COMPACT NEUTRON SOURCES IN EUROPE

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Why compact neutron sources?

- We need neutron sources
- Construction and operation costs of a reactor or a spallation sources is high
- Produce neutrons with low energy protons (qq MeV) is possible
- Intrinsic flux is low, but the neutron production volume is small and coupling with the moderator is high (source nearly in the moderator)
- Brilliance might be high enough to do efficient neutron scattering
Why now?

- In Europe, reactors are shutting down (Studsvik, Risø, Geesthacht, Jülich, Berlin, Saclay, …..)
- Proton accelerators of high intensities are available (nearly on a commercial basis)
- Compact source: a versatile concept that might be adapted to the user needs and financial possibilities
- Benefit from ESS developments (accelerator, instrument design and optimization, optics, data treatment)
- Simulations show that performances of instruments on compact sources should be similar to those on medium flux reactors
USA : LENS, Indiana university, 13 MeV, 6kW
CANS@SNS

Korea : KCANS : Korea Collaboration on Accelerator-driven Neutron Sources (Korea Multi-purpose Accelerator Complex KOMAC)

China : CCANS : China Collaboration on Accelerator-driven Neutron Sources, CPHS (Tsinghua, 13MeV 20mA peak, 16 kW), PKUNIFTY (Beijin, d on Be, 2 MeV 4mA); mainly for imaging

Argentina : Bariloche, e⁻, 25MeV, 100Hz, 2ms, 25mA average. Stopped

Israël : SARAF; in construction
p or d, 40 MeV, 5 mA, 200 kW on liquid Li
RANS (Japan) 10M€ 7MeV 100μA average

Imaging station, powder diffraction, texture measurements and SANS

Austenite volume ratio measured value (actual value)

- 6.7±0.8% (7.3%)
- 17.4±0.8% (19.1%)

~1% of accuracy

Peaks of both textures are measured

They are changed due to compressive deformation

Water behavior in steel
More than 10 small sources running or in project
Running around J-Parc

HUNS (Hokkaido) e- 35 MeV, 1 spectrometer for medium angles scattering
RANS (Wako) p on Be 7 MeV, 100 μA average, 0.7 kW diffraction, imaging
KUANS (Kyoto) p on Be 3.5 MeV, 50 μA average, 80 Hz, 80 μs, reflectivity, imaging
KURRI-Linac : e- 46 MeV 6 kW, cross sections measurements
NUANS (Nagoya) : in construction, BNCT
iBNCT nearby J-Parc, hot commissioning
OUANS (Osaka) : ultra cold neutrons
THUANS (Tohoku) p on Li or Be cyclotron 20-80Mev 10μA fast neutron physics
Projects : QUANS, THUANS, UTYANS

http://phi.phys.nagoya-u.ac.jp/JCANS/index.html
A bit informal

Organize one conference / year:

UCANS-7: Bariloche 11-15 March 2018

UCANS-8: Paris 8-10 July 2019
(satellite of ECNS in St Petersburg)

http://www.ucans.org

http://iramis.cea.fr/meetings/UCANS-8/
EUROPE : STARTING PROJECTS

**ESS-Bilbao**
- $E_p = 50$ MeV, $P = 115$ kW, rotating Be target

**HBS High Brilliance Source (JCNS)**
- $E_p = 50$ MeV, $I_{\text{peak}} = 100$ mA, $P = 100$ kW, multiple fixed Be target

**NOVA-ERA (JCNS)**
- $E_p = 10$ MeV, $I_{\text{peak}} = 1$ mA, $P = 400$ W, Be/V target, duty cycle 4%

**LINUS collaboration in Legnaro**
- $E_p = 70$ MeV, $I_{\text{av}} = 750$ µA, Lithium and Be target

**SONATE (CEA)**
- $E_p = 20$ MeV, $I_{\text{peak}} = 100$ mA, duty cycle = 4%, $P = 80$ kW, multiple fixed Be target.

**Martonvasar (Hongrie)**
- $E_p = 2.5$ MeV, $I_{\text{peak}} = 20$ mA, duty cycle = 5%, $P = 2.5$ kW, target ?.
JCNS organizes the annual Unkel meeting on CANS (October 4-5 2018)

