A New Interdisciplinary Irradiation at SPRAL2 Phase 1

Version 2

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Introduction

The international expert committee on the future of GANIL has analyzed many contributions and after a first meeting held June 9, 2020 recommended to study more into details the options described in a contribution called « A new Interdisciplinary Irradiation Area at SPIRAL2" proposed by a very large collaboration. In this contribution, an evolution of the SPIRAL2 Phase 1 facility toward 1) a multiuser facility, 2) a broader scientific scope and 3) an increase of interdisciplinary applications with a potential high societal impact was proposed. To address the request of the Committee, a dedicated Working Group (WG) has been setup which gathered people from the various relevant expertise. This WG was then organized in several sub-groups:

- neutron physics and instruments
- neutron production (reactions, targets, moderators, etc.)
- radioelements and AB-NCT (using LINAC beams or neutrons)
- material studies (using LINAC beams or neutrons)
- infrastructure aspects (including beam sharing techniques, radioprotection, safety, buildings, etc.)

The WG had meetings every 2 weeks to discuss the work done in the several subgroups. A first presentation of the progresses for the whole WG was discussed in a meeting with M Spiro, F Farget and N Alamanos on November 12, 2020. The present interim report synthesizes these discussions.

To start working, the dedicated subgroups listed above were fed by input data which are summarized in Table 1 to Table 3 and Figure 1.

LINAC beam specifications :

Particles	**H^+**	**$^3He^{2+}$**	**$^4He^{2+}/D^+$**	**ions**	**ions**
q/A	1	3/2	1/2	1/3	1/6
Max. I (mA)	5	5	5	1	1
Min. Energy (MeV/A)	0.75	0.75	0.75	0.75	0.75
Max Energy (MeV/A)	33	24	20	15	9
Max beam power (kW)	165	180	200	45	54

Table 1 : Beams available at the SPIRAL2 Phase 1 facility

Heavy ion beam intensities :

Ions	Intensity (pμA)	Intensity (pμA)
^{18}O	216	375
^{19}F	57	50
^{36}Ar	35	40
^{40}Ar	5.8	30
^{36}S	9.2	30
^{40}Ca	6	20
^{48}Ca	2.5	15
^{58}Ni	2.2	10
^{84}Kr	0	20
^{124}Sn	0	10
^{139}Xe	0	10
^{238}U	0	2.5

Table 2 : Heavy ion beam intensities in pμA available using the q/A=1/3 or 1/7 at SPIRAL2

Beam structure :

Nominal pulse rate	88 MHz
Bunch extension	1,6ns (±2σ) (depends on energy and distance between LINAC exit and experiment)
Duty cycle of the slow chopper	From 1/10000 to 1/1 (frequency of 1Hz from 1/10000 to 1/2000 and a frequency of 5Hz from 1/2000 to 1/1)
Duty cycle of the fast chopper	From 1/1000 to 1/100 (repetition frequency from 8,88 kHz to 880 kHz)

Table 3 : LINAC beam time structure

Neutron flux and energy

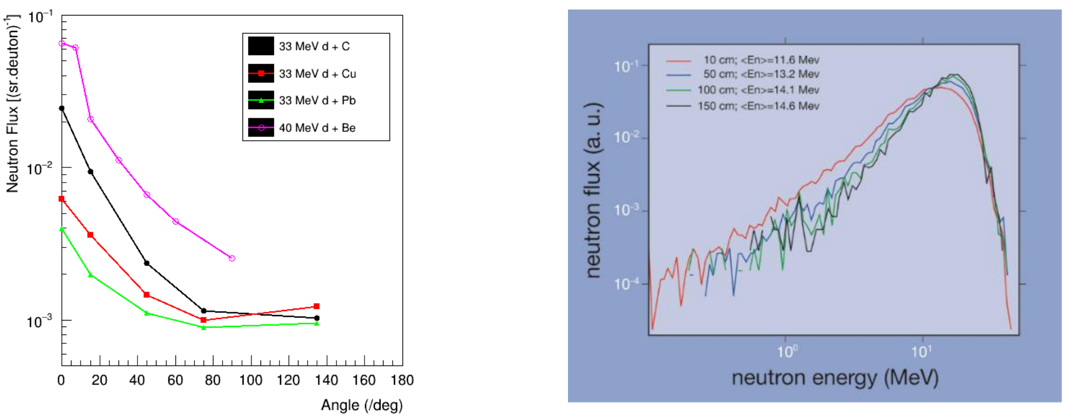

Figure 1 : left : Neutron flux produced in deuteron induced reactions using various converter materials as a fonction of the azimuthal angle. Right: neutron flux as a function of energy produced in the d(40 MeV)+C reaction.

With a 1 mA beam current, the neutron flux is of the order of 10^{14} n/s/sr at 0° (10^{12}/n/cm^2/s 10 cm downstream of the converter). These figures will be discussed in the neutron production section of the report.

Instrumentation: Neutron Scattering – Neutron Radiography

Emmanuelle Lacaze, Frédéric Ott, Marie Plazanet, Alain Pautrat, Charles Simon (spokesperson), Virginie Simonet

Task of the working group:

Explore two scenarios (neutron radiography and neutron scattering); identify the technical case, the scientific case and the community of users. The group did not explore the associated costs (construction and operating costs).

Common needs for the different topics: neutron radiography and neutron scattering

For the two scenarios, there are common needs based on experience of such instruments in reactors and spallation sources:

For each instrument, minimum 2000 hours (90 days) per year to develop a community of users and experience of technical aspects (15 runs of 4/5 days and 20 days of commissioning of new developments).

Topic 1 : Neutron radiography

The neutron tomography is a quite simple, non-expensive instrument that can be implemented on a neutron beam whatever is its time structure. 50-100 kW are enough to get rather good results. Stability and availability are necessary for tomography (rotation of the sample) and kinetic measurements. Cold neutrons (or thermal neutrons at least) are needed.

The possible user community is broad (diffusion of water in materials (concrete, rocks,), biology (diffusion of cholesterol in membranes, …), water for cultural heritage, hydrogen diffusion for fuel cells and batteries, food science, metallurgy,). These users are not well experienced and have to be helped for measurements, data processing and analysis.

Topic 2 : Neutron scattering

In the case of neutron scattering there are two technical possibilities:

<u>A/ Scenario 1: operation of a continuous source (5mA CW)</u>

In continuous beam mode, it is possible to build any type of instruments, the instrument selects the appropriate bandwidth. The instruments are compact and quite inexpensive. But this option needs a large power on the target and on the moderator (165kW).

<u>B/ Scenario 2: operation of the source in pulsed mode for Time-of-flight (ToF) measurements (Duty Cycle 4%; f = 10-50Hz, P = 7kW)</u>

This option needs a more reasonable power on the target (7kW) and uses all the neutrons in the measurement. The instruments are longer and more expensive~~.~~

In both scenarios (A or B), the performances of the instruments would be roughly equivalent, the lower power on the target in Scenario 2 being compensated by the operation in ToF. In both scenarios, the performances will be typically 1% to 10% of the Orphée instruments. In these conditions, our group estimates that the present user community will not use such a "performance reduced" instrument and to build a new user community will be difficult in the present landscape.

Summary

Neutron radiography : Sufficient performance is expected to be able to carry out a competitive and useful scientific program. Potential users will not be experts in neutron techniques Significant technical support will be required

Neutron scattering : A large community of regular users exists (~ 1500 people in France). This community is used to a high level of performance (Orphée - ILL). In the standard way of running, neutron scattering instruments on SPIRAL2 would have reduced performance (1% and 10% of instruments on Orphée).

	P faisceau	**Disponibilité**	**Utilisation**	
Radiographie	50-165kW	Min 90 jours /an (tronçons continus de 3-5 jours)	15-20 runs expérimentaux /an possibles	Performances OK pour résolution 50-100µm (3-5 jours par expérience)
Diffusion SANS	165 kW si CW 7 kW si Pulsé + Temps de Vol	Min 90 jours /an (tronçons continus de 3-5 jours)	15 runs expérimentaux /an possibles	Performances réduites (3-10% de PAXY@Orphée)
Diffraction	165 kW si CW 3 kW si Pulsé + Temps de Vol	Min 90 jours /an (tronçons continus de 3-5 jours)	15 runs expérimentaux /an possibles	Performances très réduites (1-5% de 3T1 - G41@Orphée)

Table 4 : summary of possibilities in the « standard » way of running.

Neutron production

M. Baylac (LPSC), A. Drouart (IRFU/DPhN/LENA), X. Ledoux (GANIL), L. Thulliez (IRFU/DPhN/LEARN)

Study framework

This study aims to identify orders of magnitude of thermal neutron flux that can be extracted from a target-moderator-reflector assembly located in the I2A experimental area. The production of primary neutrons due to interaction of the beam from the LINAG with different target materials is first examined (see Table 5). The neutron yields and the energy spectra of the neutrons produced are presented (Figure 2 and Figure 3). Then, these high energy neutrons (a few MeV) are slowed down to thermal energy of 25 meV using various moderators. The neutron flux that can be extracted from a moderator is looked at for different materials.

Three scenarios for the charged particle beam/target interaction were selected for this study. For each of these scenarios a light water and heavy water moderator is placed near the target to slow down the neutrons produced. The light water will effectively slow down the neutrons given the low mass of hydrogen and therefore spatially concentrate the flow in the moderator. Significant gamma background noise is produced due to the strong radiative capture of neutrons by hydrogen. The heavy water will minimize the gamma background noise but will spatially dilute the thermal neutrons.

- **Scénario 1** : 40 MeV deuteron beam on a carbon target. The geometry of the target is that of the existing rotary converter at GANIL is taken as a reference because it makes it possible to hold a deposited power of 200 kW and has already held a power of 50 kW **[GANIL_CONVERTISSEUR_CARBONE]**.
    - **Scénario 1.a :** Light water moderator placed downstream of the target for reasons of spatial obstruction.
    - **Scénario 1.b :** Heavy water moderator placed downstream of the target for reasons of space requirement.

- **Scénario 2** : 40 MeV deuteron beam on a beryllium target. The geometry of the beryllium target and the profile of the beam are those currently being studied within the framework of the SONATE **[SONATE]** project and which makes it possible to maintain a deposited power of 50 kW.
    - **Scénario 2.a :** Light water moderator placed around the target.
    - **Scénario 2.b :** Heavy water moderator placed around the target.

- **Scénario 3** : 33 MeV proton beam on a tantalum target. The geometry of the target and the profile of the beam are those currently being studied within the framework of the SONATE project for beryllium. If this solution turns out to be relevant, thermo-mechanical studies would be necessary in order to have a suitable geometry for this target, but this is outside the context of this study.
    - **Scénario 3.a :** Light water moderator placed around the target.
    - **Scénario 3.b :** Heavy water moderator placed around the target.

Primary neutrons source term

Reaction	**Yields [n/part]**	**$\langle E_n \rangle$ [MeV] at 0 degree**	**$\langle E_n \rangle$ [MeV] [5-10] degrees**	**$\langle E_n \rangle$ [MeV] [10-15] degrees**
Deutons(40MeV) + carbone	0.034	15.4	14.9	14.2
Deutons(40MeV) + beryllium	0.06	15.2	14.7	13.9
Protons(30MeV) + tantale	0.01	4.1	5.4	6.23

Table 5: Properties of neutrons produced in various reactions.

