FROM RESEARCH TO INDUSTRY

COMPACT NEUTRON SOURCES IN EUROPE

A.Menelle
LLB CEA-CNRS Saclay

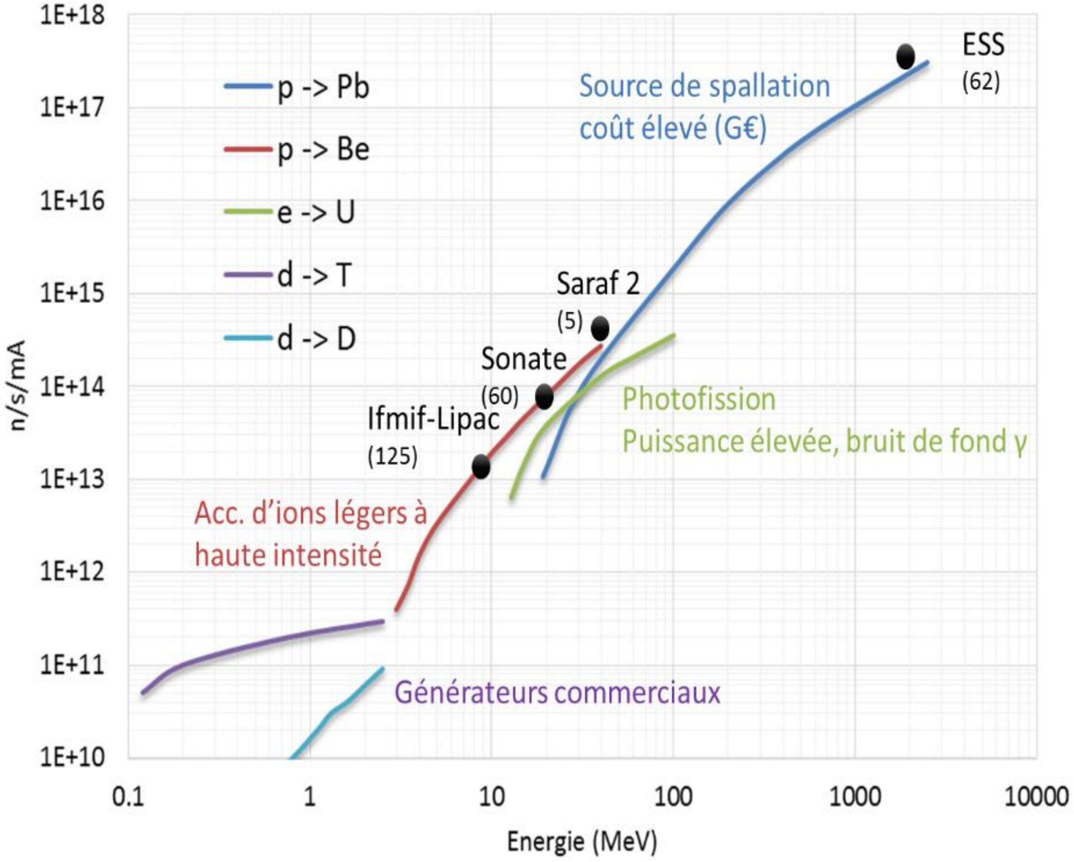
www.cea.fr

THE FUTURE AND NEXT GENERATION CAPABILITIES OF ACCELERATOR DRIVEN NEUTRON AND MUON SOURCES
RAL, UK 14/8/2018

THE COMPACT NEUTRON SOURCE CONCEPT

Why compact neutron sources ?

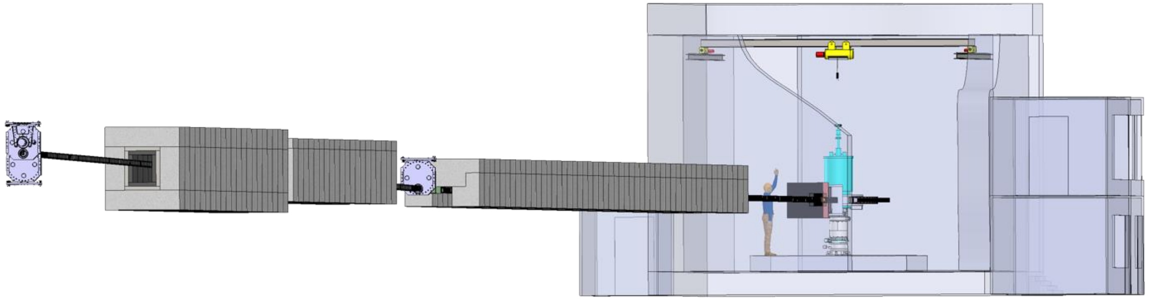
- We need neutron sources
- Construction and operation costs of a reactor or a spallation sources is high
- Produce neutrons with low energy protons (qq MeV) is possible
- Intrinsic flux is low, but the neutron production volume is small and coupling with the moderator is high (source nearly in the moderator)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



THE RIGHT TIME FOR COMPACT NEUTRON SOURCES ?

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

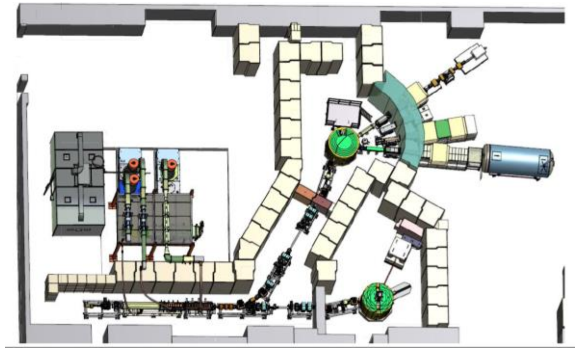


30mA DC 2MeV

CANS ALREADY IN ASIA AND AMERICA

USA : LENS, Indiana university, 13 MeV, 6kW
CANS@SNS

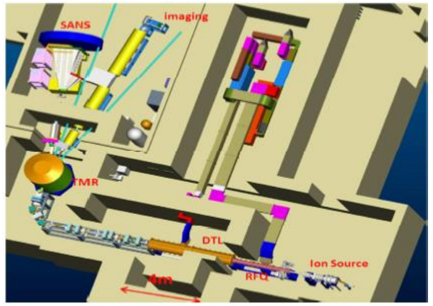
Korea : KCANS : Korea Collaboration on Accelerator-driven Neutron Sources (Korea Multi-purpose Accelerator Complex KOMAC)

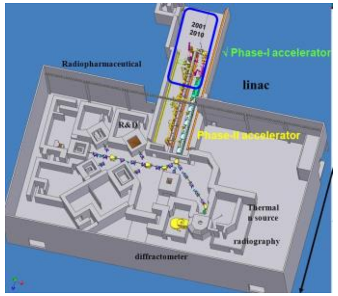


China : CCANS : China Collaboration on Accelerator-driven Neutron Sources, CPHS (Tsinghua, 13MeV 20mA peak, 16 kW), PKUNIFTY (Beijin, d on Be, 2 MeV 4mA); mainly for imaging

Argentina : Bariloche, e$^-$, 25MeV, 100Hz, 2ms, 25mA average. Stopped

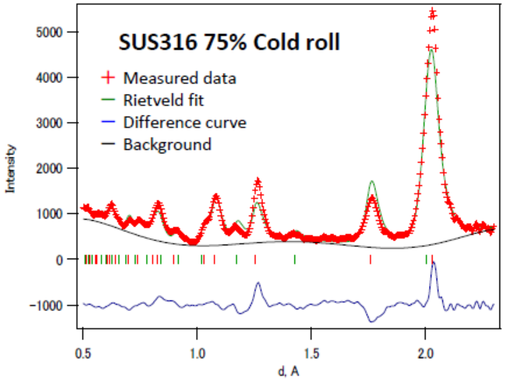
Israël : SARAF; in construction
p or d, 40 MeV, 5 mA, 200 kW on liquid Li

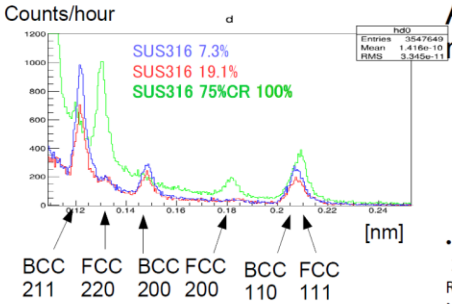




RANS (Japan) 10M€ 7MeV 100μA average

Imaging station, powder diffraction, texture measurements and SANS





Peaks of both textures are measured

Austenite volume ratio

measured value (actual value)

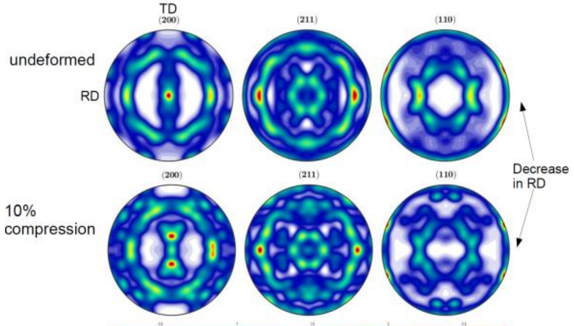
6.7±0.8% (7.3%)

17.4±0.8% (19.1%)

