NEUTRON SCATTERING ON COMPACT NEUTRON SOURCES

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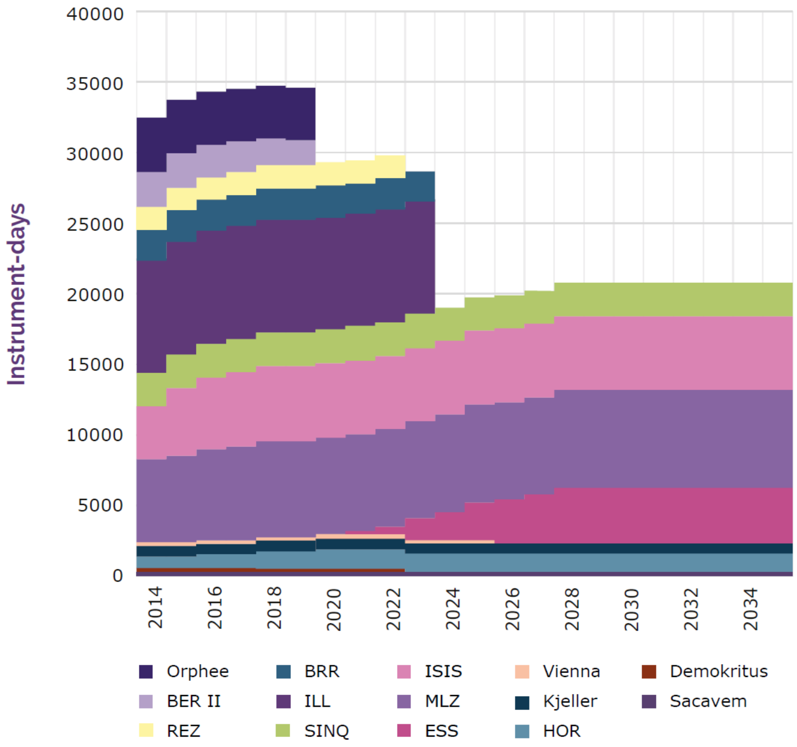
THE NEUTRON SCATTERING LANDSCAPE

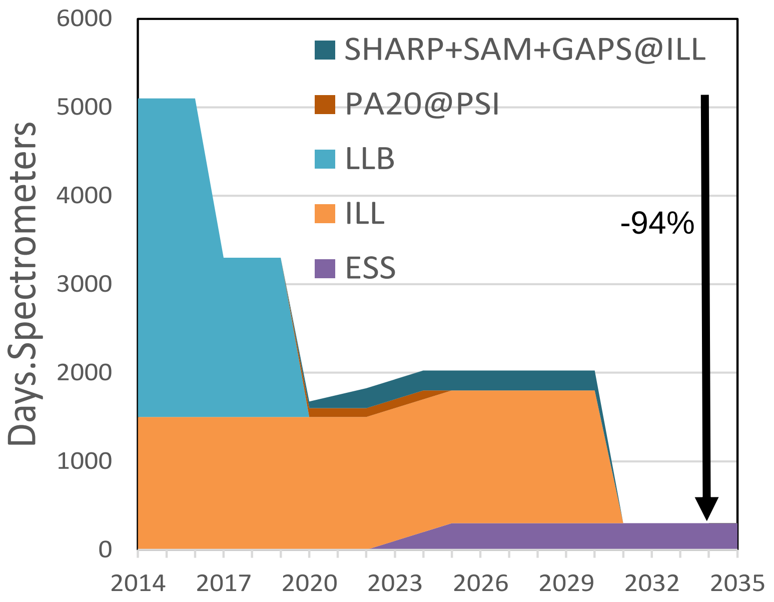
Neutrons in Europe

(baseline ERFRI scenario)



ESFRI Report, *Neutron scattering facilities in Europe, Present status and future perspectives, 2017*