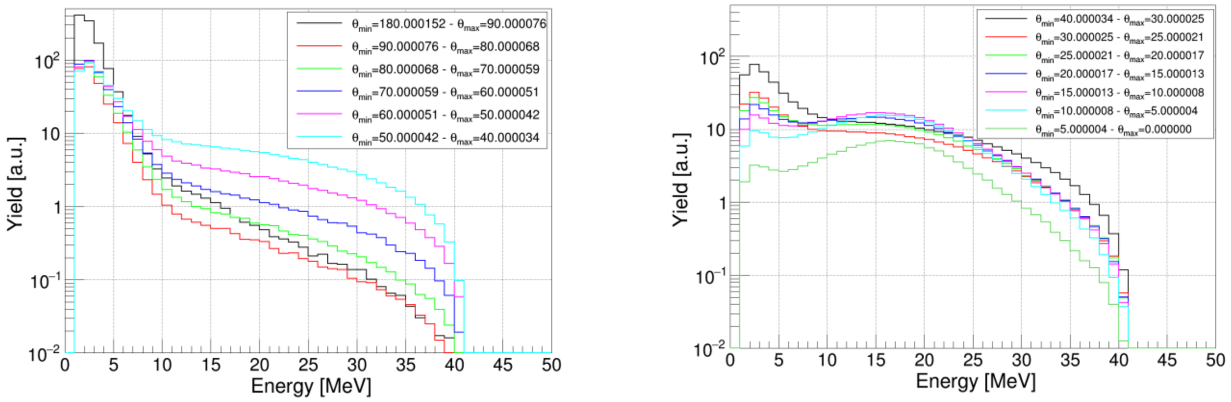

Figure 2: Neutron energy spectrum produced in the 40 MeV d+Be reaction.

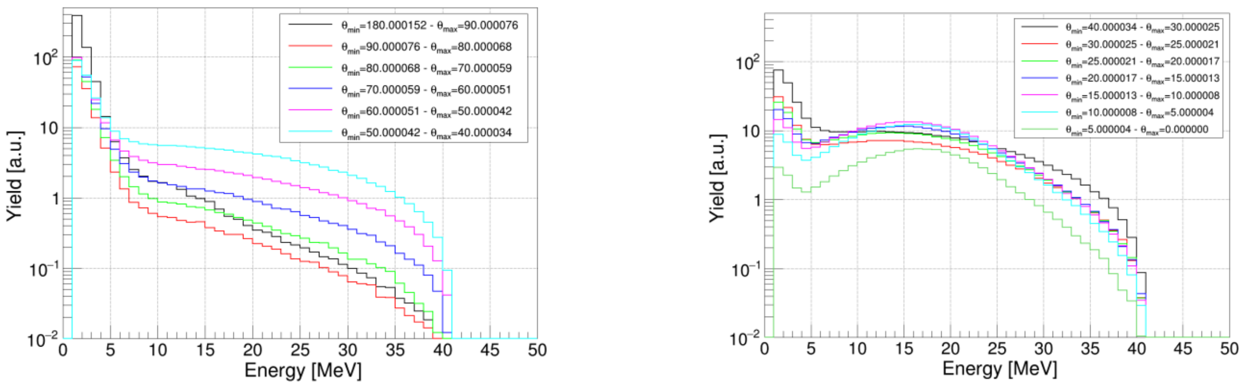

Figure 3: Neutron energy spectrum produced in the 40 MeV d+C reaction.

Geometry of target-moderator ensembles for various targets

The size of the moderator is here fixed at 120cmx120cmx80cm (Figure 4) for scenario 1 where the moderator is only present downstream of the target and 150x150x150cm (Figure 5) for scenarios 2 and 3. The maximum asymptotic flow should be reached for these moderator dimensions. A study of the influence of the moderator size on the maximum flux could be looked at in a future study. The moderator is surrounded by a shielding composed from the inside to the outside of 5 mm of boreflex to capture thermal neutrons, 5 cm of lead to attenuate gamma radiation, 10 cm of polyethylene to minimize leakage of neutrons and finally 5 mm of boreflex to minimize the presence of thermal neutrons outside the shielding. This shielding could be optimized for radiation protection reasons in a future study. In scenario 1, there is no shielding upstream of the target.

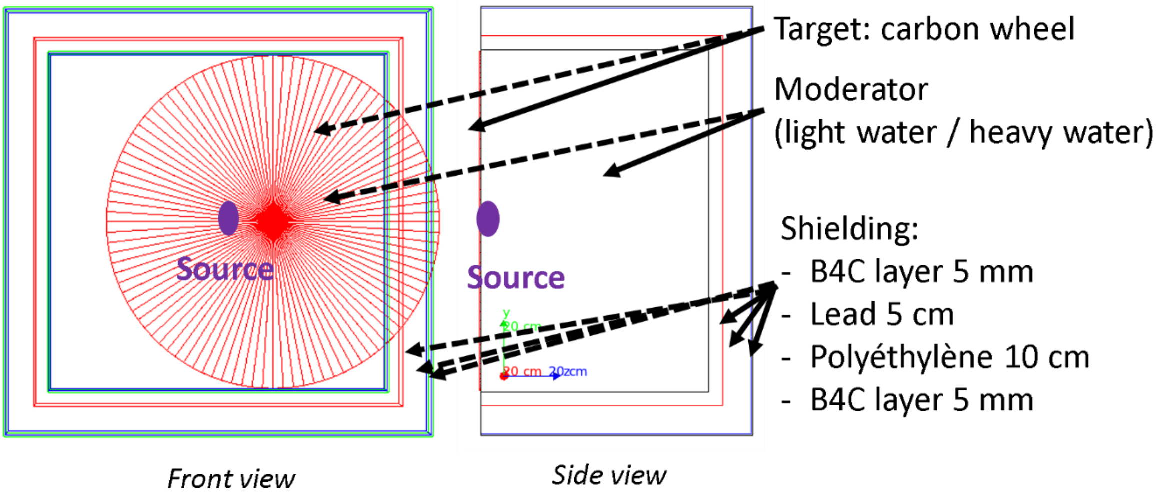

Figure 4: Geometry of the target-moderator ensemble for a 200 kW carbon converter like target (scenarios 2 and 3) 120cmx120cmx80cm.

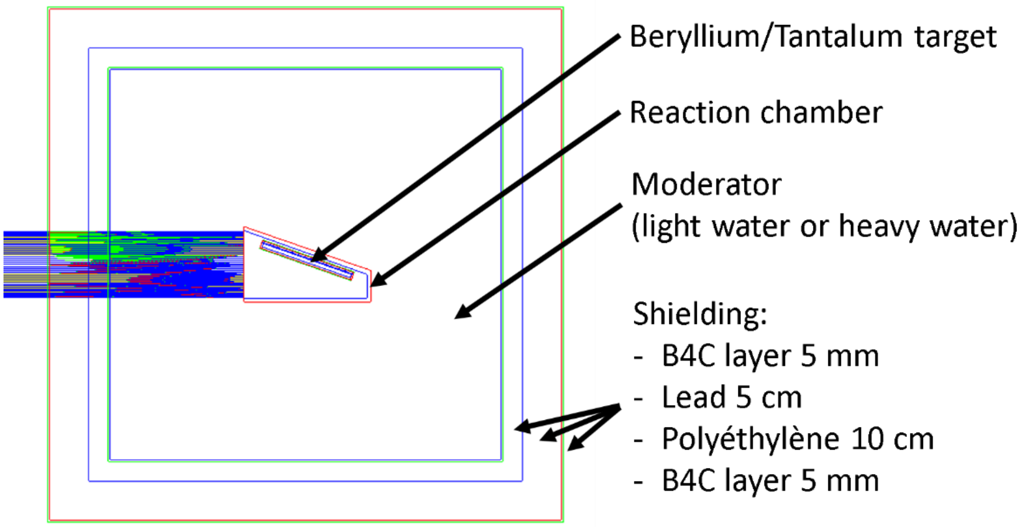

Figure 5: Geometry of the target-moderator ensemble for a SONATE like target (scenarios 2 and 3). The moderator size is 150cmx150cmx150cm.

The **spatial distribution of the neutrons production points** is given by the spatial distribution of the beam of charged particles on the target. For **scenario 1** (carbon target), the beam is assumed to be Gaussian with a variance σ = 5 mm (the diameter is therefore approximately 6 σ = 30 mm) in the horizontal and vertical direction. For **scenarios 2 and 3**, the beam is assumed to have a Gaussian shape with parameter σ X = 20 mm and σ Y = 10 mm and scanned with a scanning element to distribute the power on the target.

Neutrons are generated uniformly over a depth of 4.21 mm for 40 MeV deuterons in carbon, 5.57 mm for 40 MeV deuterons in beryllium and 1.37 mm for 33 MeV protons in tantalum. These quantities correspond to the stopping distance of the particles in the target and are obtained with the software SRIM2008.

In the following, the flux inside the moderator is viewed without a neutron extractor channel. This makes it possible to define the places where the flux of thermal neutrons is maximum and therefore to place the extractor channels at this place. This also makes it possible to have a spatial distribution of the flow, which may be relevant for certain applications (spatial homogeneity of the flow). Secondly, extractor channels are placed inside the moderator to extract the neutrons.

Simulation tool

The digital tool mainly used in carrying out this study is the GEANT4 computer library developed at CERN [GEANT4]. From this, a Monte-Carlo neutron and gamma transport application dedicated to the optimization of a compact neutron source was developed at DPhN. Application validation and qualification steps were necessary to ensure the accuracy of the predictions.

TRIPOLI-4 is a Monte-Carlo code for particle transport, the first versions of which have been developed since the 1970s at CEA Saclay. It is used as a reference code by EDF, FRAMATOME, ORANO and the CEA. As such, it benefits from a very broad validation and qualification base [TRIPOLI4].

GEANT4 was therefore validated against TRIPOLI-4 via microscopic and macroscopic benchmarks on a set of materials usually used in neutronics. The materials tested are polyethylene, light water, heavy water, graphite, beryllium and beryllium oxide. **A systematic error of the Geant4 code is estimated in the most penalizing configurations at 15%.**

It is important to remember here that this qualification gives confidence in the processing of neutron interactions using the nuclear data libraries evaluated, i.e. for neutrons with energy below 20 MeV. Beyond this energy to our knowledge no qualification has yet been achieved. The neutron / nucleus interaction is described using the intranuclear BIC (Binary Cascade Model) model, the validity of which at these energies remains to be validated. **It is important to note that to date above 20 MeV the models describing the neutron / nucleus interaction present in Geant4 have not been validated. This validation is outside the scope of this study.**

Spatial distribution of the neutron flux within the moderator

Choice of the studied moderators

The moderators studied here are light water and heavy water because they are representative of moderators that can be used for different applications. The hydrogenated moderators make it possible to have a high concentration of thermal neutrons (hydrogenated materials) but which are the source of a large gamma flow. These gamma may not be considered if it is decided that curved neutron guides will be used in order to bring only the useful neutrons to the experimental point (the fast neutrons will continue their path in a straight line and will not interact with the detector). Deuterated moderators make it possible to have a homogeneous neutron flux over a large spatial area while minimizing the production of gamma radiation.

Moderators without extraction channel

The fluxes given are normalized by incident charged particle (cf. Table 5). The thermal neutron flux maps for the different scenarios are presented in figures 6-9. **These 2D maps were obtained by integrating the flow along the third axis, here along the X axis, the Z axis being the beam axis.**

The heat flux obtained for a **moderator in light water** are shown in Figure 6 and Figure 7. The places where the heat flux is maximum are represented by the yellow spots. With a SONATE-type target, two maximums are present on either side of the target (Figure 6). With a wheel-type target, only one maximum is visible (Figure 7). The values of the maximum fluxes as well as their position are given in table 7.