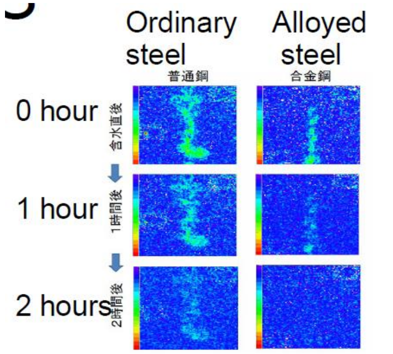
~1% of accuracy

•Rietveld analized by Dr.Suzuki
Z-Rietveld
R. Oishi et al, Rietveld analysis software for J-PARC
Nucl. Instrum. Methods, A 600 (2009) 94–96

17



They are changed due to compressive deformation



Water behavior in steel

WELL ORGANIZED IN JAPAN

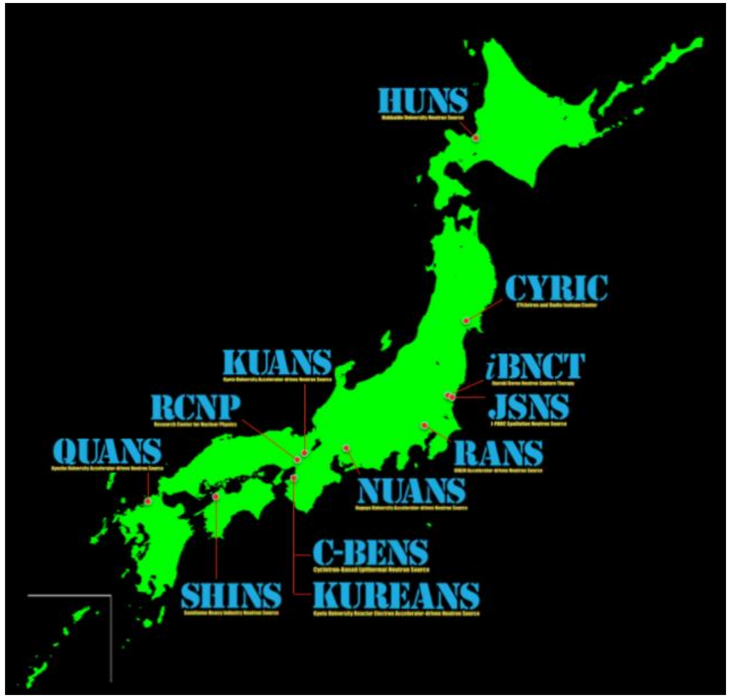

JCANS

Japan Collaboration on Accelerator-driven Neutron Sources

The Official Web Page of

Japan Collaboration on Accelerator-driven Neutron Sources

(JCANS)



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

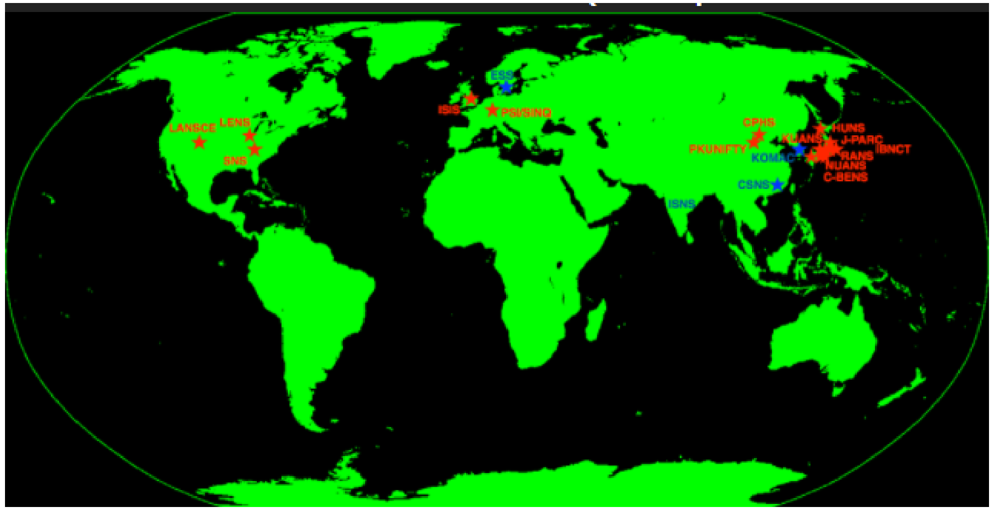
More than 10 small sources running or in project
Running around J-Parc

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 commissionning
OUANS (Osaka) : ultra cold neutrons
THUANS (Tohoku) p on Li or Be cyclotron 20-80Mev 10μA fast neutron physics
Projects : QUANS, THUANS, UTYANS

UCANS : AN INTERNATIONAL ORGANIZATION

The Official Web Page of

Union for Compact Accelerator-driven Neutron Sources (UCANS)



http://www.ucans.org

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://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_{peak} = 100 mA, P = 100 kW, multiple fixed Be target

NOVA-ERA (JCNS)

- E_p = 10 MeV, I_{peak} = 1mA, P = 400 W, Be/V target, duty cycle 4%

LINUS collaboration in Legnaro

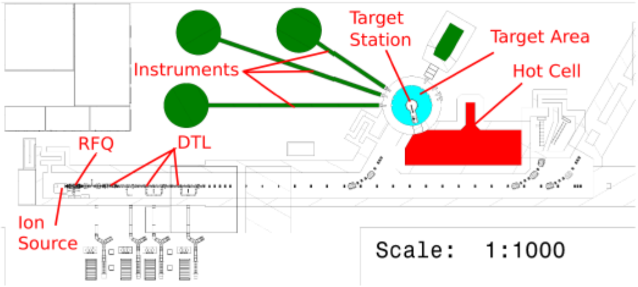
- E_p = 70 MeV, I_{av} = 750 µA, Lithium and Be target

SONATE (CEA)

- E_p = 20 MeV, I_{peak} = 100mA, duty cycle = 4%, P = 80 kW, multiple fixed Be target.

Martonvasar (Hongrie)

- E_p = 2.5 MeV, I_{peak} = 20mA, duty cycle = 5%, P = 2.5 kW, target ?.



The NT 30 mA DC H⁺ accelerator achieves proton energies of 1.85 – 2.6 MeV for research applications

SPECIALIZED WORKSHOPS IN EUROPE

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/

2017 A PROPOSITION TO A EUROPEAN CALL

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

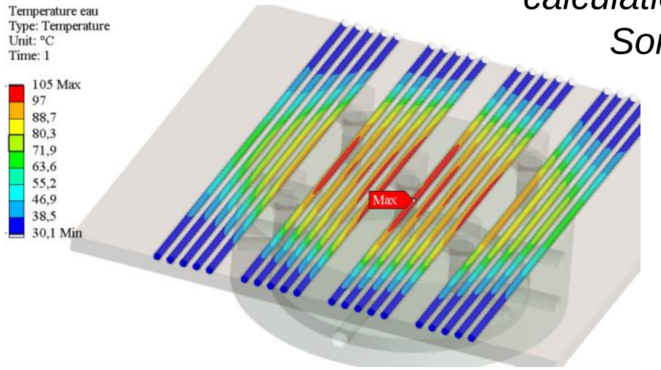
COMPACT NEUTRON SOURCE ISSUES

Limitations

- Build a compact and efficient moderator
- Heat extraction challenge (80 kW on 100 cm^2)
- 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 »

Damaged LENS Be target



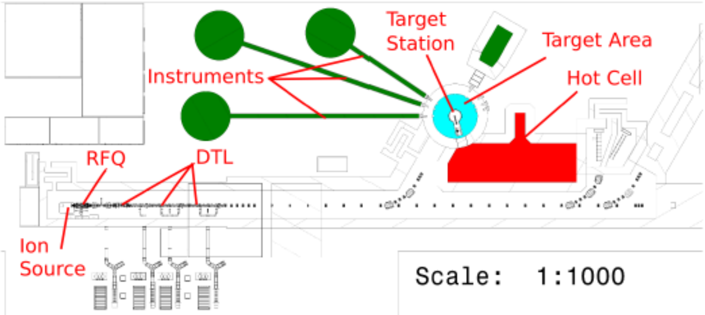
Thermo-hydraulic calculations for the Sonate target

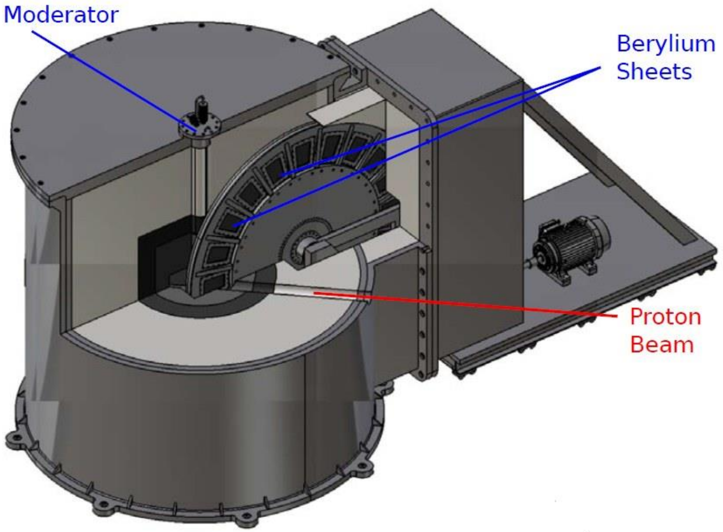
ESS-BILBAO PROJECT

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

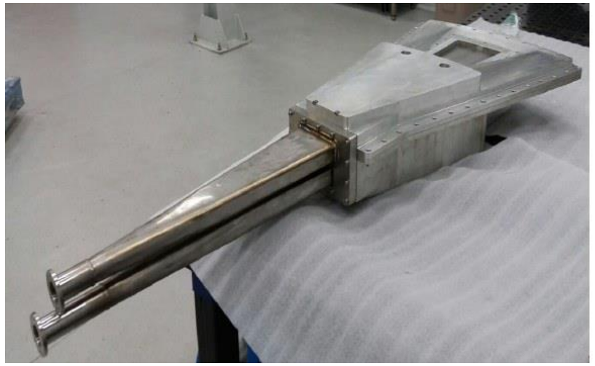
Project :