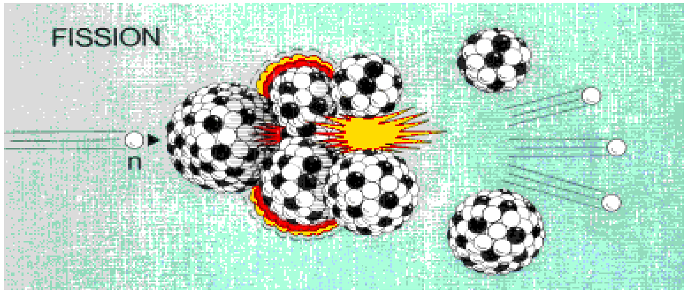
in France



Neutron production

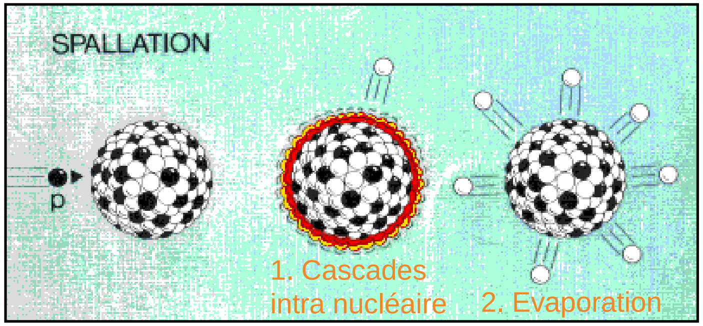
Nuclear reactor

- Technological limit reached decades ago
- Nuclear risk



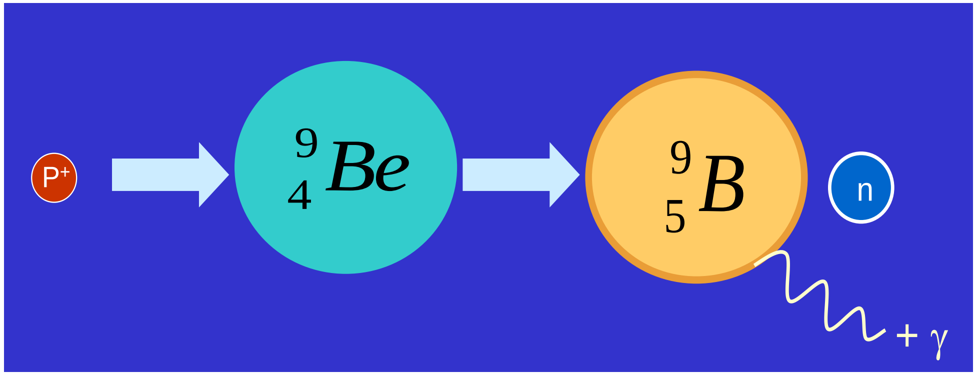
Spallation

- High energy protons (~1 GeV) excite a heavy nucleus (ex. W)
- The excited nucleus evaporates neutrons **(~15 n/p)**



Stripping

- Low energy protons (3 – 60 MeV) strip a neutron from a light element (ex. Be, Li)
- Efficiency **(0.01 à 0.1 n/p)**



CANS

- Ion source (p or d)
- Accelerator E_p ~ 7- 50 MeV
- Target Be or Li (« stripping » reaction)
- Moderator (thermal – cold)
- Thermal / cold neutron Instruments

WHAT ABOUT CANS ACROSS THE WORLD ?

Outside Europe

- LENS (USA), CANS@SNS
- HUNS, RANS, KUANS, NUANS, iBNCT, OUANS, QUANS, THUANS, UTYANS (Japon)
- SARAF (Israel), CPHS (Chine), PKUNIFTY (Pekin)