**Thematic workshops** have been organized:

- CANS target in Legnaro on 2-3 March 2017
- HBS science case workshop 6-7 April 2017 Unkel
- Accelerator in Bilbao on 6 June 2017
- CANS instrumentation Saclay, 17 July 2017

ESS-B has the project of organizing a dedicated school in 2019

**Ucans-8** will be held next year in Paris (July 8-10 2019)

http://iramis.cea.fr/meetings/UCANS-8/
The **CAN4EU** proposition in March 2017

Infradev-01-2017 design studies

Title: *Compact Accelerator Driven Neutron Infrastructure for the European Research Area*

Partners: FZJ (Jülich), CEA (LLB), CNRS (IN2P3), ESS Bilbao, INFN Legnaro, CNR Italy, MTA Hungary, PSI Switzerland

Aim: *deliver the conceptual and technical design for high brilliance neutron sources based on low energy proton accelerator*

Not financed, just below the threshold
Part describing links with industry not enough convincing
COMPACT NEUTRON SOURCE ISSUES

Limitations

• Build a compact and efficient moderator
• Heat extraction challenge (80 kW on 100 cm²)
• Target ageing: Be, Li, C, V, liquid, other?

• Financial constrains (construction and operation costs must be at least 10 times lower than ESS; our goal 2 k€ / instrument day)
• Regulations constrains: in France stay below the « Nuclear installation » criteria to stay « ICPE »

Thermo-hydraulic calculations for the Sonate target

Damaged LENS Be target
Use ESS developments they do on ion source, RF systems, RFQ and target station to build their own neutron source

Project:

- $\text{H}^+$ 50 MeV, 75 mA peak, 5% duty cycle
- One target station
- Rotating water cooled Be target: 200kW
- Primary neutron production $10^{15}$ n/s

An element of the target assembly ready to be tested
Neutrons Obtained Via Accelerator for Education and Research Activities

Design parameters

- 10 MeV protons – 1 mA current
- Frequency: 48 – 288 Hz
- Duty cycle: 4%
- Proton pulse length: 833 – 139 μs
- Target: Beryllium (Vanadium)
- Average power: 400 W
- Target cooling: water 3 m/s
- Moderator/Reflector: PE/Pb
- Biological shielding: Boron-PE/Pb

Primary neutron flux : $2.1 \times 10^{13}$ n/s
Max thermal neutron flux : $1.4 \times 10^{11}$ n/s

Should be affordable by a big university
HBS JCNS PROJECT

A high performance source ready ~2035

Multi target; 100kW par target
Each target adapted to a type of instrument:
  short pulse, high rep. rate
  Long pulse, low rep. rate
A liquid para H2 moderator tested at the AKR reactor in Dresden
Modify Cosy accelerator to have a test beam line
Measured p / d cross sections
Simulated instrument performances (Voigt, Rücker)

The JAMIE project (Jülich Accelerator for Material In-situ Experiments)
1 mA 8 MeV Tandetron
LINUS AT LEGNARO

Setting-up CANS project in the framework of the LINUS Legnaro Integrated NeUtron Sources collaboration

- FARETRA (FAst Reactor Simulator for TRAnsmutation studies)
- ANEM (Atmospheric-like Neutron spectra EMulator)
- QMN (Quasi Mono-energetic Neutron source)
- LENOS (Legnaro Neutron Source) for nuclear astrophysics with Li target

Use of the new SPES cyclotron 70 Mev 0.75 mA and Trasco accelerator (5MeV 40mA)
Large experience in fabrication of high power water cooled targets up to 3.5kW/cm²
Development of Be/V diffusion bonding with Intellion for targets
Near **Budapest by 2023**

- 4M€ Regional Technology Development Grant
- 1M€ from Mirrotron and Evopro

For industrial applications, developments and BNCT

Max spec: $H^+ 2.5$ MeV 20 mA 50 kW CW

Procurement of the accelerator going on

Construction of the building started

- Target Li or Be
- Bi-spectral tube moderator $p-H_2 + H_2O$
SONATE, OUR PROJECT