- 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

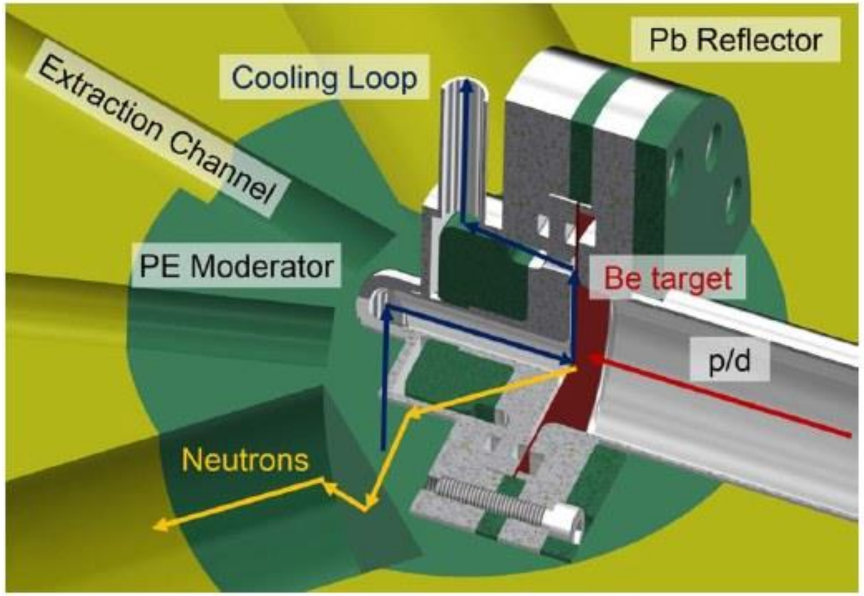


NOVA-ERA JCNS PROJECT

Neutrons **O**btained **V**ia **A**ccelerator for **E**ducation and **R**esearch **A**ctivities

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 10^{13} n/s
Max thermal neutron flux : 1.4 10^{11} n/s

Should be affordable by a big university

HBS JCNS PROJECT

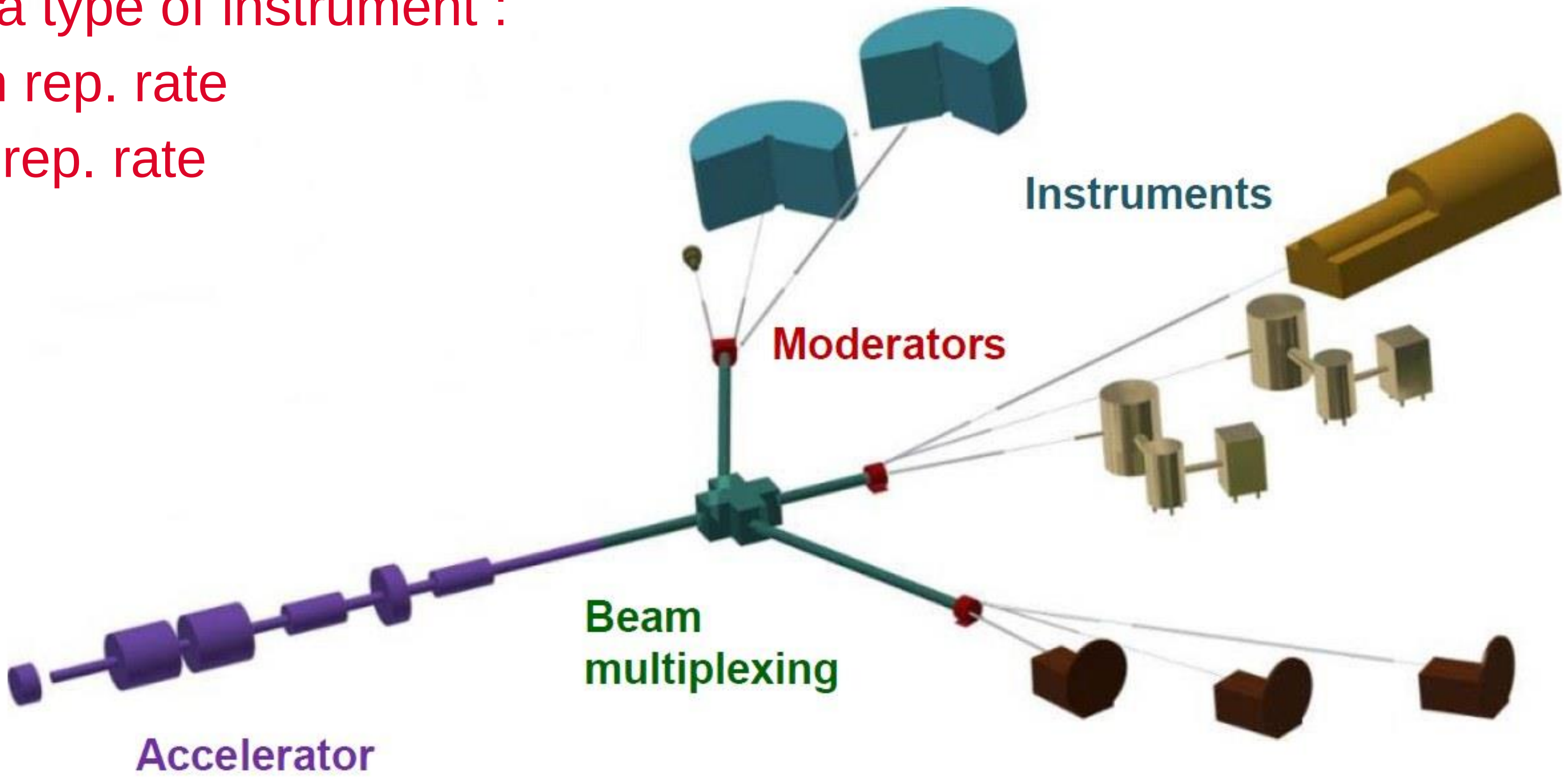
A high performance source ready ~**2035**

Multi target; 100kW par target

Each target adapted to a type of instrument :

short pulse, high rep. rate

Long pulse, low rep. rate



DEVELOPMENTS FOR THE HBS JCNS PROJECT

A liquid para H2 moderator tested at the AKR reactor in Dresden

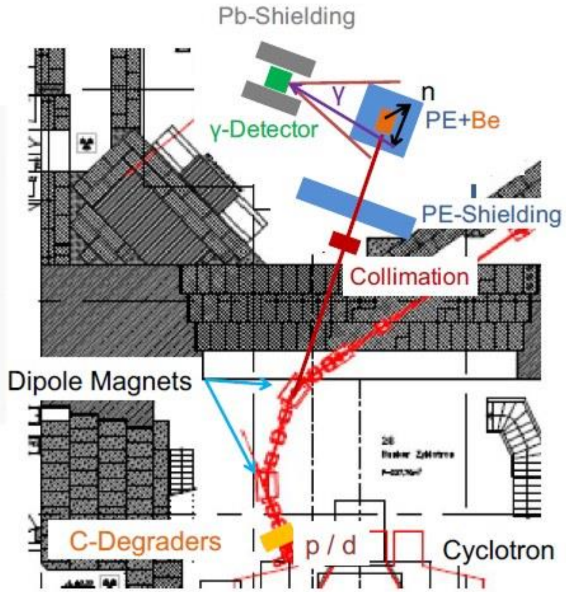
Modify Cosy accelerator to have a test beam line

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

Seting-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/cm^2

Development of Be/V diffusion bonding with Intellion for targets

MARTONVASAR HUNGARIAN PROJECTS

Near **Budapest by 2023**

4M€ Regional Technology Development Grant

1M€ from Mirrotron and Evopro

For industrial applications, developments and BNCT

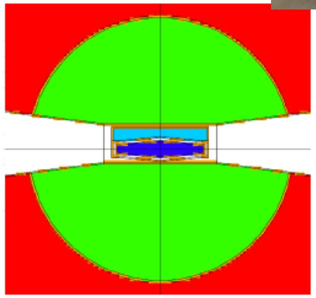
Max spec : H^+ 2.5 MeV 20 mA 50 kW CW

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

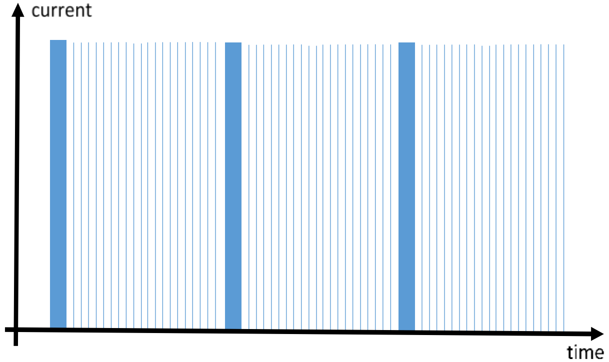
- End of 2019 on IPHI 3 MeV with 1 multi-purpose instrument