Within Europe

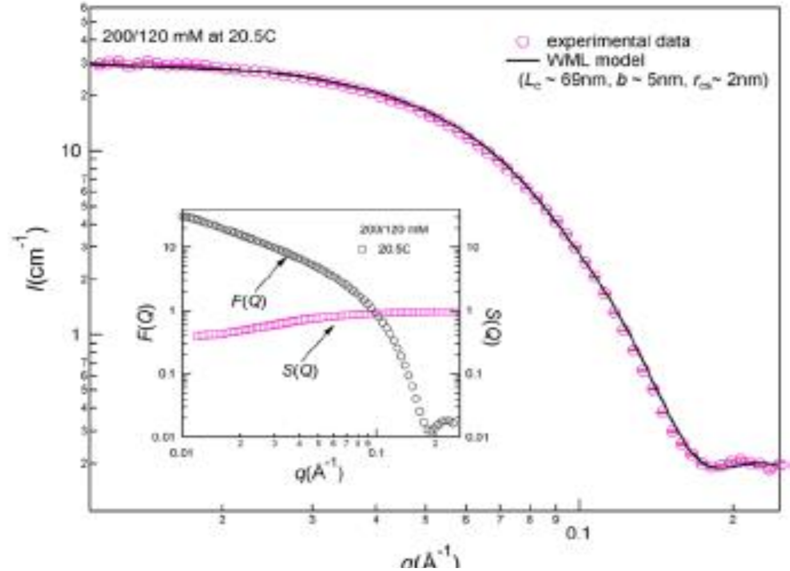
- LENOS (Legnaro) E_p = 70 MeV, I_{av} = 750 µA, Lithium target (under commissioning)
- ESS-Bilbao E_p = 50MeV, P = 115kW, rotating Be target
- HBS High Brillance Source (JCNS) E_p = 50MeV, I_{peak} = 100mA, P = 100kW, fixed Be target
- NOVA-ERA (JCNS) E_p = 10MeV, I_{peak} = 1mA, P = 1kW, Be target, duty cycle 4-10%
- LvB Ludwig Van Beethoven (Hungary) Ep = 3 MeV
- SONATE (CEA) E_p = 20MeV, I_{peak} = 100mA, duty cycle = 4%, P = 80kW, fixed Be target.

STATE OF THE ART AT CANS

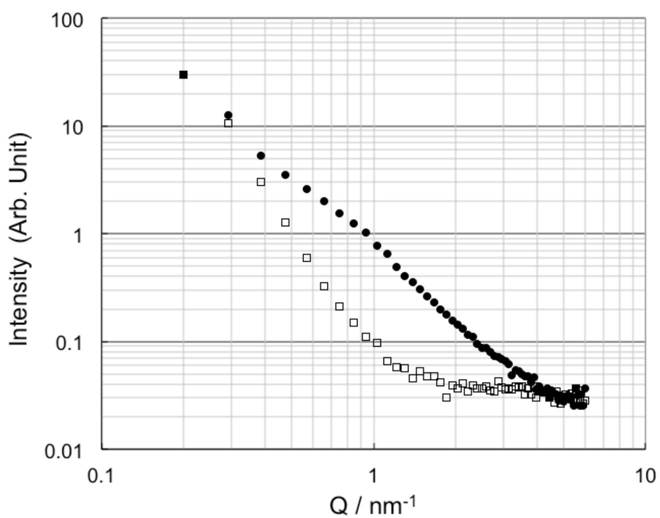
NEUTRON SCATTERING

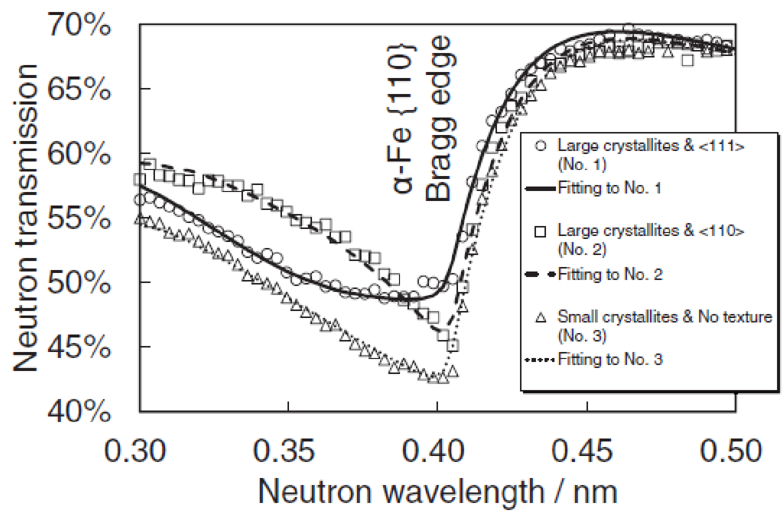
SANS data @ LENS Univ Indiana)

- *@13MeV; 20mA; 20Hz, 600µs; I_{av} = 0.24mA ;* ***P = 3kW***
- *CTAB (200mM) micelles with 120 mM NaCl.*
  (Das et al, Langmuir 2014).