Proof of concept
- End of 2019 on IPHI 3 MeV with 1 multi-purpose instrument

Compact source demonstrator
- End of 2025, 20 MeV, 2% duty cycle, 100 mA, long pulse, 1 target, 3 to 5 instruments

Full Sonate
- End of 2030, 20 MeV, 4% duty cycle, 100 mA, 2 targets (short pulses, long pulses), 10 instruments
Accelerator IPHI@Saclay: 3 MeV – 100 mA peak

Operation at **30 W** (30 mA 1 Hz 100 μs)
(to stay in our current safety authorization)

Expected 7 kW authorization by end 2018
RESULTS: SIMULATIONS VALIDATION

Exp. data
G4 Physics 1
G4 Physics 2

P=10W 30mn
1 « multi-purpose » instrument : SANS, reflectometer, imaging, diffraction
Measure a few samples, do the proof of concept, evaluate performances, test target ageing
TARGET : THE COOLING ISSUE

Test on BETSI in September (2kW)
Simulations done for 10kW
Water, 20 bars; 1 l/min/capillary
Various ideas to solve the Pb:

- Grazing beam with metal protons absorbers (requires higher energy)

**Multilayer target**

- Protons stopped in a hydrogen absorbing layer layer aux protons

**Difficulties**

- Weldings
- Differential dilatation
- Bad thermal conduction ($K_{	ext{v}_{\text{ana}}} = 31\text{W/m.K}$ Vs 200 for Be or Cu)
Let protons be stopped in the cooling circuit

- Target does the isolation between cooling and vacuum
- Can only be done if $E_p > 13$ meV (thickness > 1 mm)

LENS@Bloomington (in operation since 2008)

- $E_p = 13$ MeV $\rightarrow$ target 1.3 mm / diameter 50 mm / 3 kW $\rightarrow$ ~200 W/cm²
- Operation ~ 1000 hours / target

ESS-Bilbao

- $E_p = 50$ MeV, target 9 mm in thickness,
- Power density 100 W/cm² (keep low pressure in water)
- Expected lifetime >2000 heures
- In construction, not yet tested
- Rotating target
Lithium target (liquid)

- High neutron yield at low energy
- Less efficient at high energy
- Stopping distance
  - at 10MeV <1mm, at 20 MeV ~ 2.5mm

Examples

- LiLIT @ SARAF
  - Boucle liquide, 2.5kW/cm²
  - Demonstration at 3kW / 3MeV, a few hundred of hours

- NUANS@Nagoya
  - Encapsulated liquide Lithium (2.8 MeV, 15mA, 42kW)
  - In commisionning

- NASBEE at NIRS@Japan
  - Evaporated thin layer of solid Lithium on Cu
  - Tested up to 500W/cm² for BNCT

- IFMIF/EVEDA
  - Liquid loop 75kW (2.5MeV, 30mA)
  - In operation?
SONATE reference design

- $E_p = 20$ MeV, $I_{\text{peak}} = 100$ mA, duty cycle = 4%, $P = 80$ kW

LLB simulations confirmed by JCNS simulations
CONCLUSIONS

CANS will open new opportunities for neutron scattering

Some principles

- The source is optimized for the instruments
- Repetition rate can be tuned (10Hz, 40Hz, 100Hz, 400Hz)
- Pulse length can be tuned (100 µs → 2ms)
- One extraction channel per instrument
- Cold sources
  → One cold source per instrument is possible
  → Colder neutrons should be available
- Few instruments per source (~5 max)
- Not too far from one source one instrument

- Instruments may have similar performances than on closing reactors
- The target ageing: the key issue
- CANS will support large scale facilities by enlarging the user community
PERFORMANCES OF INSTRUMENTS