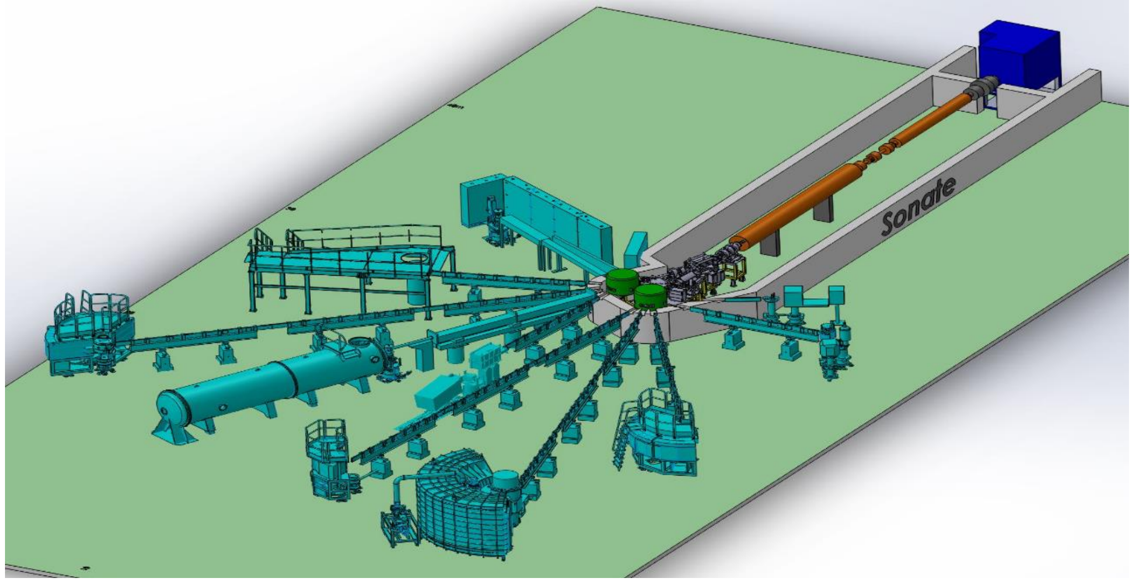
Compact source demonstrator

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

Full Sonate

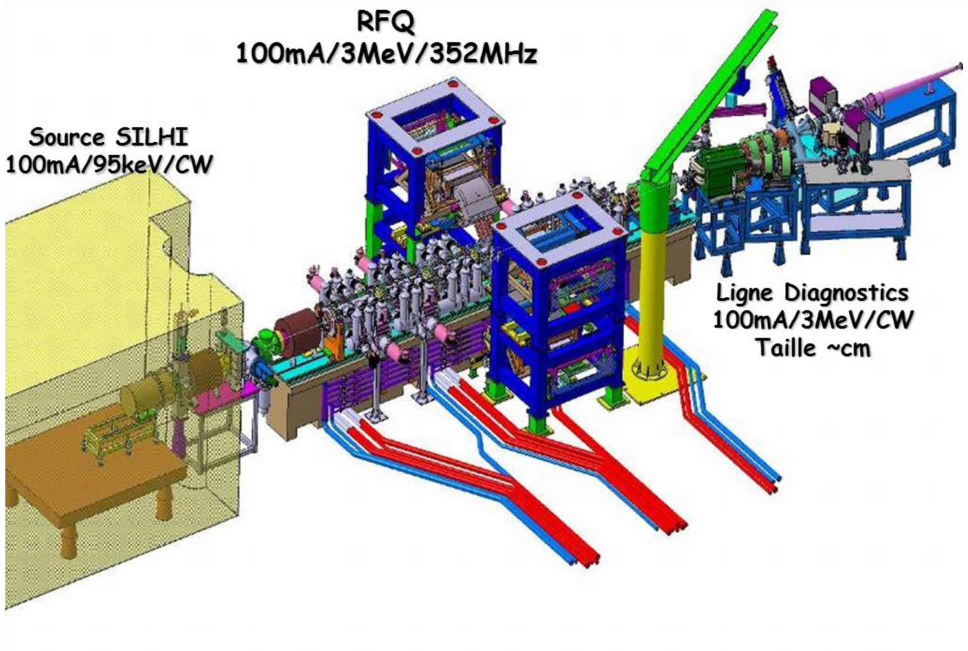
- End of 2030, 20 MeV, 4% duty cycle, 100 mA, 2 targets (short pulses, long pulses), 10 instruments





TESTS : JUNE 2016 AND FEBRUARY 2018

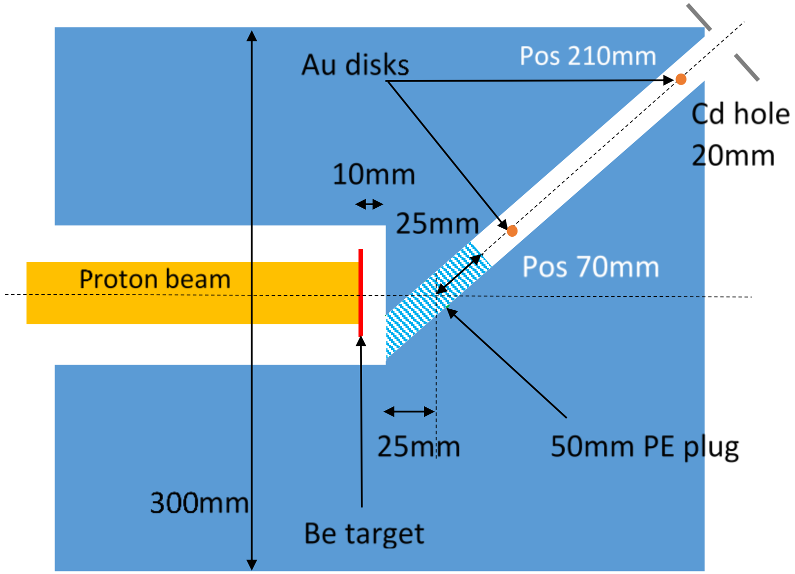
Accelerator IPHI@Saclay: 3 MeV – 100 mA peak

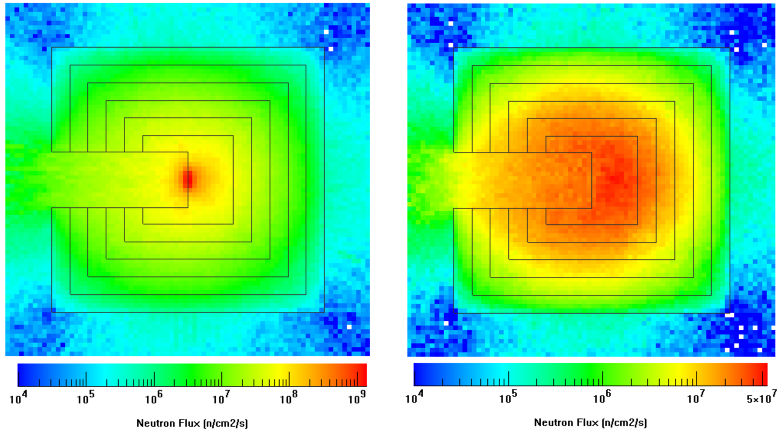


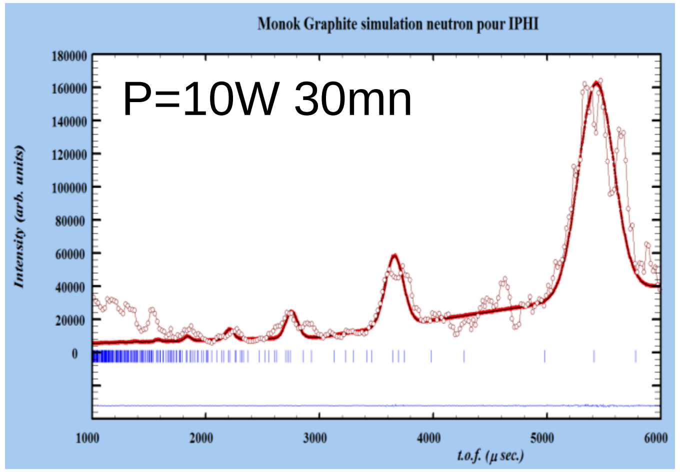
Operation at 30 W (30 mA 1 Hz 100 μs)
(to stay in our current safety authorization)