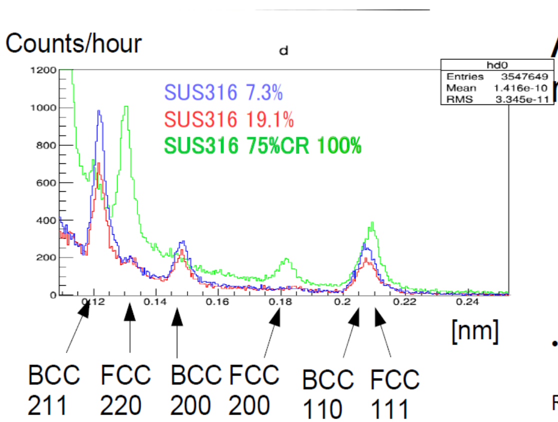
HUNS @ Hokkaido





- *(left) SANS in steel samples with (filled markers) and without (open markers) nanoscopic precipitates. (right) Bragg-edge transmission spectra measured at HUNS, and the profile fitting curves obtained by RITS.*

RANS @ RIKKEN, JAPON



Peaks of both textures are measured

Powder diffraction pattern in steel (austenite – martensite ratios)

Austenite volume ratio

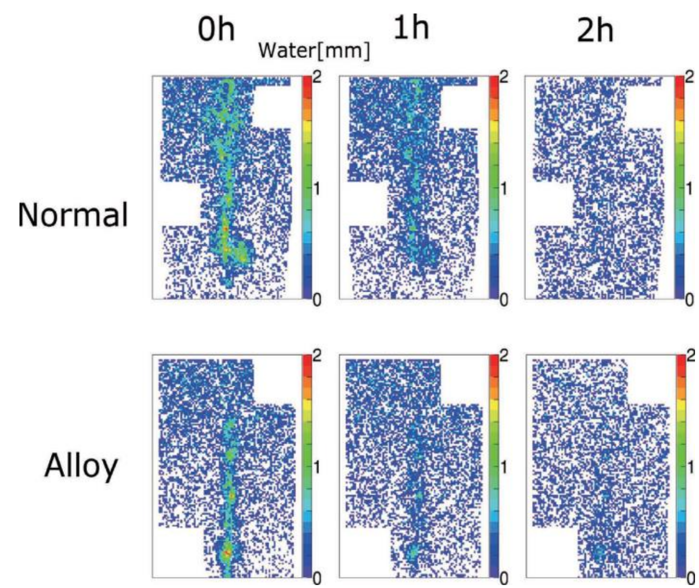
measured value (actual value)

6.7±0.8% (7.3%)

17.4±0.8% (19.1%)

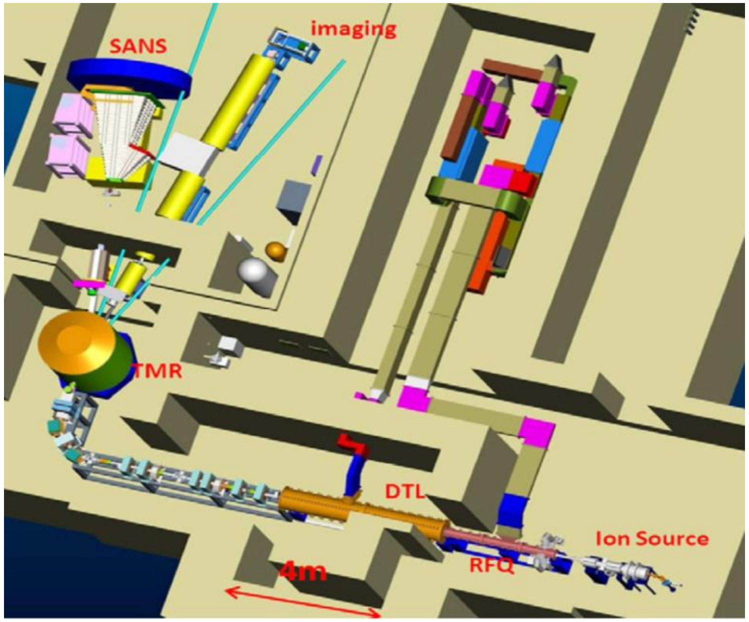
~1% of accuracy

•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



Radiography of corroded steel plates and humidity up-take as a function of time. Pixel Size 0.8x0.8mm² ; 5 minutes exposure time; Ep = 7 MeV ; I_{av} = 15µA ; P = 100W.