LLB simulations with SONATE reference design

- $E_p = 20$ MeV, $I_{\text{peak}} = 100$ mA, duty cycle = 4%, $P = 80$ kW

<table>
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<th>Flux on sample</th>
<th>Reference spectrometers</th>
<th>Potential gains</th>
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</thead>
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<tr>
<td>Reflectivity</td>
<td>$0.8 \times 10^7$ n/s/cm$^2$</td>
<td>HERMES@LLB $1 \times 10^7$ n/s/cm$^2$</td>
<td>ESTIA@ESS concept x10</td>
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<tr>
<td></td>
<td></td>
<td>POLREF@ISIS $\sim 1 \times 10^7$ n/s/cm$^2$</td>
<td>Advanced Deconvolution x3</td>
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<tr>
<td>SANS</td>
<td>$0.7 \times 10^6$ n/s/cm$^2$ (low Q)</td>
<td>PAXE@LLB (low Q) $0.7 \times 10^6$ n/s/cm$^2$</td>
<td>Slit setup x10</td>
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<td></td>
<td>$2.2 \times 10^6$ n/s/cm$^2$ (med Q)</td>
<td>SANS2D@ISIS $1 \times 10^6$ n/s/cm$^2$</td>
<td>Focusing optics for VSANS (small Q) x10</td>
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<tr>
<td></td>
<td>$6.7 \times 10^6$ n/s/cm$^2$ (high Q)</td>
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<tr>
<td>Powder diffraction</td>
<td>$2 \times 10^6$ n/s/cm$^2$</td>
<td>G41@LLB $2 \times 10^6$ n/s/cm$^2$</td>
<td>Large solid angle detector (7C2 type) x20</td>
</tr>
<tr>
<td>Imaging (white beam)</td>
<td>$1.5 \times 10^6$ n/s/cm$^2$ (for L/D = 240)</td>
<td>ICON@PSI $1 \times 10^7$ n/s/cm$^2$</td>
<td>MCP detectors x5</td>
</tr>
<tr>
<td></td>
<td>$1.3 \times 10^7$ n/s/cm$^2$ (for L/D = 80)</td>
<td>CONRAD@PSI $1 \times 10^7$ n/s/cm$^2$</td>
<td>Coded Source Imaging x10</td>
</tr>
<tr>
<td>Imaging (time resolved)</td>
<td>$1 \times 10^5$ n/s/cm$^2$ (for L/D = 500)</td>
<td>ANTAES@FRM2 $5 \times 10^5$ n/s/cm$^2$</td>
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</tr>
<tr>
<td></td>
<td>$dl/l = 1%$</td>
<td></td>
<td></td>
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<tr>
<td>Direct TOF</td>
<td>$3 \times 10^4$ n/s/cm$^2$ (thermal)</td>
<td>IN5@ILL $6.8 \times 10^5$ n/cm$^2$/s</td>
<td>MUSHROOM (LETx70 on single crystals)</td>
</tr>
<tr>
<td></td>
<td>$1.8 \times 10^5$ n/s/cm$^2$ (cold)</td>
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</tr>
<tr>
<td>Inverse TOF</td>
<td>$1 \times 10^7$ n/cm$^2$/s</td>
<td>OSIRIS@ISIS $2.7 \times 10^7$ n/cm$^2$/s</td>
<td></td>
</tr>
<tr>
<td>Spin-Echo</td>
<td>$2 \times 10^6$ n/s/cm$^2$</td>
<td>MUSES@LLB $2 \times 10^7$ n/s/cm$^2$ (at 5A$^+$)</td>
<td>Multi-MUSES (x70)</td>
</tr>
</tbody>
</table>

Other simulations done by JNCS and ESS-B give similar results
LES PISTES DE RÉFLEXION

Attendre un mûrissement des technologies accélérateurs

- Mise sur le marché de produits « industriels »
- Positionnement TECHNICATOME ?
  (structure lourde)
- D-PACE (12 personnes jeunes)
- Simplifier les specs
  - faisceau pas propre « acceptable »

Réduire les ambitions → « NOVA-ERA »

- On travaille plus sur les instruments
- PRESTO = 100 x G41
  - On peut faire de la bonne science avec une instrumentation modeste (e.g. G4.1)
  - Facteur limitant = le scientifique
- Focus shift
  - Activités « périphériques »
  - Radiographie, irradiations, sections efficaces

Etre prêt en cas de « crise »

- Ex. fermeture ILL
- Radiographie
CANS IN EUROPE

after 2030

ESS

Bringing the neutrons to the users!
UTILISATION ACTUELLE DES PETITES SOURCES

Univ Indiana

Iav = 0.24 mA; P = 3 kW

CTAB (200 mM) micelles with 120 mM NaCl.