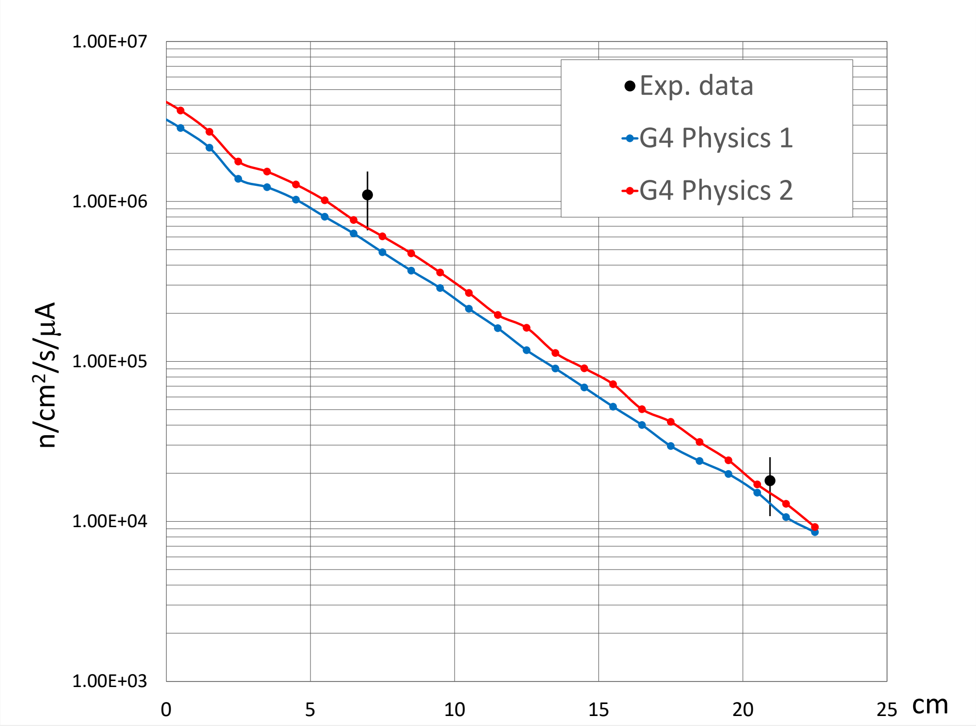
Expected 7 kW authorization by end 2018

RESULTS : SIMULATIONS VALIDATION





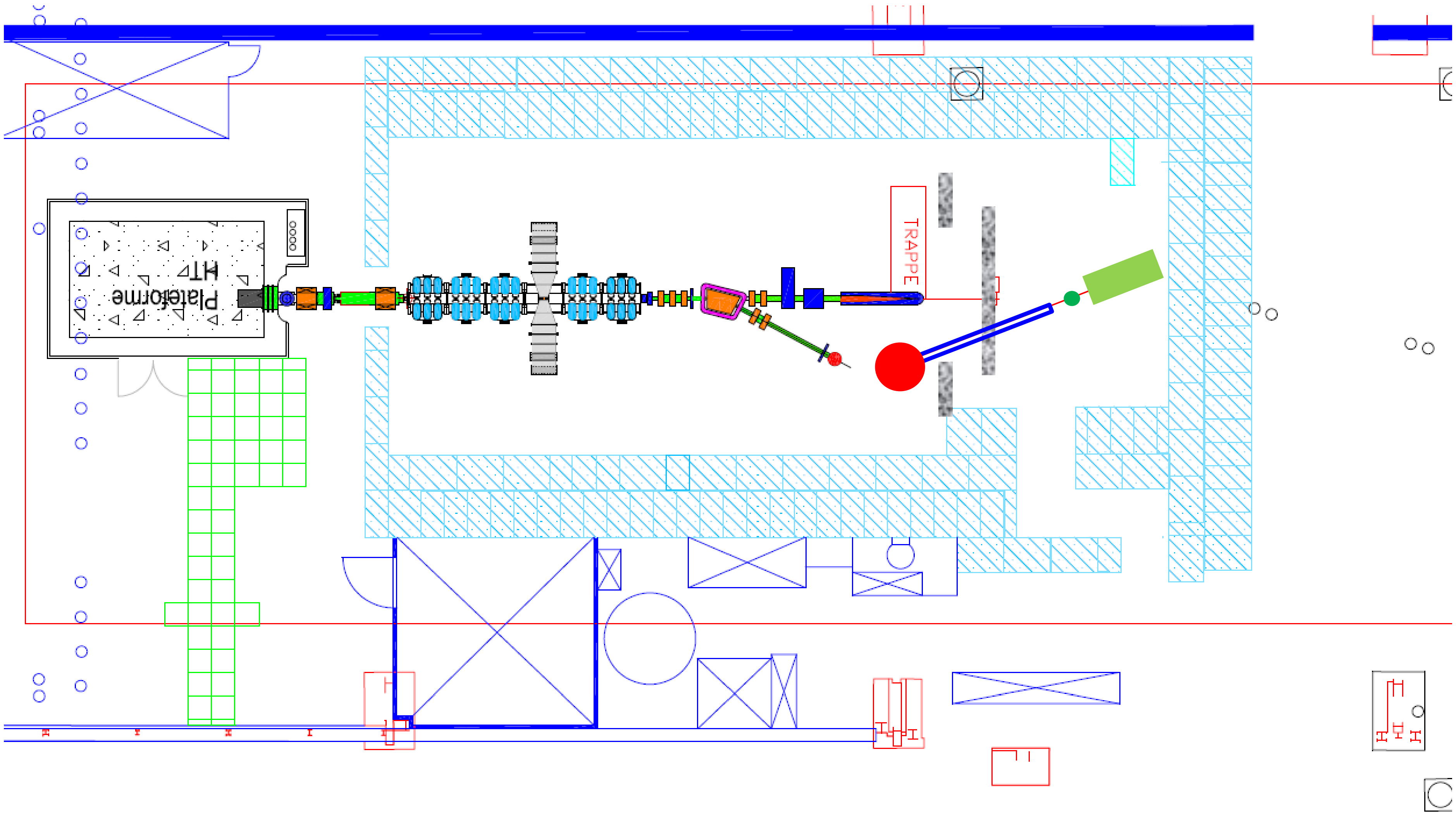




PROJECT 2019

Sesame IPHI-Neutrons 430k€

DRF CMR50 500k€

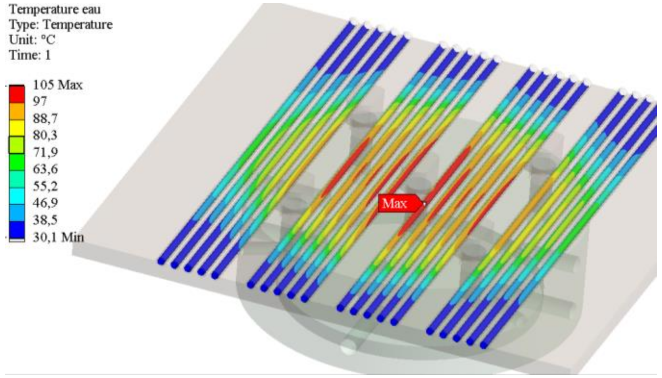


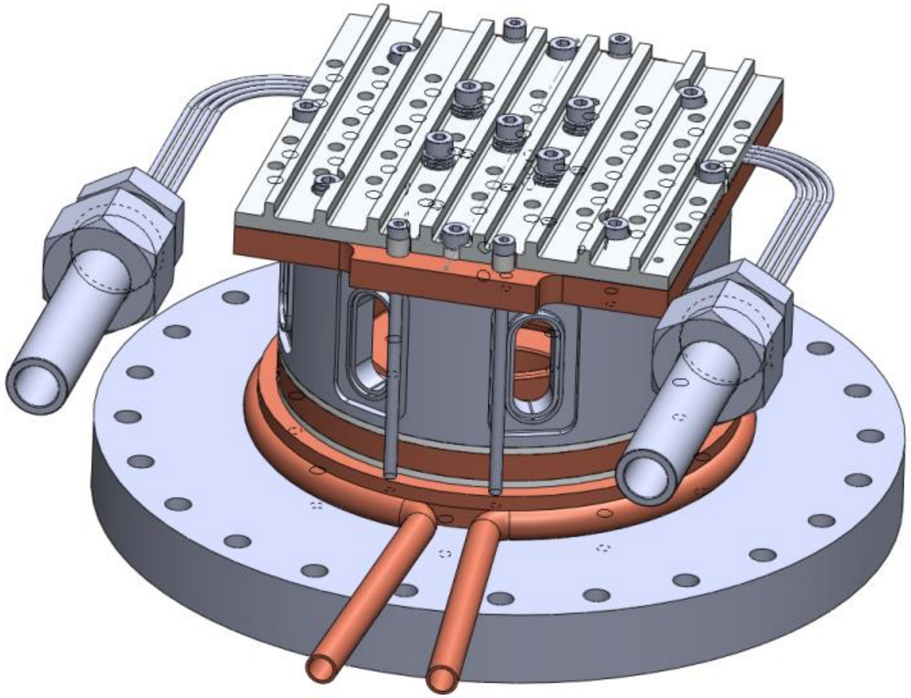
1 « multi-purpose » instrument : SANS, reflectometer, imaging, diffraction

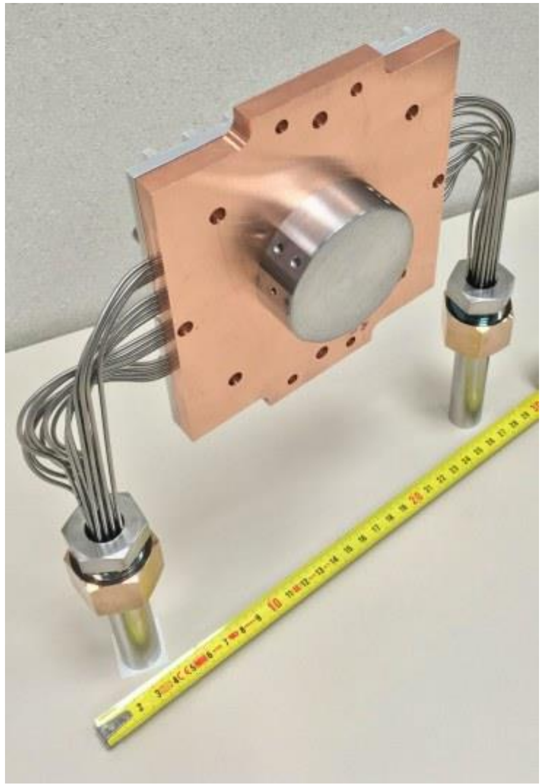
Measure a few samples, do the proof of concept, evaluate performances, test target ageing