CPHS (CHINA)



NOMINAL

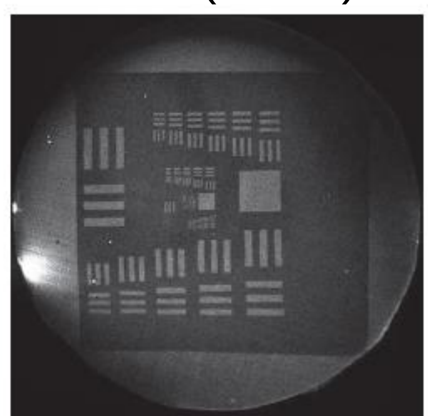
- E_p = 13MeV, I_{peak} = 50mA, duty cycle = 2.5%, P = 16.3kW

ACTUAL

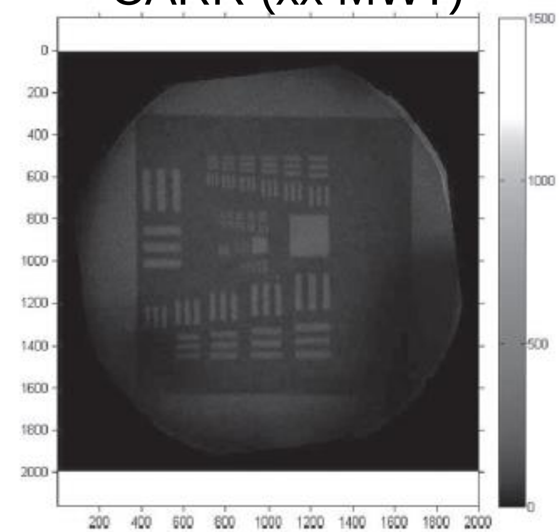
- E_p = 3MeV, I_{peak} = 50mA, duty cycle = 2.5%, P = 3kW

MCP image of a USAF-1951 Gd-mask measured with the beam line of CPHS (left) and CARR (right). Note that the measuring conditions are not documented (measuring time, L/D ratio, CARR power…)

CPHS (3MeV)



CARR (xx MW?)



USERS EXPECTATION

Users want something as good as what they are used to

- Reference level = Orphée

How far can we push CANS ?

MAXIMISING THE PERFORMANCES

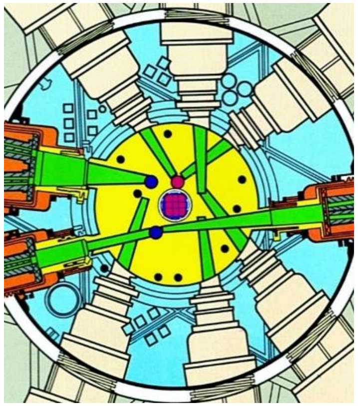
Very high proton current

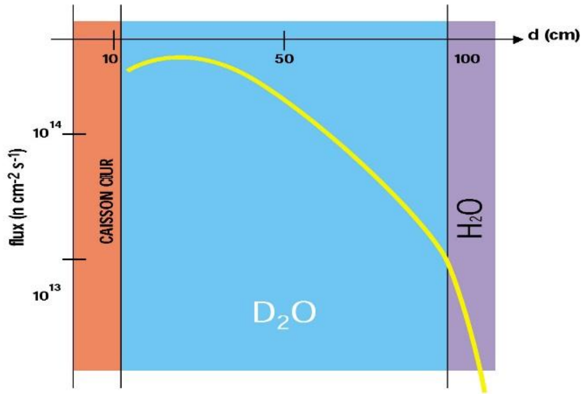
- ISIS TS2 : E = 0.8 GeV ; I = 50µA
- IPHI : E = 3 MeV ; I = 100mA
- ESS: E = 2GeV ; I = 60mA
- IFMIF: E = 10MeV; I = 125mA

