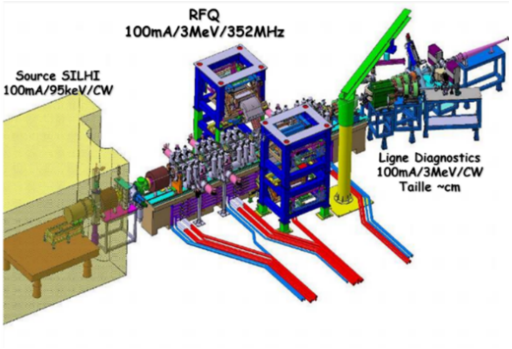

Fig. 3. Sketch of the IPHI accelerator. The machine is using an ECR proton source, a 4-vanes RFQ and a conical beam dump (able to withstand 300 kW). A deviated beam line is available to perform experiments.

In the case of the accelerator of the ICONE facility, we are considering using components derived from the ESS accelerator front-end, namely an ECR source, a 4-vane RFQ with a final energy of 3.6 MeV and a hot DTL section. There should be no major technical hurdle to boost the peak current from 62 mA (nominal value at ESS) to higher values (80 – 100 mA).

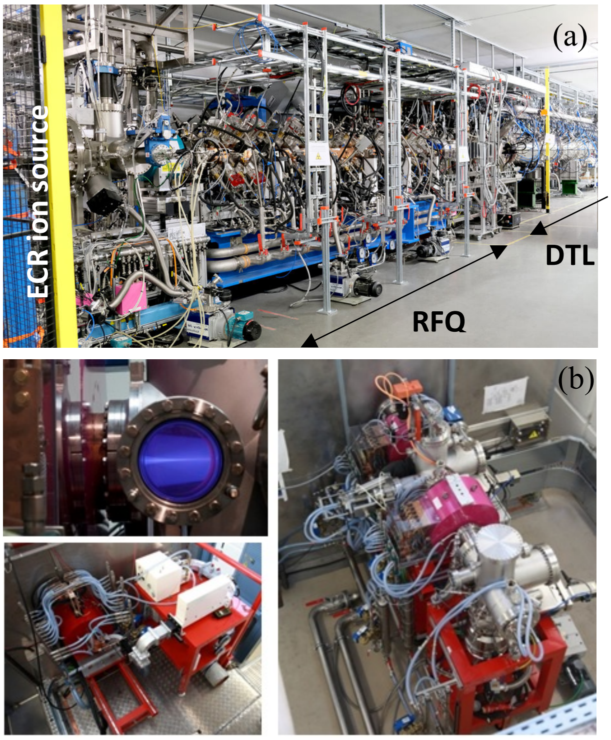

Fig. 4. (a) Front-end of the ESS accelerator: ion source, RFQ and first section of the DTL. (b) Ion source of the IFMIF Prototype Accelerator capable to produced currents up to 150 mA in continuous mode.

3.2 Target

As we aim to operate an accelerator with a proton energy as low as possible to minimize the costs of construction and operation and also to minimize activation issues, we have opted for a beryllium target which offers the best neutron yield in the range 10-30 MeV [16].

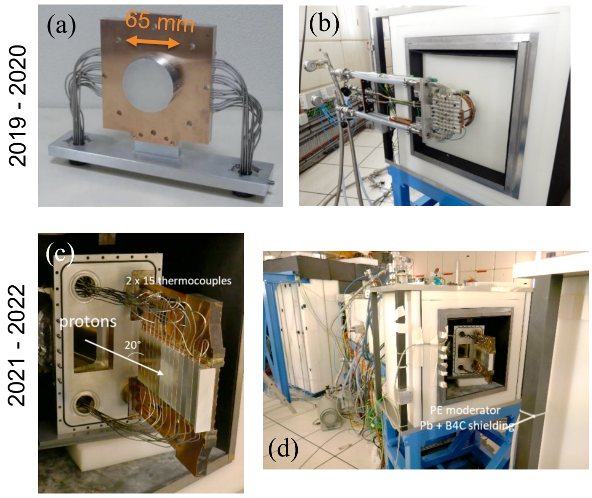

Fig. 5. (a) Beryllium targets mounted on a cooling plate. (b) Target in the moderator box. (c) 50 kW target prototype operating at a 20° incidence angle. (d) Target integrated in the moderator box.

The motto of the design was to build a system as sturdy as possible as we are aiming for very high reliability. It was thus decided to physically separate the target and the cooling system so that a failure of the target would have no impact on the accelerator as could be the case for a water leak in the accelerator circuit. Hence it was decided to attach beryllium blocks with screws on a copper cooling support (see Fig.5b). We started with a « lower power » prototype of a few kW. The power density on the target can go up to 500 W/cm². For the current full scale 50 kW prototype, we used an inclined geometry at 20° with respect to the incident proton beam. The target is composed of several 20 mm sub-bricks which can be individually replaced in case of a failure. The proton beam can be redirected in order to evenly spread the power over the whole target surface.

The high power target was tested over a period of 100 hours in a 2 weeks run to evaluate its durability [17].

3.3 Moderators

The TMR assembly is currently only comprised of a polyethylene moderator with one extraction hole (see Fig. 5b). The TMR is installed on trolleys so that it can be easily opened for maintenance and operation.