TARGET : THE COOLING ISSUE

Test on BETSI in September (2kW)
Simulations done for 10kW
Water, 20 bars; 1 l/min/capillary



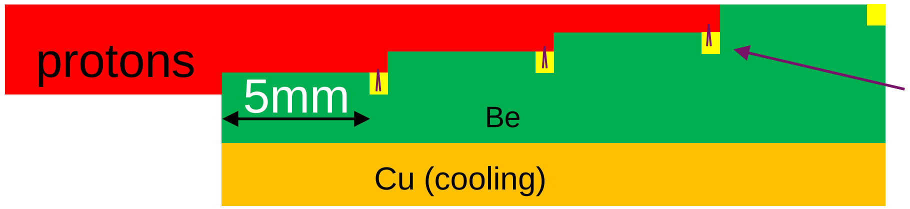




TARGET : THE AGEING ISSUE OF EMBRITLEMENT OF BE

Various ideas to solve the Pb :

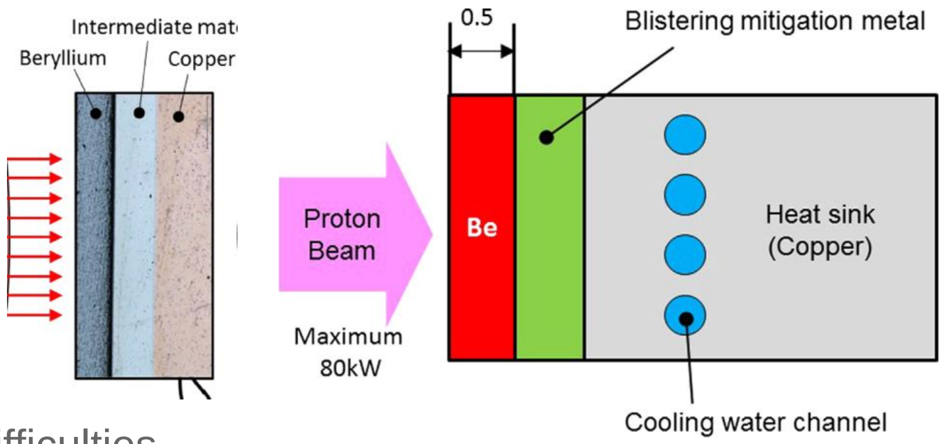
grazing beam with metal protons absorbers (requires higher energy)



Protons absorber metal
(Pd for example)

Multilayer target

- Protons stopped in a hydrogen absorbing layer layer aux protons



Tested in
- iBNCT (Kumada, 2015)
- RANS (Yamagata, 2015 test Be on V 10 mA.h)
- HBS (Zakalek, 2018 to be tested in 2019)
- Legnaro

Mitigation metal :
Vanadium, Palladium
(niobium, tantalum)

- Difficulties
  - Weldings
  - Differiential dilatation
  - Bad thermal conduction (K_{vana} = 31W/m.K Vs 200 for Be or Cu)

TARGET : THE AGEING ISSUE OTHER IDEAS

Let protons be stopped in the cooling circuit

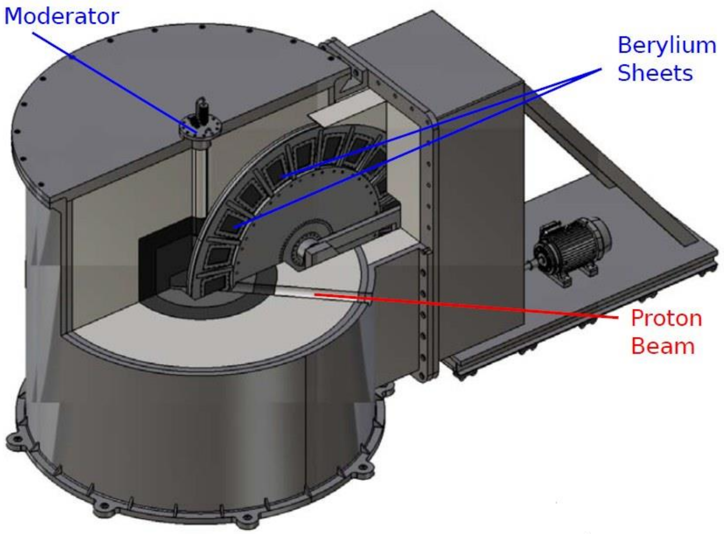
- Target does the isolation between cooling and vacuum
- Can only be done if E_p is high >13meV (thickness >1mm)

LENS@Bloomington (in operation since 2008)

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

ESS-Bilbao

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



TARGET : THE AGEING ISSUE : LIQUID TARGET CERTAINLY EXPENSIVE BUT IT WORKS

Lithium target (liquid)

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

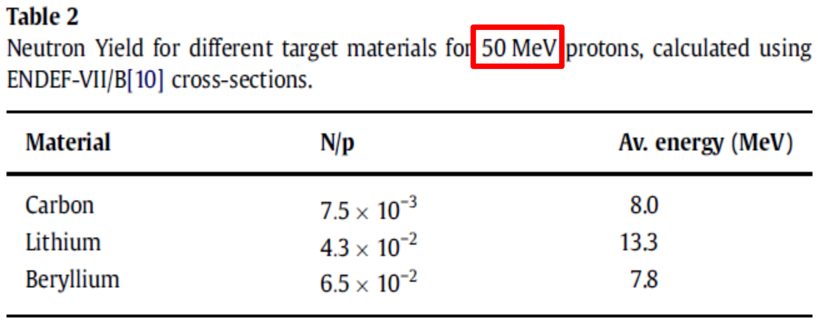


Table 2
Neutron Yield for different target materials for 50 MeV protons, calculated using ENDEF-VII/B[10] cross-sections.

Material	N/p	Av. energy (MeV)
Carbon	7.5×10^{-3}	8.0
Lithium	4.3×10^{-2}	13.3
Beryllium	6.5×10^{-2}	7.8

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_{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

THANK YOU

SPARE SLIDES

PERFORMANCES OF INSTRUMENTS

LLB simulations with SONATE reference design

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

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

- Other simulations done by JNCS and ESS-B give similar results

LES PISTES DE RÉFLEXION

Attendre un mûrissement des technologies accélérateurs

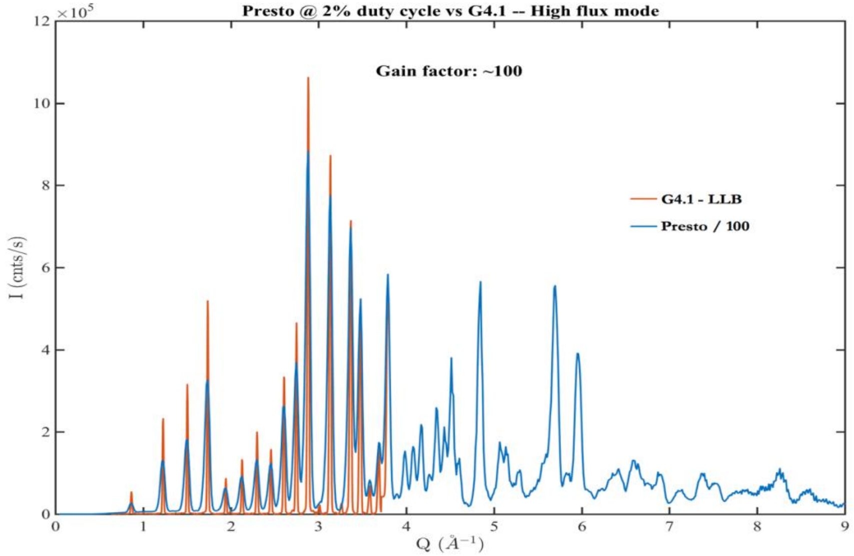
- Mise sur le marché de produits « industriels »
- Positionnement TECHNICATOME ? (structure lourde)
- D-PACE (12 personnes jeunes)
- Simplifier les specs
  - faisceau pas propre « acceptable »

D-Pace **Model: H+26.30**

The NT 30 mA DC H^+ accelerator achieves proton energies of 1.85 – 2.6 MeV for research applications

Réduire les ambitions → « NOVA-ERA »