The heat flux for a **heavy water moderator** is shown in Figure 8 and Figure 9. These flux maps show that the thermal neutron flux is more spatially diluted than with a light water moderator. This is due to the elastic scattering cross section for deuterium which is about ten times lower than that for hydrogen. The maximum heat flux value covers a larger spatial area than with a light water moderator because the deuterium capture cross section is about one hundred times smaller than that of hydrogen. The flow is homogeneous over a larger spatial area, which can be advantageous for certain applications.

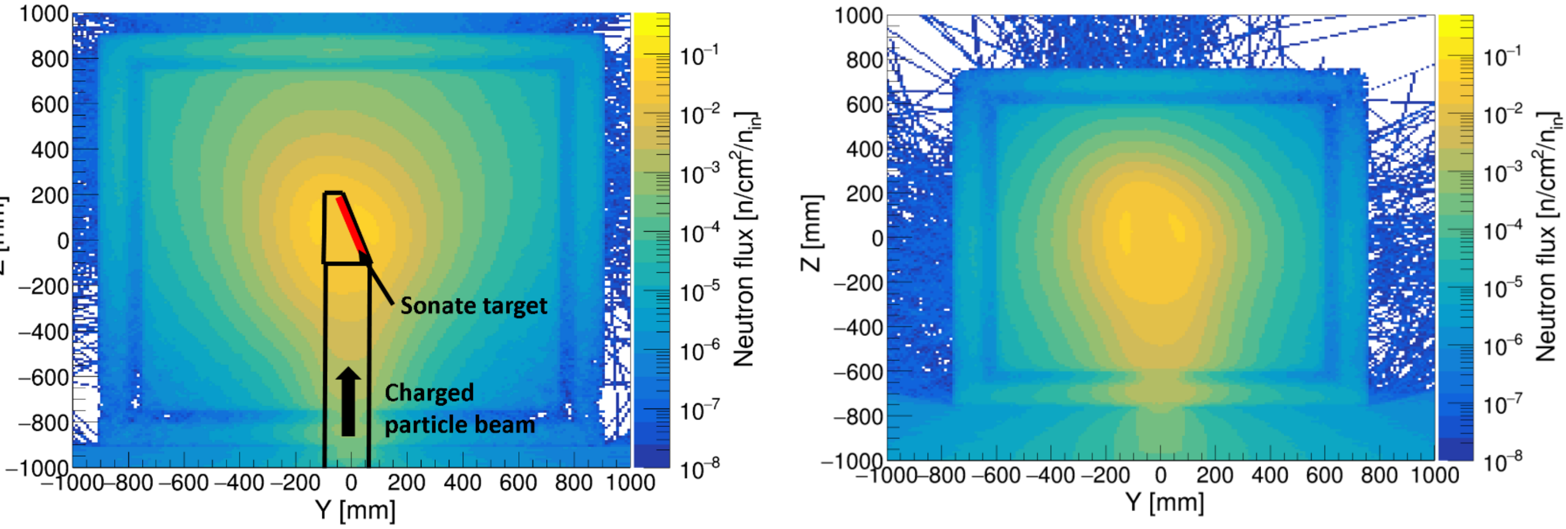

Figure 6: 2D map of thermal neutron flux with a SONATE-type target geometry for a beryllium (left) and tantalum (right) target. The moderator is light water. The flow is integrated along the X axis.

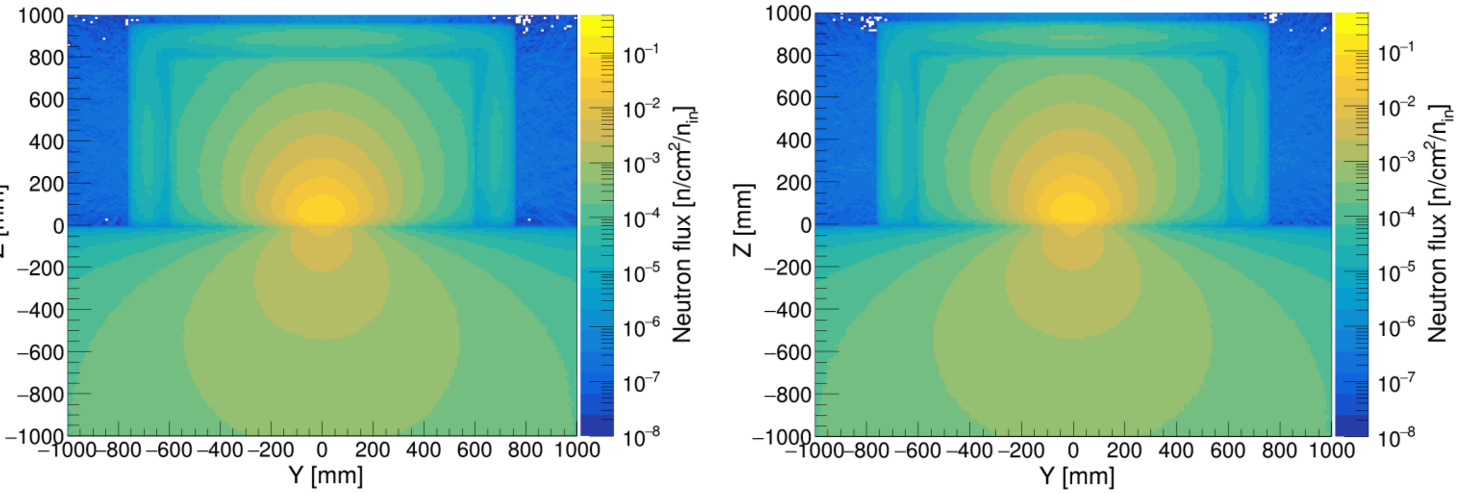

Figure 7: 2D map of thermal neutron flux with a wheel-type target geometry for a beryllium (left) and tantalum (right) target. The moderator is light water. The flow is integrated along the X axis.

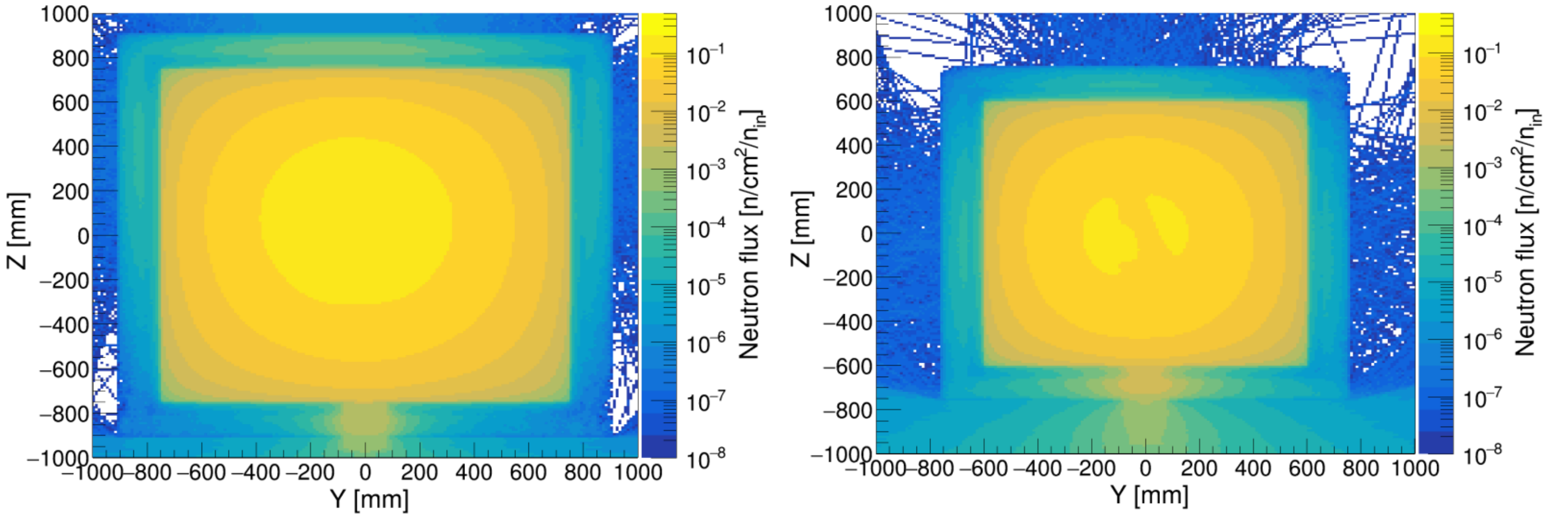

Figure 8: 2D map of thermal neutron flux with a SONATE-type target geometry for a beryllium (left) and tantalum (right) target. The moderator is heavy water. The flow is integrated along the X axis.

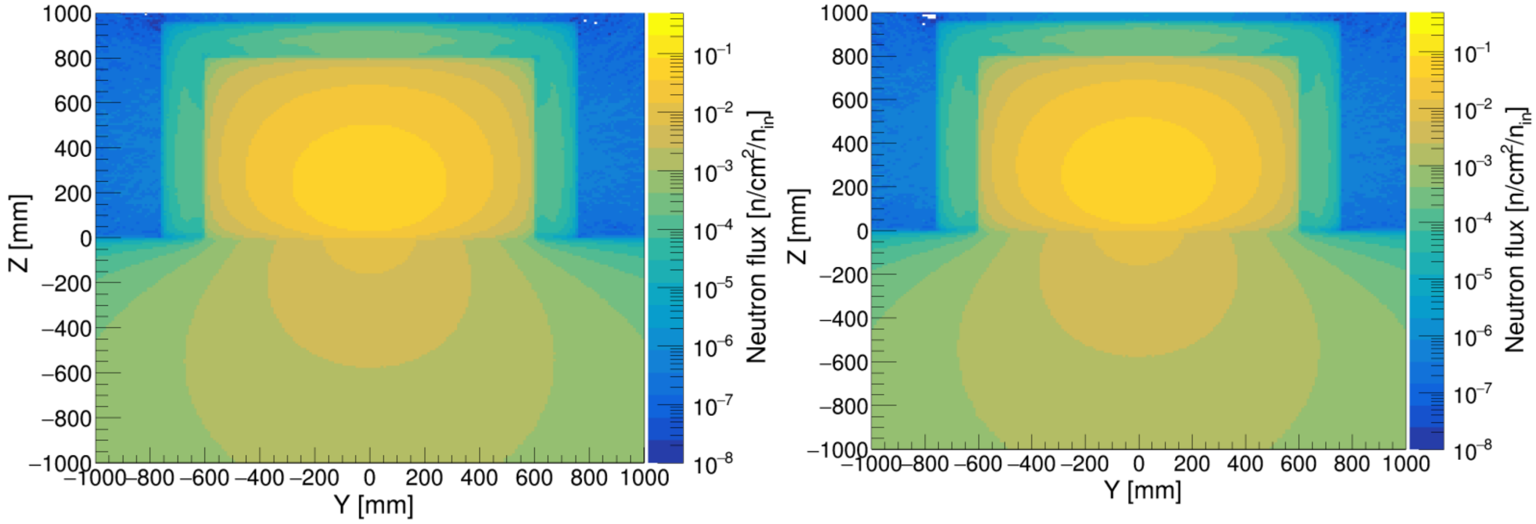

Figure 9: 2D map of thermal neutron flux with a wheel-type target geometry for a beryllium (left) and tantalum (right) target. The moderator is heavy water. The flow is integrated along the X axis.