MAXIMISING THE BRILLANCE: STRONG COUPLING

Réacteur

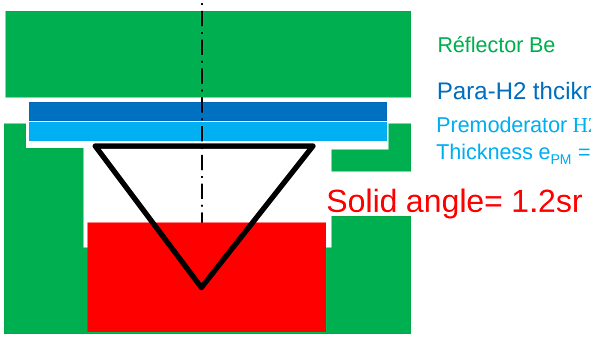
- Core = 0.1 m^3
- Moderator vessel D_2O ~ 1m^3





Spallation

- target = 4 litres
- moderator ~ 1 litre (not too well coupled)

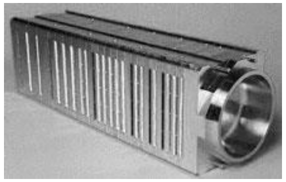


Réflector Be

Para-H2 thcikness 1.5cm, diamètre D_M = 15 cm

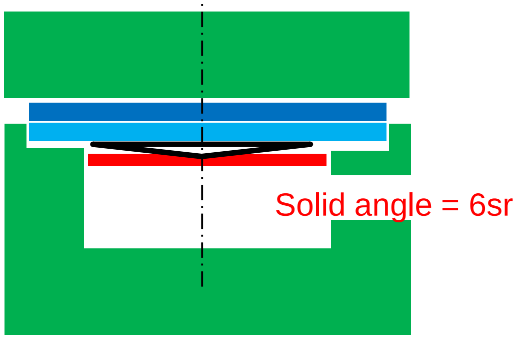
Premoderator H2O

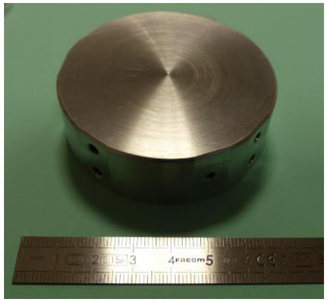
Thickness e_{PM} =2cm – diameter D_{PM} = 15 cm



Stripping

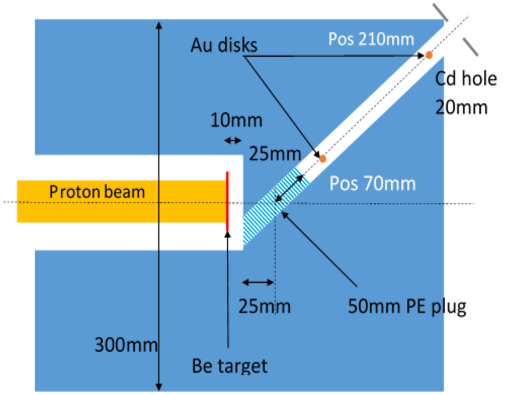
- Target = 0.05 litres
- moderator ~ 1 litre (coupling 90%)



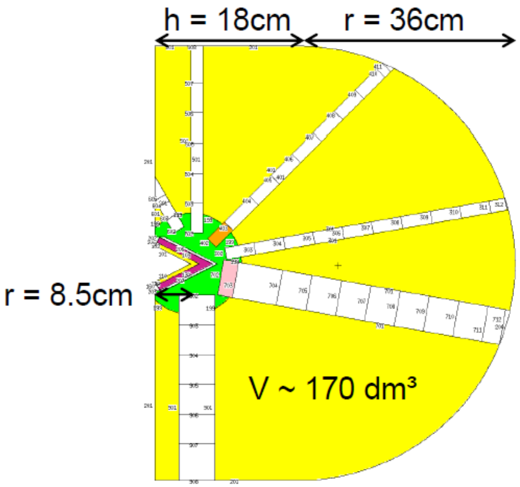


MAXIMISING THE BRILLANCE: TUBE MODERATOR

Prototype moderator (LLB)