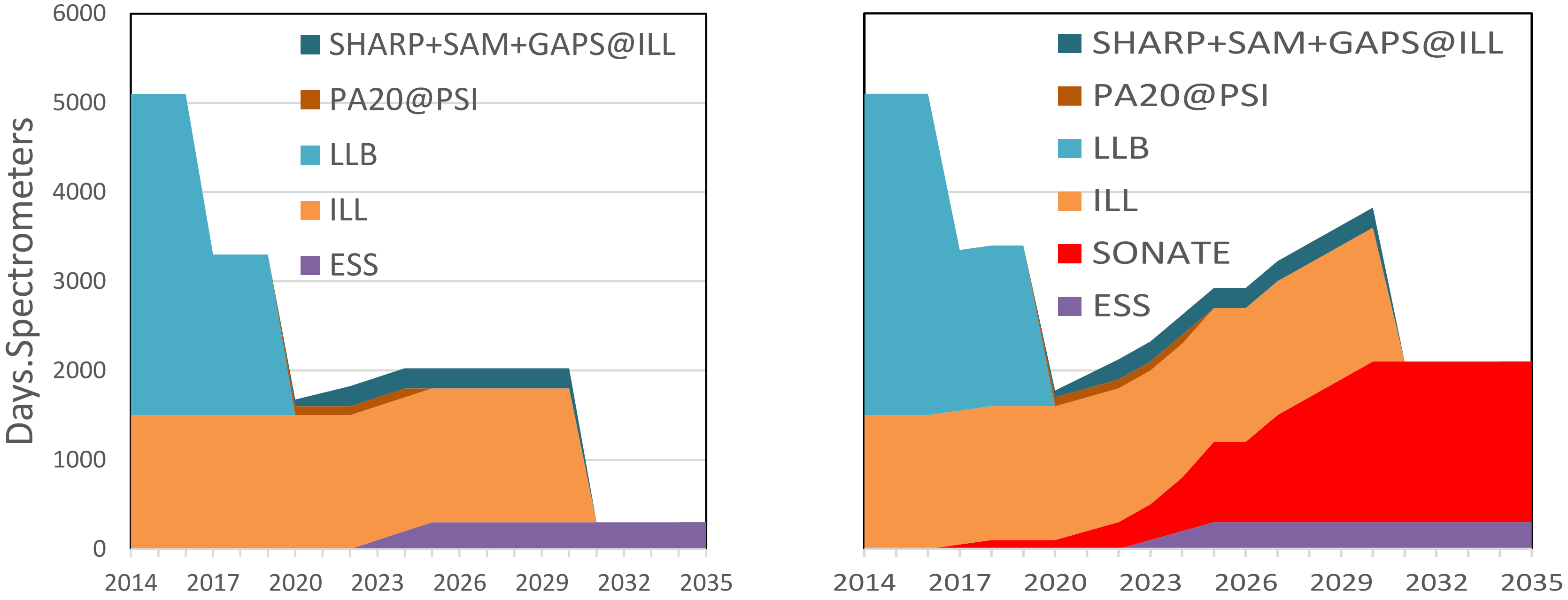
- On travaille plus sur les instruments
- PRESTO = 100 x G41
  - On peut faire de la bonne science avec une instrumentation modeste (e.g. G4.1)
  - Facteur limitant = le scientifique
- Focus shift
  - Activités « périphériques »
  - Radiographie, irradiations, sections efficaces



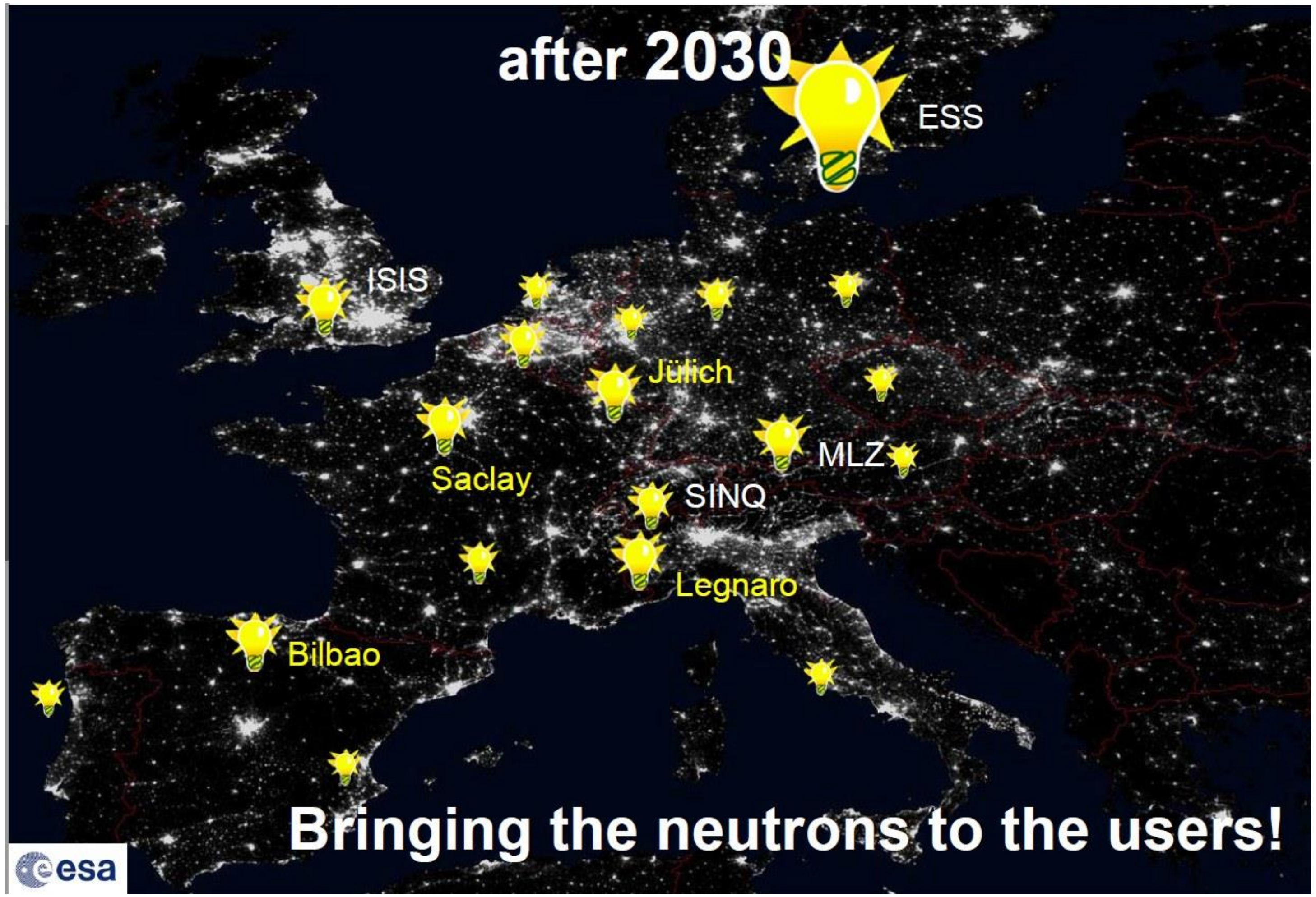
Etre prêt en cas de « crise »

- Ex. fermeture ILL
- Radiographie

FRENCH ROADMAP WITH AND WITHOUT SONATE



CANS IN EUROPE



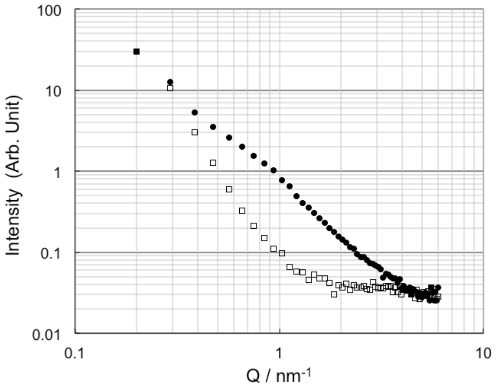
UTILISATION ACTUELLE DES PETITES SOURCES

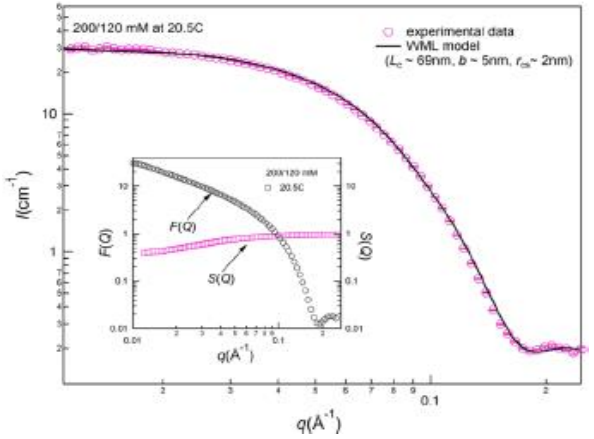
SANS data @ LENS Univ Indianna)

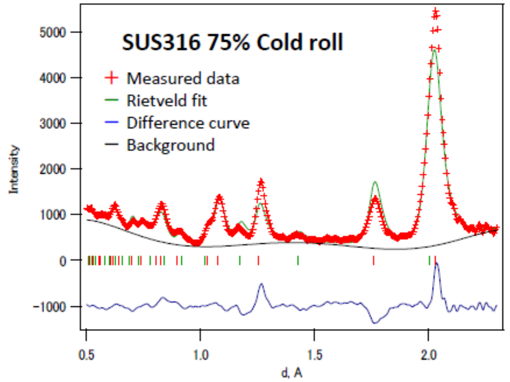
@13MeV; 20mA; 20Hz, 600µs; I_{av} = 0.24mA ; ***P = 3kW***

CTAB (200mM) micelles with 120 mM NaCl.

(Das et al, Langmuir 2014).