(Das et al, Langmuir 2014).

SUS316 75% Cold roll

MCP image of a USAF-1951 Gd-mask

CARR

CPHS

RANS
OPTICS FOR SPECTROMETERS

Situation at ESS

- The source is flat with a small height (3cm), instruments are at more than 15m
- Guide system starts at 2m from the moderator: best angular acceptance around 1°
- This is enough for most spectrometers except: reflectometry and inelastic spectrometers
  (open guide entrance ⇒ increase accepted divergence but not full illumination)
- Long guides for ToF resolution

At CANS,

- Moderator might be small in both directions
- Optics installed inside the moderator ⇒ full illumination at any useful divergence
- Are such optics feasible with high space constrain and without too much perturbation of the moderator?
- Instruments might be very close < 2m without guides
- Fast neutrons issue: use guides as filter?
- ToF resolution done by short pulses ⇒ shorter guides
FROM MODERATOR TO SAMPLE

**Possible intensity gain on CANS → easy increase** $\Omega_m$ (5-10°) ($A_m \sim 2-3$cm)

**Consequence (depending on optics)**
- large illumination area (e.g. 20-30cm) and lower divergence (0.5 – 1°)
- small illumination area (2-3cm) and very high divergence (5-10°)

**A key for an efficient instrument: optimization starting at the moderator**

- $A_m$ moderator size (small on CANS)
- $A_s$ sample size
- $\Omega_m$ solid angle accepted by the optics
- $\Omega_s$ solid angle usable by the instrument
- Phase space conservation: $A_m.\Omega_m \sim A_s.\Omega_s$
- $\Omega_s$ limited to ~1° for most scattering techniques

![Diagram showing illumination areas and solid angles](image_url)
Electronic circuits irradiations
- $d\Omega_s$ is not relevant; $A_s$ is small
- The largest possible solid angle should be accepted from the moderator

PGAA Prompt gamma activation analysis
- $d\Omega_s$ is not relevant
- The largest possible solid angle should be accepted from the moderator

Imaging
- $A_s$ sample size often big (5-15cm); $d\Omega_s$ should be kept small
- The use of Wolter optics type-1 may enable to have a large field of view with high resolution

Transmission diffraction
- $d\Omega_s$ can be very large in theory
- The sample size does not impact the resolution, but usually $A_s$ small
- The efficiency of the technique has to be evaluated vs standard powder scattering

Other techniques
- Spin-Echo → Fresnel coils may be difficult to build. We foresee to have a test line on Sonate
OTHER IDEAS?

One key advantage of CANS: low radiation level inside the moderator.

- The source is operated at low protons energy.
  No energetic particles are created (E<20-30MeV)
- The heat load on the cold moderator is low: a few mW!
- A closed fridge refrigerator can be used to cool the moderator

See LENS, RANS, CPHS

JCNS liquid H2 cold source
PRODUCE COLDER NEUTRONS

Cool down the moderator to 4K or lower is possible

However
- No data on the cross sections at very low temperature → no reliable simulations
- No experimental demonstration

The gains
- Shifting the spectrum to colder neutrons (8-12 Å) may boost performances

<p>| WORKSHOP ON APPLICATIONS OF A VERY COLD NEUTRON SOURCE (Argonne, 2005) |</p>
<table>
<thead>
<tr>
<th>resolution at fixed geometry</th>
<th>Intensity at fixed resolution</th>
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<tr>
<td>SANS</td>
<td>$\lambda^{-1}$</td>
</tr>
<tr>
<td>Reflectometry</td>
<td>$\lambda^{-1}$</td>
</tr>
<tr>
<td>TOF-INS</td>
<td>$\lambda^{-3}$</td>
</tr>
<tr>
<td>NSE</td>
<td>$\lambda^{-3}$</td>
</tr>
</tbody>
</table>

« Free gain »
- Neutron optics become 2-3 times more performing or cheaper
- This probably opens new possibilities but in-depth investigation is needed