Reactions	Beam power for a 5 mA intensity	Particle rate	Neutron rate [$n_{primary}$/s]
d(40MeV) +carbone	200 kW	3.12 10^{16} d/s	1.06 10^{15}
d(40MeV) +béryllium	200 kW	3.12 10^{16} d/s	1.87 10^{15}
p(33MeV)+tantale	165 kW	3.12 10^{16} p/s (165kW)	3.12 10^{14}

Table 6 : Particle and primary neutron rates for a 5 mA beam intensity

	Maximal thermal neutron flux In the moderator [n/cm²/n$_{primaire}$]		Maximal thermal neutron flux In the moderator [n/cm²/particule chargée]		Position of the maxima (Y, Z) [cm]	
Reactions	Light water	Heavy water	Light water	Heavy water	Light water	Heavy water
d(40MeV)+carbon (Wheel)	$3.8\ 10^{-3}$	$1.0\ 10^{-3}$	$1.3\ 10^{-4}$	$0.3\ 10^{-4}$	(-0.5, 5.5)	(-0.5, 22.5)
d(40MeV)+beryllium (Wheel)	$3.6\ 10^{-3}$	$9.7\ 10^{-4}$	$2.2\ 10^{-4}$	$5.8\ 10^{-5}$	(-0.5, 5.5)	(-1.5, 21.5)
d(40MeV)+beryllium (Sonate)	$1.6\ 10^{-3}$	$1.4\ 10^{-3}$	$9.6\ 10^{-5}$	$8.4\ 10^{-5}$	(6.5, 4.5)	(10.5 , 13.5)
p(33MeV)+tantalum (Sonate)	$1.3\ 10^{-3}$	$9.8\ 10^{-4}$	$1.3\ 10^{-5}$	$9.8\ 10^{-6}$	(6.5, 3.5)	(-17.5, 1.5)

Table 7: maximum fluxes and their position in the moderator

Moderators with neutron extraction channels

The neutron extractor channels are cylinders with a radius of 2 cm.

For each of the moderators studied previously, extractor channels are placed at the points where the heat flow is maximum to have a first estimate of the order of magnitude of the thermal neutron flux that it would be possible to extract from these moderators. **These extractors are placed at +/- 45 degrees from the beam axis** to reduce the flow of extracted gamma rays (Figure 10).

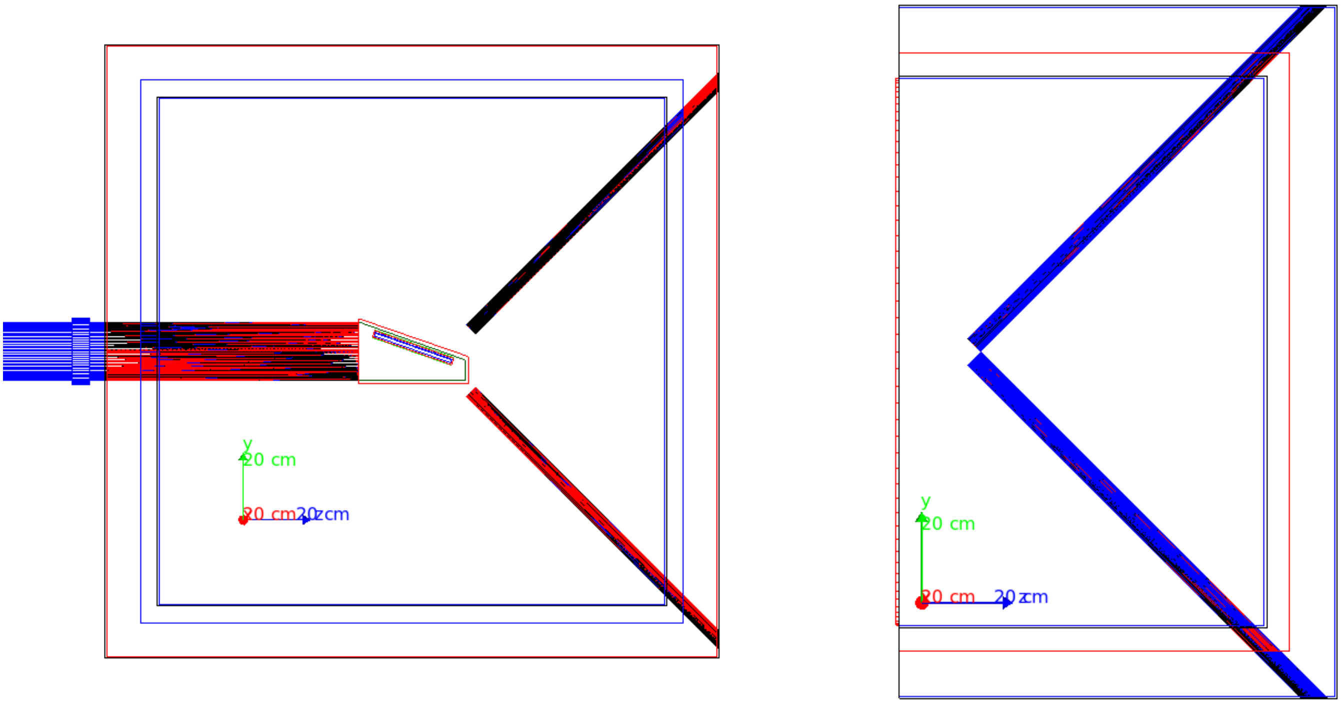

Figure 10: Geometries with two extractor channels placed in the moderator at +/-45 degrees from the beam axis, where the flow is maximum. SONATE-type target (left) and wheel type target (right).

For each of the targets and each of the moderators, the following configurations were studied:

- Carbon target
    - ➔ Light water
        - **Configuration v1** : **1 extractor channel** located on the **overall maximum**
        - **Configuration v2** : **2 extractor channels** located on the **overall maximum**
    - ➔ Heavy water
        - **Configuration v1** : **1 extractor channel** located on the **overall maximum**
        - **Configuration v2** : **2 extractor channels** located on the **overall maximum**
- Beryllium target

For the beryllium target, the neutron efficiency is reduced by about 20%, because a beryllium target is effectively made of a mixture of aluminum and beryllium in order to avoid the phenomenon of blistering.

- ➔ Light water
    - **Configuration v1** : **2 extractor channels**, the starting point of each of the extractor channels is positioned on one of the **two local maximums**
    - **Configuration v2** : **2 extractor chan**nels, the starting point of each extractor channel is positioned on the **overall maximum**
- ➔ Heavy water
    - **Configuration v1** : **2 extractor channels**, the starting point of each of the extractor channels is positioned on one of the **two local maximums**
    - **Configuration v2** : **2 extractor channels**, the starting point of each extractor channel is positioned on the **overall maximum**

The evolution of the thermal (E <100 meV) and fast (E> 0.1 MeV) neutron flux are shown in the Figure 11 and Figure 12 below. Inside the moderator, the flow of thermal neutrons over an area of approximately 12 cm^2 is of the order of 1 10^{10} $n/cm^2/s$ / kW, ie of 2 10^{12} $n/cm^2/s$ for a power of 200 kW . At a distance of 3 meters from the starting point of the extraction channel, the thermal neutron flux is of the order of some 10^5 $n/cm^2/s/kW$, i.e. some 2 10^7 $n/cm^2/s$ (see Table 8 and Table 9).

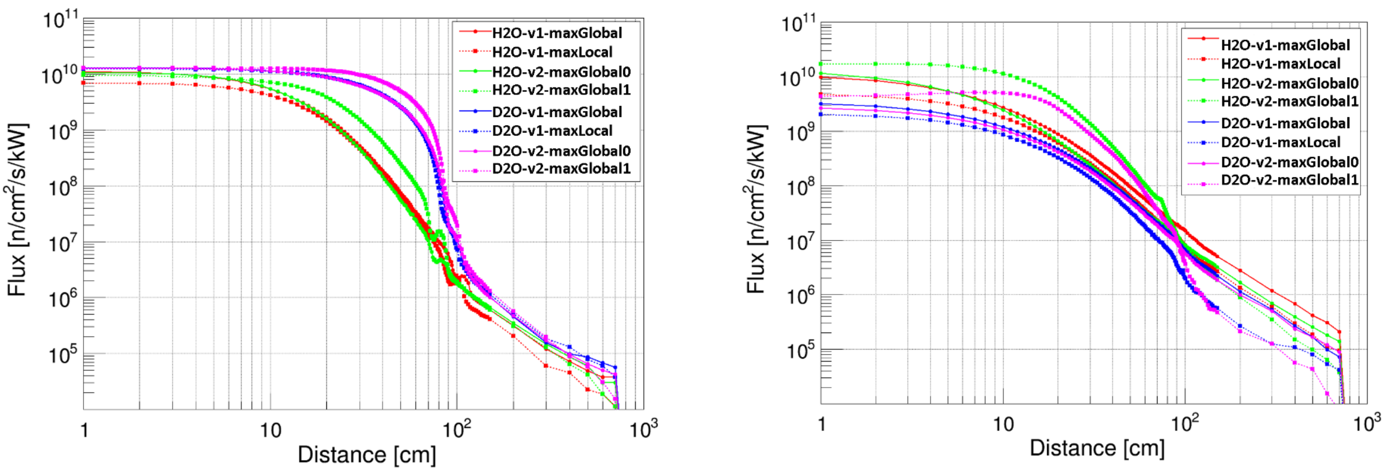

Figure 11: Geometries presented above with two extractor channels placed in the moderator at +/-45 degrees from the beam axis, where the flow is maximum. SONATE-type target (left) and wheel type target (right).

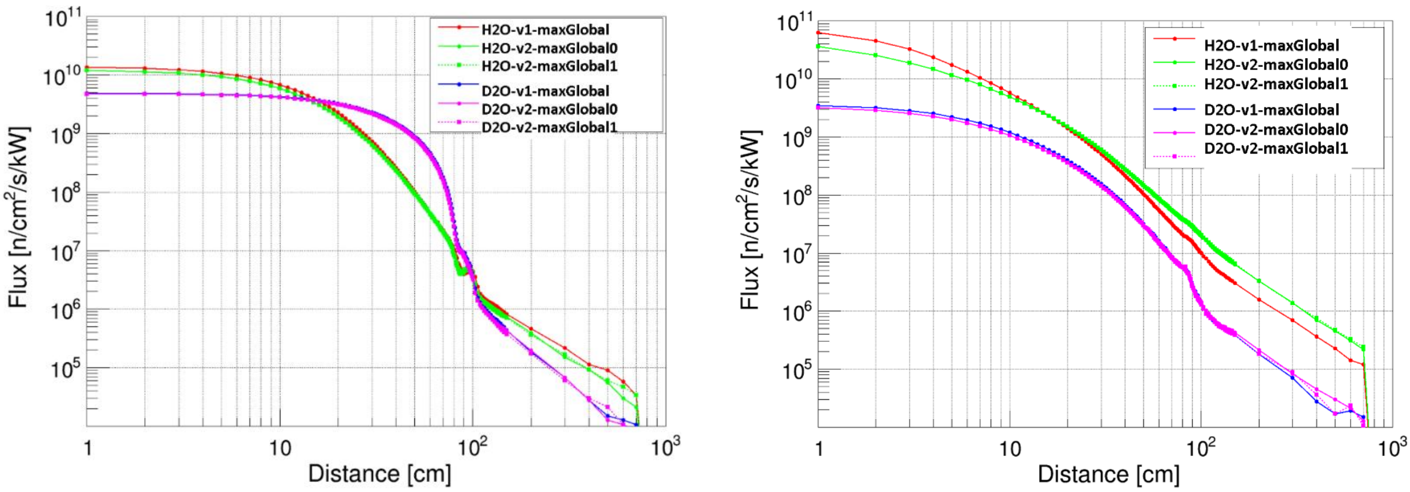

Figure 12: ***Deuterons of 40 MeV on a beryllium target****, evolution of the neutron flux as a function of the distance from the start of the extractor channel. Left: thermal neutron flux (E <100meV). Right: fast neutron flux (E> 0.1MeV). The v1 and v2 configurations are detailed in the text.*