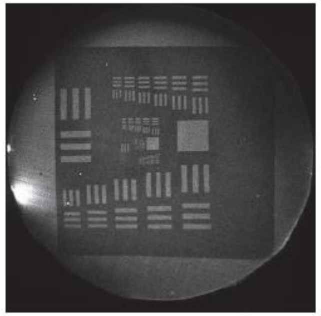


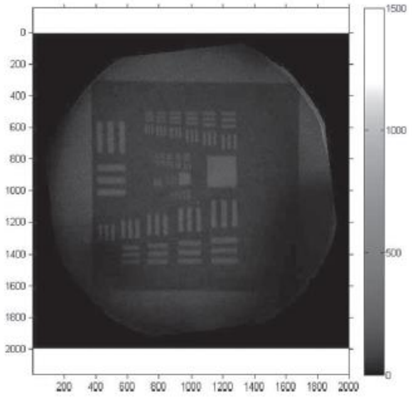


RANS

MCP image of a USAF-1951 Gd-mask

CARR





CPHS

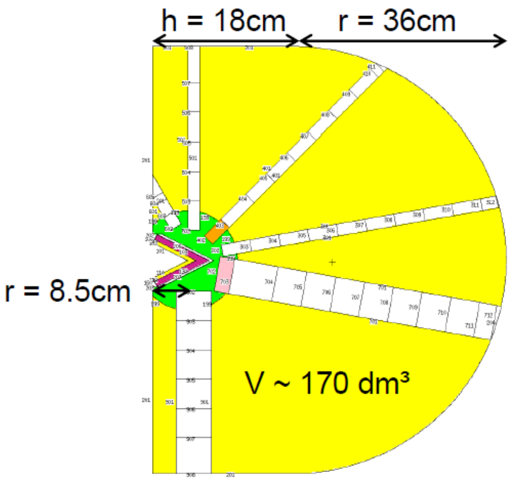
OPTICS FOR SPECTROMETERS

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,

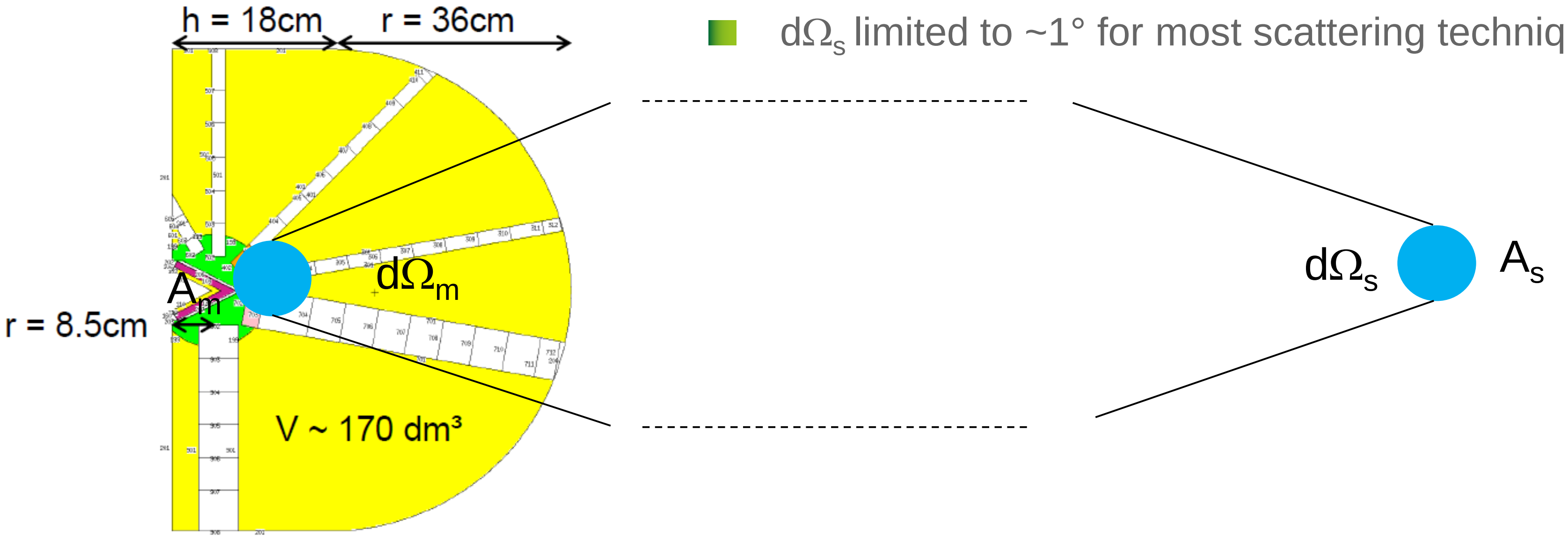
- Moderator might be small in both directions
- Optics installed inside the moderator ⇨ full illumination at any useful divergence
- Are such optics feasible with high space constrain and without too much perturbation of the moderator ?
- Instruments might be very close < 2m without guides
- Fast neutrons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



FROM MODERATOR TO SAMPLE

- A_m moderator size (small on CANS)
- A_s sample size
- $d\Omega_m$ solid angle accepted by the optics
- $d\Omega_s$ solid angle usable by the instrument
- Phase space conservation: $A_m.d\Omega_m \sim A_s.d\Omega_s$

- $d\Omega_s$ limited to ~1° for most scattering techniques



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

SOME TECHNIQUES MIGHT BENEFIT

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.

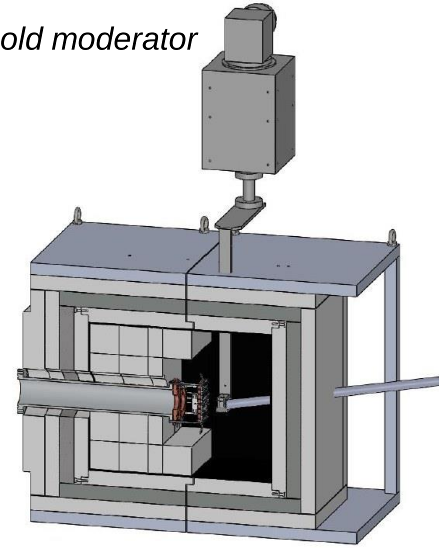
- The source is operated at low protons energy.

  No energetic particles are created (E<20-30MeV)

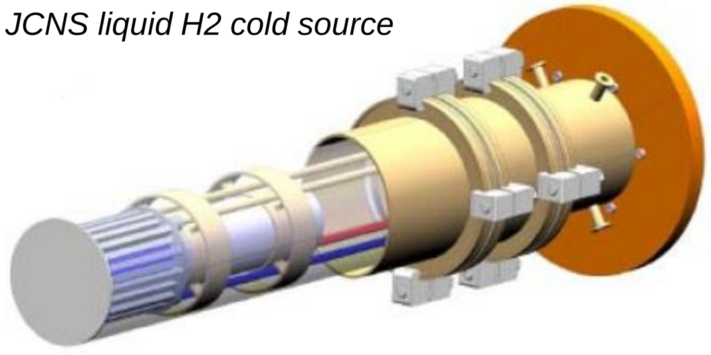
- The heat load on the cold moderator is low : a few mW !
- A closed fridge refrigerator can be used to cool the moderator

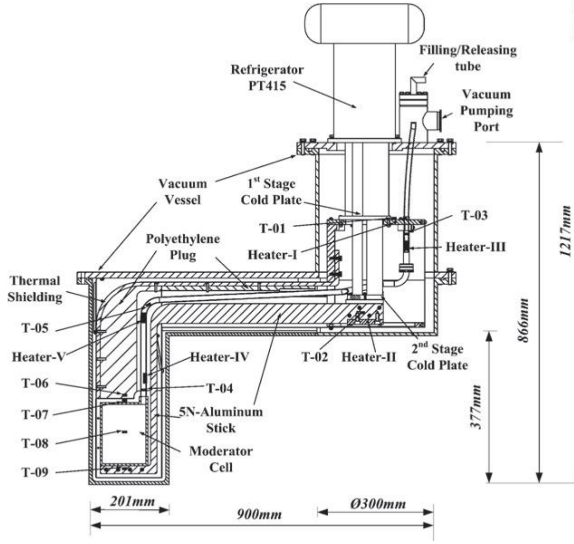
  See LENS, RANS, CPHS

LLB test cold moderator



JCNS liquid H2 cold source





CPHS@Beijing

PRODUCE COLDER NEUTRONS

Cool down the moderator to 4K or lower is possible

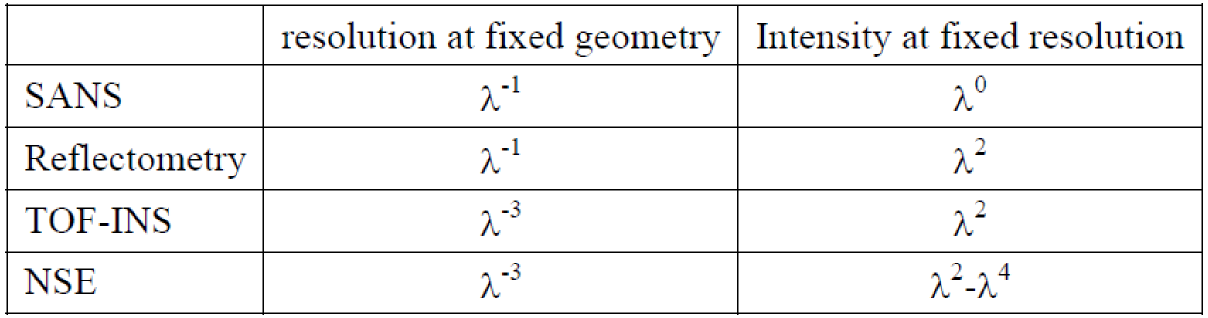
However

- 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

WORKSHOP ON APPLICATIONS OF
A VERY COLD NEUTRON SOURCE
(Argonne, 2005)



	resolution at fixed geometry	Intensity at fixed resolution
SANS	λ^{-1}	λ^{0}
Reflectometry	λ^{-1}	λ^{2}
TOF-INS	λ^{-3}	λ^{2}
NSE	λ^{-3}	λ^{2}-λ^{4}

« Free gain »

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