We are currently developing the technologies necessary to build a directional moderator using para-hydrogen. We recently achieved a para-hydrogen polarisation of 99.7% (without neutron irradiation). The system will be using a thermosiphon to fill the hydrogen finger moderator. Liquid hydrogen will serve as the cooling fluid and avoids an extra helium cooling circuit. The cooling can be achieved with an entry level cryogenerator as the radiation heating in a HiCANS TMR is rather limited. This facilitates the design of the cold source and makes its integration in the TMR easier. This is especially important as the use of finger moderators will require that each instrument using cold neutrons on ICONE has its own dedicated moderator.

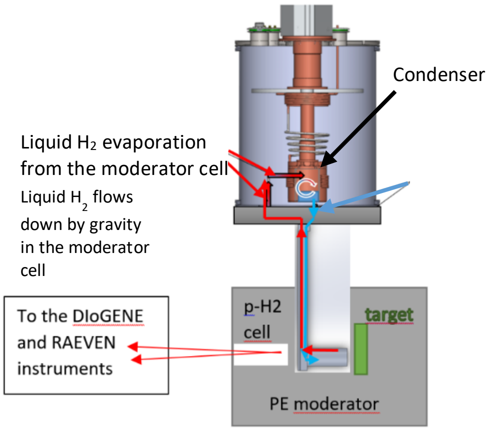

Fig. 6. Sketch of a cold finger moderator using para-hydrogen. The setup is using the principle of the thermo-siphon where the hydrogen is itself the cooling fluid. This configuration has been used in the MINOS and COCOTIER nuclear physics experiments to build liquid hydrogen targets [18].

3.4 Instrumentation

The DIoGENE instrument, DIffusion GEnérique de NEutrons, has recently been installed around the IPHI source. The instrument is a general-purpose neutron scattering instrument aimed at investigating the performance of the neutron TMR, the issues related to background noise due to fast neutrons and gamma rays productions and more generally the ToF data acquisition protocols and processing in event mode. The picture below shows the instrument in the *IPHI – Neutron* casemate. One limitation of the instrument concerning its resolution is its short flight path (L = 6.6 m).

Fig. 7. The IPHI – Neutron facility: the accelerator in the back, the TMR + shielding box (white) with one small extraction hole and the DIoGENE instrument.

During a recent operation of the source, it was nevertheless possible to observe the diffraction of an austenite steel rod when operating the machine in pulsed mode at a power of 200 watts [19].

Due to the low power used for the measurement, the counting time was 60 minutes. However, we think that a number of rather simple improvements are possible which could boost its flux by almost two orders of magnitude. This would reduce the acquisition times from hours to minute.

The long-term goal would be to increase the proton energy from 3 MeV to 25 MeV which would multiply the neutron flux by a factor of 300 bringing the instrument at a performance level comparable to the high flux powder diffractometer G41 around Orphée.

In order to acquire as much experience as possible, we are also collaborating with the JCNS Jülich Centre for Neutron Science. The HERMES reflectometer was recently transferred from the Orphée reactor to the JULIC test platform at the Forschungszentrum Jülich [20-21].

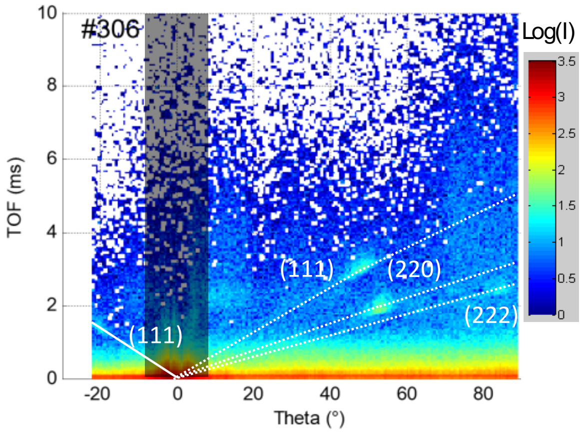

Fig. 8. Representation of the diffraction on a steel rod in the ToF Vs diffraction angle plane. The diffraction peaks have been indexed as (111), (220), (222) in the austenite phase.

4 Conclusion and outlook

We are convinced that the performance of a compact source is potentially equivalent to a medium scale research reactor or spallation source while offering low construction and operation costs.

There are no identified technological hurdles. The accelerator technology, while still quite ambitious, is available. Various technological solutions for the target are being considered and developed by several institutes within the ELENA network. The moderator technology is rather simple and does not require complex cryogenic systems, making the construction and handling of cold sources much easier than on fission or spallation sources. A number of new instrumentation concepts have been developed in the past decade during the R&D effort for ESS and are currently being implemented.

From a more specific French perspective, it is possible to benefit from a rich ecosystem: (i) scientific and technical expertise at Saclay and Grenoble, (ii) a wide user base, (iii) the possibility to reuse the R&D efforts injected into ESS and the acquired expertise.

The last point is that all developments for the ESS in the field of data reduction and data processing could be reused and would not require extra efforts.

We are thus proposing the construction of the HiCANS source ICONE in France [22] to support the French users in materials science research. This source would conduct its own research programs and does not aim at being in competition with ESS. ICONE would be integrated into a future European neutron ecosystem consisting of a network of local CANS or HiCANS national facilities and a few high-end national facilities, while ESS would be the reference source if ultimate capabilities are required.

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It is also part of the collaboration within ELENA and LENS on the development of HiCANS.

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