3 meters	ϕtotal [n/cm2/s/kW]	ϕthermal [n/cm2/s/kW]	ϕthermal/ϕtotal	ϕgamma [g/cm2/s/kW]
C-H2O-v1-maxGlobal	1,06E+06	2,20E+05	0.2	2,26E+05
C-H2O-v2-maxGlobal0	1,70E+06	1,49E+05	0.1	2,47E+05
C-H2O-v2-maxGlobal1	1,68E+06	1,68E+05	0.1	2,32E+05
C-D2O-v1-maxGlobal	1,86E+05	6,82E+04	0.4	9,08E+04
C-D2O-v2-maxGlobal0	1,90E+05	6,82E+04	0.4	6,69E+04
C-D2O-v2-maxGlobal1	2,05E+05	5,96E+04	0.3	1,30E+05
Be-H2O-v1-maxGlobal	1,10E+06	9,23E+04	0.1	6,18E+05
Be-H2O-v1-maxLocal	5,54E+05	4,64E+04	0.1	3,63E+05
Be-H2O-v2-maxGlobal0	7,22E+05	1,13E+05	0.2	5,44E+05
Be-H2O-v2-maxGlobal1	4,23E+05	9,83E+04	0.2	7,65E+05
Be-D2O-v1-maxGlobal	6,29E+05	1,22E+05	0.2	5,75E+05
Be-D2O-v1-maxLocal	3,22E+05	1,42E+05	0.4	3,59E+05
Be-D2O-v2-maxGlobal0	5,95E+05	1,30E+05	0.2	4,85E+05
Be-D2O-v2-maxGlobal1	3,23E+05	1,51E+05	0.5	4,17E+05

Table 8 : Total and thermal neutron fluxes, ratio of the two and gamma flux at a distance of 3 m from the starting point of the extraction channel

5 meters	ϕtotal [n/cm2/s/kW]	ϕthermal [n/cm2/s/kW]	ϕthermal/ϕtotal	ϕgamma [g/cm2/s/kW]
C-H2O-v1-maxGlobal	2,88E+05	8,93E+04	0,2	5,98E+04
C-H2O-v2-maxGlobal0	4,50E+05	5,54E+04	0,1	1,06E+05
C-H2O-v2-maxGlobal1	4,64E+05	5,96E+04	0,1	6,83E+04
C-D2O-v1-maxGlobal	4,60E+04	1,49E+04	0,3	2,99E+04
C-D2O-v2-maxGlobal0	4,61E+04	1,28E+04	0,2	2,14E+04
C-D2O-v2-maxGlobal1	4,26E+04	2,13E+04	0,4	4,49E+04
Be-H2O-v1-maxGlobal	3,04E+05	3,77E+04	0,1	2,00E+05
Be-H2O-v1-maxLocal	1,37E+05	1,74E+04	0,1	1,28E+05
Be-H2O-v2-maxGlobal0	2,29E+05	4,64E+04	0,2	2,09E+05
Be-H2O-v2-maxGlobal1	1,04E+05	3,18E+04	0,2	2,56E+05
Be-D2O-v1-maxGlobal	1,76E+05	6,65E+04	0,3	2,12E+05
Be-D2O-v1-maxLocal	1,23E+05	6,07E+04	0,4	1,55E+05
Be-D2O-v2-maxGlobal0	1,58E+05	5,03E+04	0,3	1,57E+05
Be-D2O-v2-maxGlobal1	8,16E+04	4,43E+04	0,4	1,67E+05

Table 9 : Total and thermal neutron fluxes, ratio of the two and gamma flux at a distance of 5 m from the starting point of the extraction channel

For neutronography applications, the important setup parameter is the L/D ratio where L is the distance from the start of the extractor channel to the imaging point and D is the diameter of the extractor channel. Here for a D = 4 cm, a length L = 500 cm allows to have an **L/D = 125**. This ratio enables objects with a resolution of less than 100 µm to be neutronographied. For this L/D, for the carbon and beryllium targets studied, thermal neutron fluxes between 1 10^4 and 2 10^5 n/cm^2/s/kW.

Assuming that 200 kW of power can be deposited on the targets, **thermal neutron fluxes of between 3 10^6 and 1.5 10^7 n/cm^2/s** can be obtained. It is important to note that a fast neutron flux as well as a large gamma neutron flux are extracted along with thermal neutrons. The beam could optimized by placing neutron filters in the beam in order to purify it. These studies are outside the scope of this work. Work to optimize the positioning of the extractor channels could be carried out in order to optimize the ratio of heat flow/total flow and heat flow/gamma flow. Additional studies could be considered in order to study the influence of neutron amplifying materials (materials with a large cross-section (n, 2n) at the considered energies) or of neutron reflecting materials. This would require a lot of optimization work.

Conclusions

This document provides the first orders of magnitude of the flows that it would be possible to extract from a target / moderator assembly in hall I2A. Many areas for improvement are to be considered to optimize the geometry and materials of these assemblies, in particular the study of the influence:

- the angle of the extractor channels.
- the number of extractor channels that can be used.
- a neutron reflector (beryllium, lead, etc.).
- a neutron amplifier. For example a beryllium layer which has a non-negligible cross-section for the reaction (n, 2n) for neutron energies greater than 3 MeV.
- radiobiological shielding (geometry, materials)

References

[GANIL_CONVERTISSEUR_CARBONE] Dossier de Justification de la Definition (DJD) «The Neutron Converter Design », J. Bermudez et al. 2010 (SP2_DT_8324_1020637V1.0)

Radioelements and AB-NCT

G. de France, F. Haddad, S. Leray, D. Santos

Objectives

The goal is to investigate the different opportunities that would be offered in the domain of radioisotope production and Accelerator Based-Neutron Capture Therapy (AB-NCT) by the construction of a new hall (I2A) hosting targets able to withstand a high beam intensity (several mA), working alone or in parallel with other applications. For each considered option, we have tried to evaluate the medical interest, the existing or possible future competition, the potential customers and the specificities and assets of GANIL/SPIRAL2. This allowed us to select the options that can be considered as promising and deserving to be explored further. Since the possibility to send the unused beam of NFS into this hall seems to be definitely ruled out, this "shared beam" option is not considered.

Radiosotope production possibilities

We have considered the production of radioisotopes for therapy, diagnostics or theranostics applications, to be used for pre-clinical research, clinical studies or routine use. The different possibilities offered by beams of light charged particles, protons, deuterons, alphas and other light ions, either alone or in parallel with the proposed CANS, which probably would use a deuteron beam on a Be target, have been explored.

- ### Proton beams

Many radioisotopes of high medical interest can be produced with proton beams and there exists many centers, equipped with cyclotrons[1] mostly bought from industrial companies, supplying radiopharmaceuticals for preclinical researches, clinical studies or routine use. Commercial cyclotrons can now reach high intensities of the order of 1 mA. IBA for instance sells a 30 MeV machine capable

[1] See for instance IAEA Database of cyclotrons for radionuclide production: https://nucleus.iaea.org/sites/accelerators/Pages/Cyclotron.aspx

of producing 1.2 mA of protons[2] and proposes a fully integrated solution combining equipment and services. Even if SPIRAL2 can reach 5 mA and is more flexible in terms of incident energy, it is unlikely that it could be competitive given the large number of existing and foreseen centers specifically designed and optimized for radioisotope production.

- ### Deuteron beams

The situation is somewhat different for the production with deuteron beams. First, there are much less centers equipped with accelerators delivering deuterons and the maximum intensities reachable by commercial accelerators are, up to now, nearly two orders of magnitude lower than SPIRAL2 (50 µA for the IBA accelerators). Second, some isotopes can be produced only or much more efficiently with deuteron beams although these production channels have generally not yet been thoroughly investigated. It seems therefore clear that SPIRAL2 has assets in this field and a beam line in the I2A hall delivering a deuteron beam on high-power target stations able to sustain high, if not the full, beam power could be competitive to other installations, likely providing that the beam be shared with the CANS. Table 10 presents the radioisotopes that could be considered, with the quantities that could be produced (in GBq per mA and hours of beam), the known and possible competition, potential partners and possible advantages of SPIRAL2. The quantities that could be produced with the high intensities available at SPIRAL2 make it possible, if regularly (weekly) produced, to envisage pre-clinical research and clinical studies, and maybe in a longer term commercial supply. Since the envisaged I2A hall will not be available before at least 5 years and in the meantime some of the listed isotopes may have proved really promising or on the contrary not so interesting and other ones may emerge, it is difficult to define now on which isotope SPIRAL2 could focus. However, the fact that there are many cases for which the high intensity reachable at SPIRAL2 may be necessary suggests that SPIRAL2 could be competitive and that it could be worth building a dedicated line.

[2] https://www.iba-radiopharmasolutions.com/cyclotrons

Isotope	Half life	Application	Production channel	Beam energy on target	Possible production at GANIL	Competition	Potential partners	GANIL assets	Comments
Production with deuteron beams									
^{67}Cu	61,8 h	Targeted β-therapy; theranostics coupled to PET with ^{64}Cu	^{70}Zn(d,x)^{67}Cu	26 MeV	~10 GBq/mA/h	- DOE Photoproduction: 2 batches of 74 GBq/month - ARRONAX: 24 GBq after 72 h irradiation 80µA, 97.5% enrichment	Clarity (Australia)	high intensity deuteron beam allowing large quantities to be produced in short time (8h-24h)	SPECT imagining is possible
^{186}Re	89,3 h	Targeted β-therapy; theranostics coupled to PET with ^{99m}Tc	^{186}W(d,x)^{186}Re	17.6 MeV	~17 GBq/mA/h with 100% enriched target	No known producer; can be produced in reactors by (n,γ) on ^{185}Re or as by-product of ^{188}W/^{188}Re generators or via (p,n) with commercial cyclotrons	Academic institutions (for preclinical / clinical studies ???)	High purity product (specific activity). Not available through reactor production. High production capabilities thanks to deuteron intensity available.	
^{44m}Sc	58,6 h	PET imaging; theranostics coupled to β⁻-emitter ^{47}Sc or ^{177}Lu; 3 photons imaging	^{44}Ca(d,x)^{44m}Sc	~30 MeV	~35 GBq/mA/h with 99% enriched target	none on ^{44m}Sc; many centers (PSI, POLATOM…) on ^{44}Sc	Many academic institutions	High production capabilities thanks to deuteron intensity available.	adpated for molecules with long distribution time (as antibodies)
^{44}Ti	60 ans	generator ^{44}Ti/^{44}Sc - PET imaging - Theranostic pair with ^{47}Sc (targeted β⁻ therapy)	^{45}Sc(d,x)^{44}Ti	40 Mev on a thick target	~1.6 MBq/mA/h	possible production studied by DOE	Academic institutions	high intensity is mandatory so GANIL is well positionned	Isotope very difficult to produce due to the long T1/2
^{64}Cu	12,7h	PET imaging - Theranostic pair with ^{67}Cu (targeted β⁻ therapy)	^{64}Ni(d,x)^{64}Cu	12-15 Mev	~200 GBq/mA/h with 99% enriched target	Production with protons.	Many academic institutions and industry. One production available on routine for neuro endocine tumour in the US.	Production with deuterons equivalent to protons with a 25% lower thickness and comparable specific activity - Interest if produced in parasitic mode.	due to half life, local production only
Production with alpha beams									
^{211}At	7h	Alpha therapy	^{209}Bi(α,x)^{211}At	28 MeV	35 GBq/mA/h	10 centers in the world.	Many academic institutions and industry (Telix pharmaceutical)	alpha beam at high intensity are very few	due to its half life, regional production only.
^{43}Sc	4h	PET imaging - Theranostic pair with ^{47}Sc (targeted β⁻ therapy) or ^{177}Lu	^{40}Ca(α,x)^{43}Sc	20 MeV	100 GBq/mA/h with enriched target	Little competition as the proton channel requires very expensive ^{42}Ca enriched targets	Many academic institutions	alpha beam at high intensity are very few	better characteristics than ^{44}Sc. Molecules for ^{44}Sc can be used for it without changes
^{117m}Sn	13,8 d	Therapy with internal conversion e-. Targeted therapy especially in cardiology and for veterinary applications. SPECT imaging possible.	^{116}Cd(α,x)^{117m}Sn	40 MeV	400 GBq/mA/h with enriched target	1 production site in US (Washington U). Possible competition by proton but not operational to date.	1 company in US	alpha beam at high intensity are very few	
^{97}Ru	2,8 d	SPECT Imaging - chemotherapy drug imaging for personalized medicine	^{nat}Mo(α,x)^{97}Ru	40 MeV	7 GBq/mA/h with enriched target	production through ^{99}Tc(p,xn)^{97}Ru, experimental production at ARRONAX	Academic institutions	alpha beam at high intensity are very few	
Production with neutrons									
^{47}Sc	3,3 d	Targeted β-therapy; theranostics coupled to PET with ^{43,44}Sc	^{46}Ca(n,γ)^{47}Ca			Not really competition but studies for photoproduction	Strong potential	Interesting if neutrons available	

Table 10: examples of radioisotopes that could be considered for I2A: quantities (in GBq per mA and hours of beam); known and possible competition; potential partners and possible advantages of SPIRAL2

- Alpha beams

Several radioisotopes can be produced only or advantageously with alpha beams. They are shown in Table 10. As for deuterons, SPIRAL2 has a definite advantage since there are very few centers delivering alphas and for those existing the intensities are orders of magnitude lower. Even if the production with alpha beams cannot be coupled to another application, it may still be interesting. A research activity on the production of ^{211}At is currently developing at GANIL in the converter room of the NFS area through a collaboration with INP Rez (Czech rep.) and an approved ANR grant (REPARE) in collaboration with ARRONAX, SUBATECH, LDM-TEP and CERN.

- Other light Ions

Production of radioisotopes using reaction channels involving other light ions, such as Li or Be, would be very specific of SPIRAL2. However, although this has not been thoroughly investigated, only very few possible production routes have been identified.

- Neutrons produced on a specific target

Radioisotopes could also be produced using secondary neutrons generated by proton or deuteron beams impinging on a specific target. This could be done in parallel with the CANS, a AB-NCT device or the production by ions. An example of possibility is given in Table 10 with ^{47}Sc which is rather new, but other ones should be considered. For many isotopes that can be produced with neutrons, and in particular the most used one, ^{99m}Tc, it is unlikely that SPIRAL2 could compete with reactors (in France the RJH will enter into operation in the coming year and produce ^{99m}Tc and probably other isotopes). However, especially if a AB-NCT would be built and could be used alternately, there may be some new or less used isotopes that could be interesting to produce.

- The necessary conditions

In the preceding section, we have only looked at the potential production of isotopes given the reaction channels and the known cross sections. It is clear that from the production of the isotope in a target to the delivery of a radiopharmaceutical, the route is not straightforward. The main challenge is probably the sustainability of the targets at very high power (several tens of kW). A dedicated R&D, probably different for each target elements, will be mandatory before being able to estimate if and in which conditions the production of a given radioisotope is possible. It will also be necessary to have radiochemistry means or a partnership with a lab that has the means to do radiochemistry (CYCERON could be this partner).

A tentative list of the necessary means is given below:

- A dedicated and shielded room so as not to hinder the work around,
- A dedicated ventilation with filters in case of problems
- A beam line with scanning systems to distribute the power to the target
- A rotating target system, possibly accommodating several different targets, with its cooling circuit (preferably installed outside the casemate))
- means of manufacturing targets (pelletizing, electroplating, vacuum evaporation, etc ...)
- A robotic system for target processing without entering the casemate and at the end an enclosure to switch to a transport package going to the chemical treatment site
- transport package
- Radioactivity measurement means adapted to the targeted isotopes
- mobile shielding for protection

Finally, it should be clear that producing radioisotopes for pre-clinical research and a fortiori for clinical trials makes sense only if the production is reliable and regular enough. It is estimated that a weekly production for at least a half-day or a whole day is the minimum that would be viable.

AB-NCT

The possibility to host an AB-NCT system in the I2A hall has been investigated. AB-NCT requires a high epithermal (0,6eV - 10 keV) neutron flux (~10^9 n/s/cm^2) and a low gamma neutron background. Several facilities are presently under construction in the world[3]. They generally rely on a very high intensity (~tens of mA), low energy (a few MeV) proton beam in order to avoid the background generated by high-energy neutrons. At GANIL, the beam exiting the RFQ has the suitable energy. Unfortunately, there is no space to accommodate a target close to the RFQ or build a second line. The only possibilities to have a few MeV beam on a AB-NCT target in the I2A hall would be either to conduct it without acceleration after the RFQ through the LINAG or to decelerate a high energy beam to the required energy. In the latter case, in addition to being energetically unfavorable, it would generate background during deceleration and would probably require significant shielding. The first case is therefore the best solution but has the drawback that AB-NCT would not be able to run in parallel with other applications, except the production of radioisotopes with thermal or epithermal neutrons. The advantage of GANIL, compared to building an AB-NCT system from scratch, is the small investment required and the availability of qualified personnel. Studies have already been performed at the LPSC in Grenoble and a Be target able to sustain a 3 kW/cm^2 power has been built and tested, and a liquid Li target is under construction. In addition, with ARCHADE close by, the possibility of a multimodal treatment center could be envisaged in the longer term, a quite unique combination.

Some disadvantages have nevertheless been pointed out: the relatively low intensity of SPIRAL2 compared to what is generally foreseen in other facilities, the fact that it would not be possible to share the beam with other applications, and especially the likely impossibility to welcome patients in the INB.

Rather, this would lead to proposing studies of high-power targets and appropriate moderators, which could lead to a proof of concept for subsequent deployment elsewhere.

Conclusions

Various options for radioisotope production and AB-NCT in a dedicated I2A hall have been considered. Some of these options do not seem interesting because of the possible competition, particularly by the installations proposed by industrial companies.

However, GANIL has assets and specificities and some options have been retained and deserve a more in-depth study :

- The production of radioisotopes with deuteron or alpha beams. In particular, the option to run this production in parallel with the CANS using the deuteron or proton beams should be strongly encouraged to optimize beam time usage.
- Studies and proof of concept for AB-NCT

[3] See for instance: Dymova et al., Cancer Communications. 2020;40:406–421

Material under irradiation

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Understanding the mechanisms of materials damage under irradiation and their consequences on the optical, electronic, mechanical, dimensional properties... requires accelerator beams to simulate the radiative environment of these materials. This is an activity in which GANIL is heavily involved thanks to the presence of the interdisciplinary CIRIL platform, managed by CIMAP. Thus, irradiation experiments are carried out at all stages of acceleration of GANIL beams (ion source, injector cyclotrons, CSS1 and CSS2). With the start-up of SPIRAL2, new possibilities for experiments are opening up for the "materials under irradiation" community.

SPIRAL2, a tool for the "materials under irradiation" community?

The characteristic of SPIRAL2 is to deliver high intensity beams of ions and neutrons with possibly a temporal structure.

Neutron irradiation

Places where materials are irradiated by neutrons are rare: near the core of fission or fusion reactors and in military applications.

In a nuclear reactor, the vessel which is relatively far from the core undergoes a neutron fluence of the order of 10^{20} n/cm², i.e. a damage of 0.2 dpa (displacement per atom[4]). The irradiation dose is much higher for internal structures (50 dpa) and even more for fusion reactors (150 dpa for DEMO).

The estimated neutron flux at 10 cm behind the converter for a 40 MeV deuton beam on a beryllium target is 1.2 10^{12} n/cm²/s., or 0.08 dpa/year. These values must be compared with 2 10^{14} n/cm²/s in the future research reactor (RJH).

In conclusion, the SPIRAL2 neutrons are not competitive for the simulation of the ageing of metallic structure of nuclear reactor. For the nuclear fuel, we can make the same remark.

On the other hand, neutron fluences are also needed to studies the effects of fast neutrons on electronic components. Researchers from the Military Applications Division of CEA have expressed their interest in having access to SPIRAL2 neutron beams. But the demand for beam time is low (a few runs per year) and only comes from one CEA/DIF group. This does not justify a dedicated line for this use. Nevertheless, **it would be interesting to have a removable irradiation chamber behind a conversion target for this application and for radiobiology studies with neutrons.** The minimum area to be irradiated homogeneously is 10 cm².

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[4] Displacement per atom indicates the number of times an atom is ejected from its site: 0.1 dpa = 1 atom of 10 has been moved

Ion irradiation

Many studies on the ageing under irradiation of nuclear metallic materials are carried out with ion irradiations, which the advantage to have larger damage cross-sections. With He 40MeV and 2 kW on target, about 7 dpa/day is created.

At SPIRAL2 energies, the simulation is not perfect, the size distribution of the displacement cascades is different and the gas production in the target is higher. In addition, the target activation is far from negligible. An evaluation of the activity after one year of cooling indicates that for the same damage the activity with protons is two orders of magnitude higher than that with neutrons.

Despite these limitations, **high intensity ion irradiation (~kW) is relevant for the study of certain mechanisms on simplified model materials.** Temperature control during irradiation and the management of irradiated targets and their transfer to laboratories authorised to work with radioactive materials are prerequisites. Considering the limited number of laboratories that can study radioactive samples (CEA/Saclay DMN, GPM/Rouen and EDF Les Renardières)[5] and also considering that these beams are not very representative of neutron irradiations, it is difficult to justify a dedicated room. However, **it is probably possible to couple material irradiation and radioelement production** either by inserting a device in place of the production cell or by placing the samples in the cell.

Many others classes of materials are irradiated in the nuclear cycle: nuclear glasses, organic materials in waste canister or transmutation matrices. These materials are more sensitive to irradiation than metals, so they requires lower fluences but also lower fluxes because they have a low thermal conduction coefficient.

As shown in Figure 13, the energy and ion range of SPIRAL2 covers a very interesting area from the energy of C0 cyclotrons (IRRSUD) to the Medium Energy Line (SME) with an extension down to the lightest ions.

The installation of an irradiation chamber on SPIRAL2 would therefore make it possible to offer new beams to the interdisciplinary research community and, to increase GANIL beams capacity in this field. The success of this installation will depend on the quality of the beams (stability, homogeneity over a large area, accuracy of fluence measurement...) and the possibility of inserting on-line instrumentation.

5 these three laboratories are members of the Materials Ageing Institute, which groups together the main industrial producers of nuclear energy

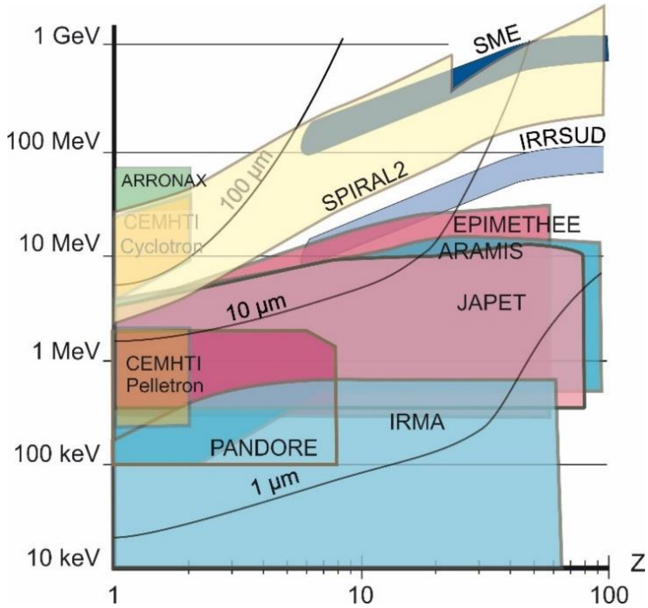


Figure 13: Energy and ion ranges of SPIRAL2 (yellow area) compared to the domains covered by the French accelerators used for irradiations. The Orléans cyclotron (CEMHTI) should be stopped in the coming years.

Using the time structure of the beam

In liquids and certain solids such as polymers, the ionisations created by irradiation are followed by a phase of complex free-radical chemistry which has been described in detail in water using time-resolved radiolysis experiments and the use of scavengers. There is still much to understand in other liquids, in the case of radiolysis at liquid - solid interfaces and for organic solids.

With a beam time structure consisting of an ion pulse, as intense and short as possible, followed by a beam extinction for a duration in the range millisecond – second, SPIRAL2 can be used for pulsed radiolysis experiments. This type of experiment requires an intense sub-nanosecond laser synchronised with the beam or vice versa.

Room and equipment needed for irradiation

The energy range is approximately the same as that of GANIL's medium energy. It is therefore the equivalent of the IRASME device that should be installed on I2A. Figure 14 below gives an indication of the size of the equipment. The minimum size is 6.6 x 3.5 m² (23.1 m²), but 7 x 4 = 28 m² would be more comfortable.

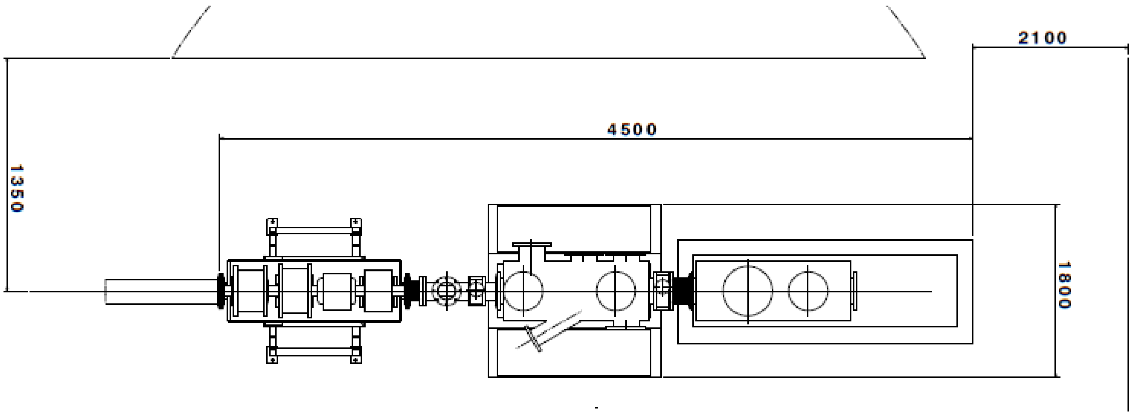


Figure 14: sketch of a possible implementation for a material irradiation station in I2A from the IRASME device

With an investment, the amount of which remains to be determined, the community of materials under irradiation can become an important user of the opportunities offered by SPIRAL2.

This new irradiation facility could be integrated into the EMIR&A federation, which groups together all the French irradiation facilities, but which has worldwide visibility. CIMAP has created this federation and IRRSUD and IRASME are recognised as facilities giving access to its beams to the international community. EMIR&A is included in the national "infrastructure" strategy of the Ministry of Higher Education, Research and Innovation (MESRI).

Infrastructure

X Hulin, R Duperrier, JM Lagniel, M Baylac, M Di Giacomo

The objective of the subgroup is to propose an implementation and an architectural process for the I2A installation. In addition, an estimated envelope of the cost of the project is requested, as well as a draft of a planning.

The technical scope includes:

- Beam sharing
- The building dedicated to I2A, that is to say all the related technical infrastructures: earthworks, Civil Engineering, High / low currents, Handling, Bridges and Gallows, Heavy doors and casemates, Classic ventilation, Nuclear ventilation, Radiation protection, Refrigeration
- The process related to clean I2A, ie beam lines and line equipment, instrumented, vacuum and powered and cooled.
- The process linked to the existing one which must be retaliatory / adapted to allow connection to the existing one, i.e. SPIRAL2 Phase 1

In a first step, the work of this group has concentrated on the beam sharing possibility. Then on the aspects related to buildings, radioprotection, safety, etc which are more directly linked to the scientific aspects of the project.

Note: Neutron production equipment is integrated into another subgroup.

- Beam sharing

The Neutron For Science (NFS) area hosts a Time of Flight (ToF) facility. Eighty percent of the proposed NFS experiments use this facility, in which 1% of the beam intensity is driven toward the facility to avoid burst overlap for time-of-flight measurement. This means that 99% of the primary beam is wasted on a beam dump. Today, a beam bunch selector, installed after the RFQ, permanently deviates the beam particles on a beam dump, an electric field restoring only the selected bunches to the LINAC. We evaluated the opportunity to use this wasted beam in parallel to NFS.

The beam pulses are built at 88MHz by the RFQ. The distance between two pulses is therefore 11ns. The low energy beam selector has a 6ns rise/descent time to allow only one bunch to be sent to NFS. It is built from a dipole permanently deviating the beam pulses on a beam dump and a beam line putting back the selected bunch into the LINAC axis. With a 5 mA, 40 MeV deuteron beam and a 1/100 beam pulse selection, the remaining mean beam power is 2 kW. Any loss due to an approximate pulse formation (ie loss of pulses that are adjacent to the select one) would cause beam losses into the LINAC and induce emergency beam stop to avoid activation and damages to the cavities. To select 1 pulse over 100, the repetition of the bunch selector has to be of the order of the MHz. The technical solution adopted for the low energy beam selector is the travelling wave technique. A scheme in which M bunches would be selected (see upper part of Fig 15) to envisage a longer rise/descent times has been studied in order to evaluate its feasibility.

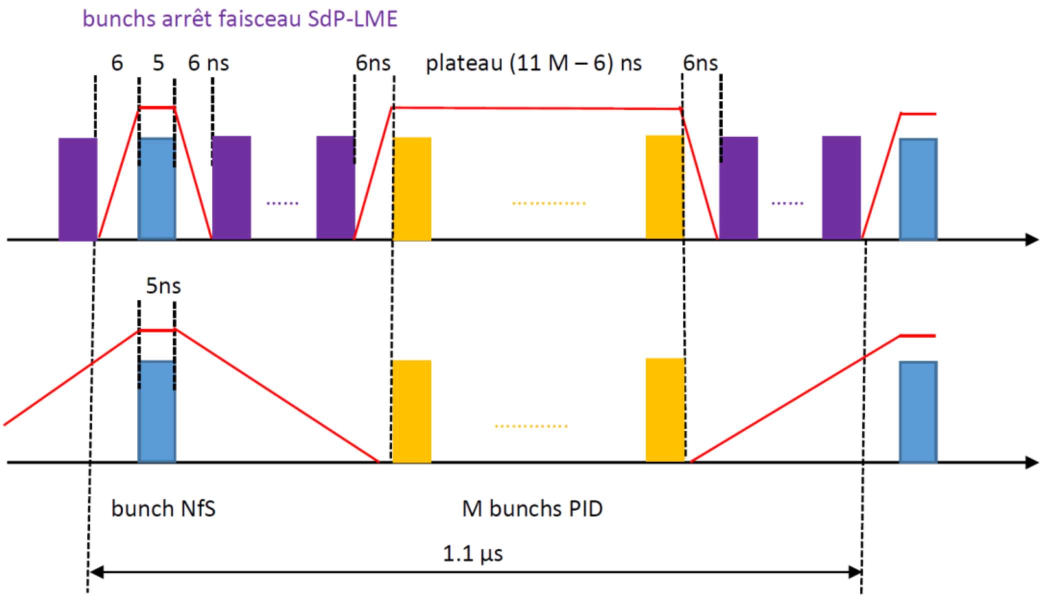


Figure 15: top : Schematic representation of the packets and voltage of the low energy bunch selector (the NFS and I2A packets are accelerated by the linac, the other ones sent to the beam dump). Bottom: the high energy bunch selector (kicking 1 packet/100 to NFS)

In this scheme, the bunch selector should produce long periods to allow sending the M bunches to the new I2A area. With the adopted travelling wave technique the required power is estimated to be unrealistic. Another option discussed at the early time of the design for SPIRAL2 was to used switches. It is not clear whether this technology has progressed in a significantly enough way to satisfy the new requirement. If the rise times (on low capacitive load) and the repetition frequencies of these devices have since increased considerably, the minimum duration of the pulses (50ns) still seems too long for the selection of a single bunch.

Although a solution is possible for the low energy bunch selector, the feasibility of a high energy one operating at ~ 1 MHz with rise / fall times of ~100 ns (see bottom part of Fig. 15) for 40 MeV beams (maximum rigidity ~ 1.3 Tm) is far from being demonstrated. Therefore, and in current state of the art of the technology, the option of sharing between NFS and I2A is not retained.

- Implementation of I2A

The following top view (Fig 16) shows the existing GANIL and the Spiral 2 Phase 1 implementation.

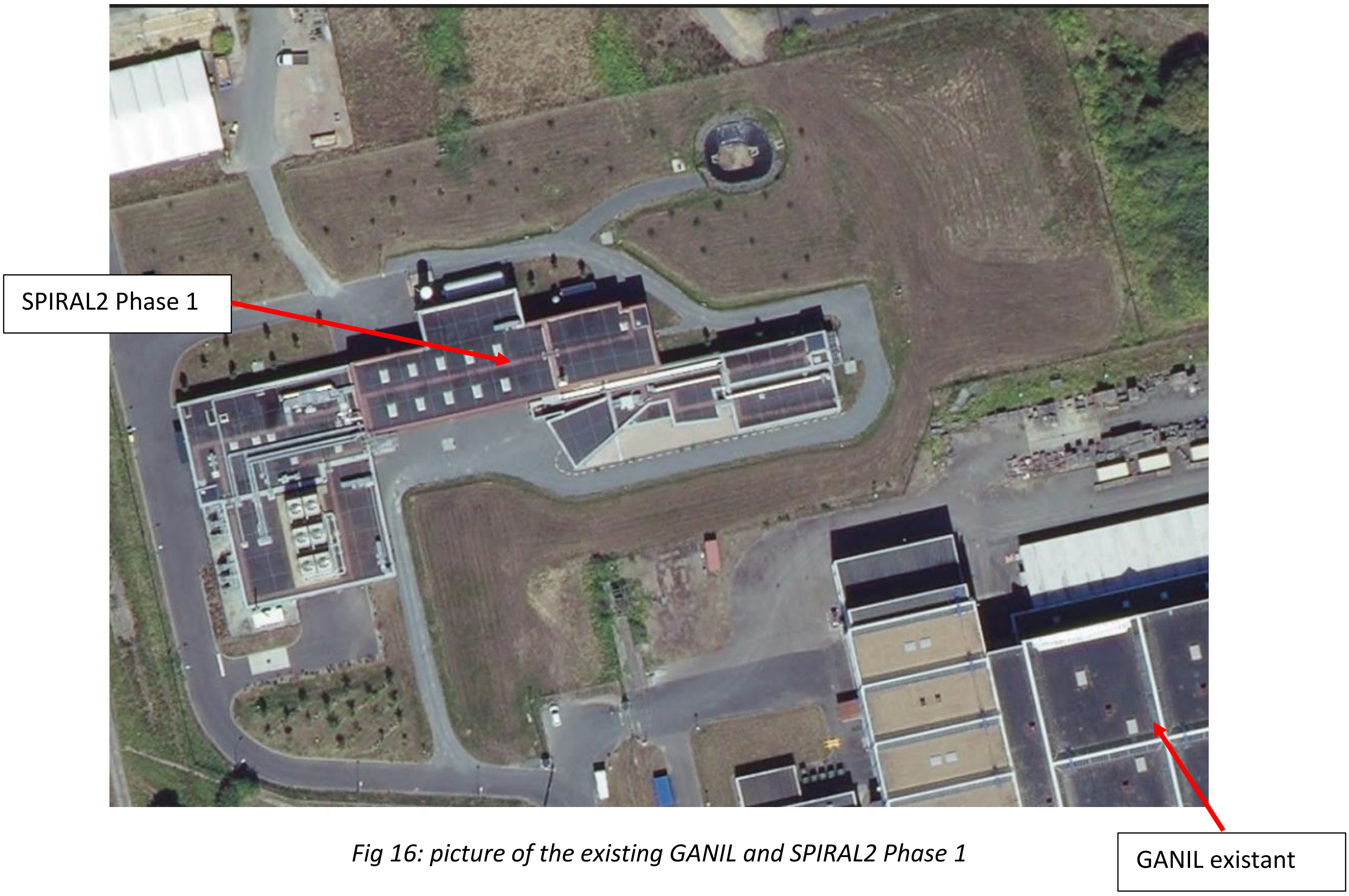


Fig 16: picture of the existing GANIL and SPIRAL2 Phase 1

The future I2A hall will receive a beam coming from SPIRAL2, more precisely from a line that will leave the High Energy Line (LHE) area. This is located at level -2 of SPIRAL2, at a depth of -9.5 m (see Fig 17).

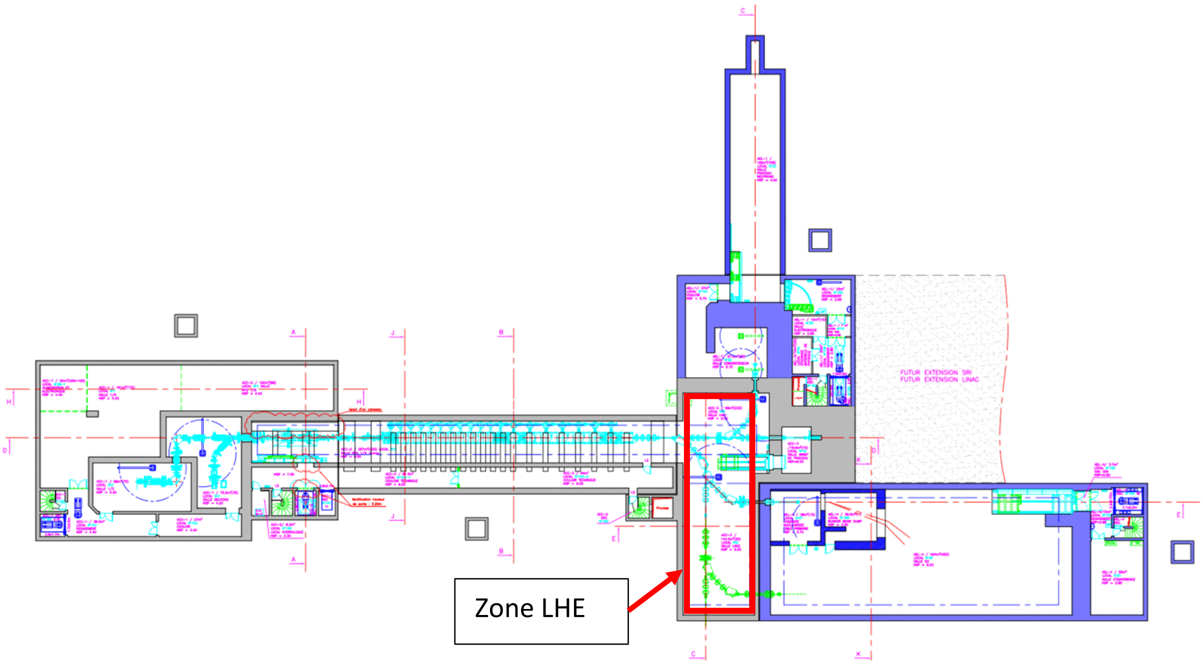


Fig 17: layout of the -2 level of SPIRAL2 building with the High Energy Line area highlighted.

Several locations were considered for this experiment hall.

- South of the High Energy Line area of SPIRAL2: this is the area dedicated to what was phase 2 of the SPIRAL2 Project. A 40 m X 50 m building was planned there, but the area is then constrained by the existing GANIL and Phase 1 refrigeration installations.

  The interface between the existing beam line in LHE and the I2A extension there is the simplest: creation in the LHE area of SPIRAL2 of a beam line, crossing the south wall and new building of the new hall.

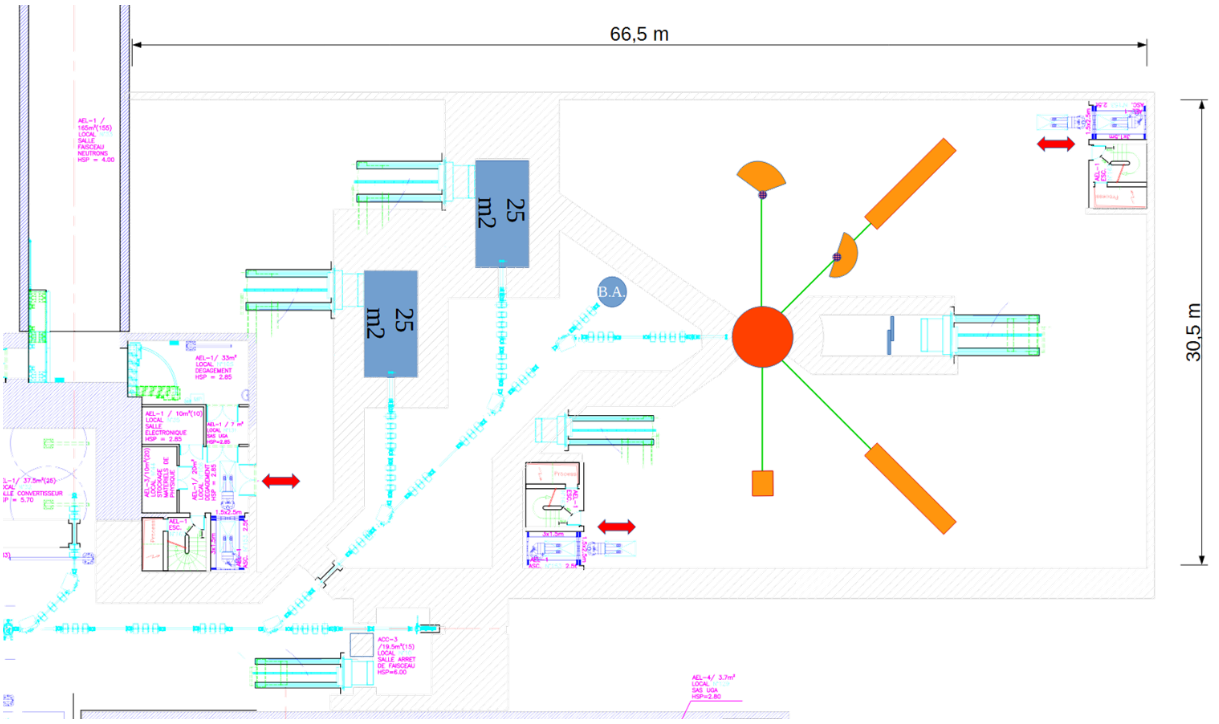
- North of S3 and East of LHE: this area has historically been reserved for future extensions. The installation of I2A at this location will require a repositioning of the existing beam stop of SPIRAL2, which will de facto increase the downtime of SPIRAL2 at the time of the work and also increase the cost.

In the following, we consider the implementation in the North East zone since this assumption is an upper limit in terms of cost and downtime of the facility, and also because it preserves the possibility of a future development of GANIL (Presentation by M SPIRO of the Codir "Futur du Ganil" Dec 2020). This however should be discussed in a more global view of the future overall project.

- Layout

The following elements have been selected to meet the needs of potential users; these elements were validated during an interim review in February 2021;

Option 1 is as follows:



Three rooms: a 25 m2 radioisotope room, a 25 m2 material (n,ions) irradiation room and a neutron production room with a target. These rooms are accessible by dedicated shielded doors.

The neutron production room will be accessible during the experiment. The choice of protection “as close as possible” is made. Dedicated storage as closely as possible envisaged.

- Pulses delivered to the I2A hall might be distributed in parallel in the various rooms
- Power in each room, base 50kW or even 100 kW on neutron target
- Modularity: we keep the possibility of carrying out a future extension of the LINAC and of extending the central beam stop in I2A for a later extension (neutron scattering)

Access to level -2 is made possible by elevators / goods lifts and were a priori arranged to allow compliance with the regulatory evacuation distance (40 m)

This diagram is for level -2, with a ceiling height of 6 m. The surface area of the level is around 2000 m2. The intermediate level will be made up of cells filled with biological concrete protection and / or hollowed out according to the need for protection, which will be specified at the time of the radiation protection pre-calculations. On the ground floor, we will find the dedicated utilities, but also the acquisition, supply and instrument control rooms.

Option 2, not shown, integrate the requested simplification of a neutron production room on the ground floor. In this case, a beam from the -2 level to the ground floor would be planned instead of the bifurcation to the east towards the neutron target. This alternative, provided that radiation protection calculations validate the possibility of building this room, would give a room area of 40 m X 45 m, or 1800 m2 at the ground level. This option in the South LHE area can also be envisaged. A slight cost reduction might be anticipated in this configuration.

- ## Planning

A very rough estimate: similar to that of the DESIR hall (10 years).

Need to clarify the work to be done, which will require a shutdown of SPIRAL2 if the implementation in the North East zone is chosen (not in the case of an implementation in the South zone). In this case, investigate and refine possible scenarii to reduce from 2 years to 1 year of interruption.
Cost: not consolidated and this just gives an order of magnitude: range of 25 to 35 M€ for the building. For beam lines and neutron production > 15 M€.

Conclusions

This prospective document shows that very interesting scientific opportunities can be developed at GANIL in a dedicated, high intensity irradiation area called I2A. This opportunities cover neutron tomography with a new, compact neutron source, irradiation studies using neutrons and ions for material studies, R&D for radioelements or AB-NCT. In addition, in the French strategy to design a high performance neutron source for neutron scattering experiments, the proposed cans in I2A would be the ideal R&D facility to study, design and test a high power target/converter device.

In terms of cost, planning and human resources, a very rough estimate has been made with a conservative proposed implementation scheme. A more detailed analysis including radioprotection calculations is required to refine this estimate in particular considering more closely the two possible implementations. An option with the neutron source at the ground level must be preferred. The choice of the implementation will have a significant impact on the downtime of the facility (moving or not the SPIRAL2 beam dump). This refined analysis will be made once we have a more clear vision of the overall project for the future of GANIL.