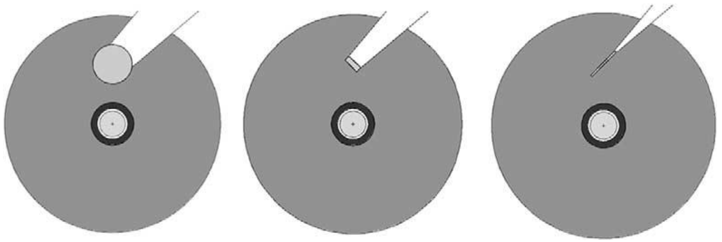


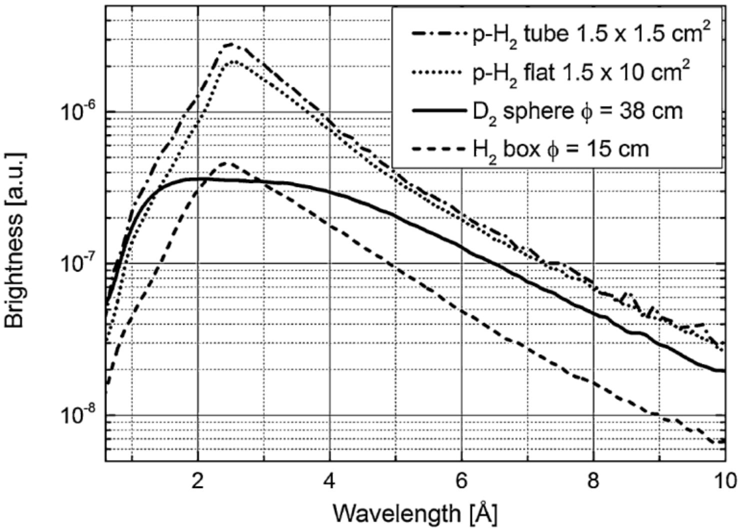
Possible « final design »



J.P. Dabrück
Univ. Aachen

Flux penalty <10%
with 5 holes





F. Mezei et al , Journal of Neutron Research 17 (2014) 101–105 101 DOI 10.3233/JNR-140013,

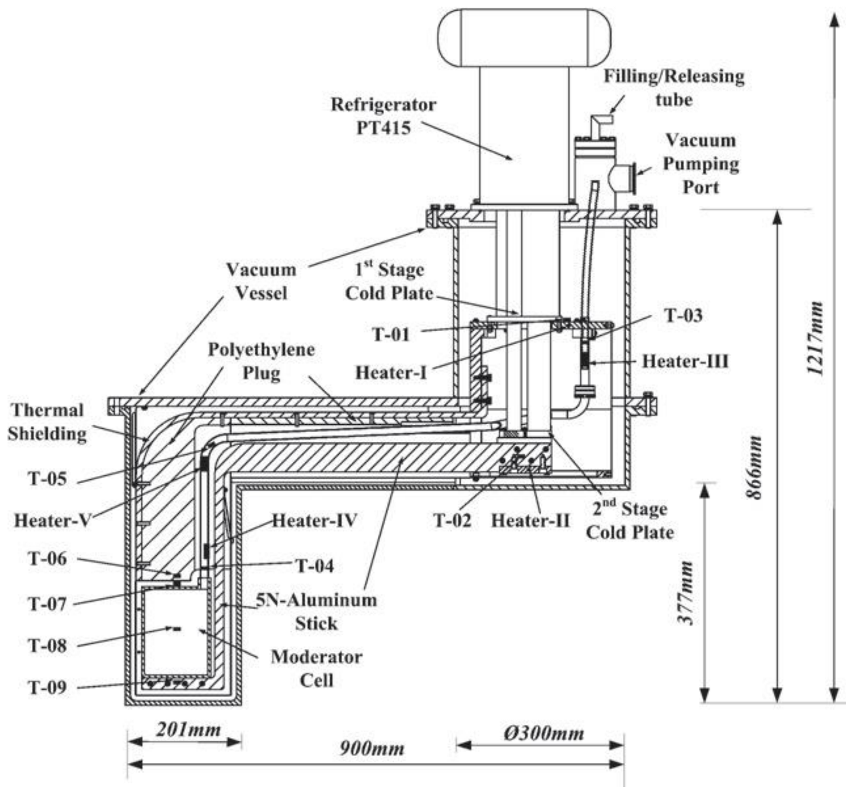
COLD MODERATORS

Design « rather easy » / Very low heat load:

- 1.5W on cryogenic components / 3.3mW/cm3 on methane
- Nothing developed at Saclay yet

Other examples

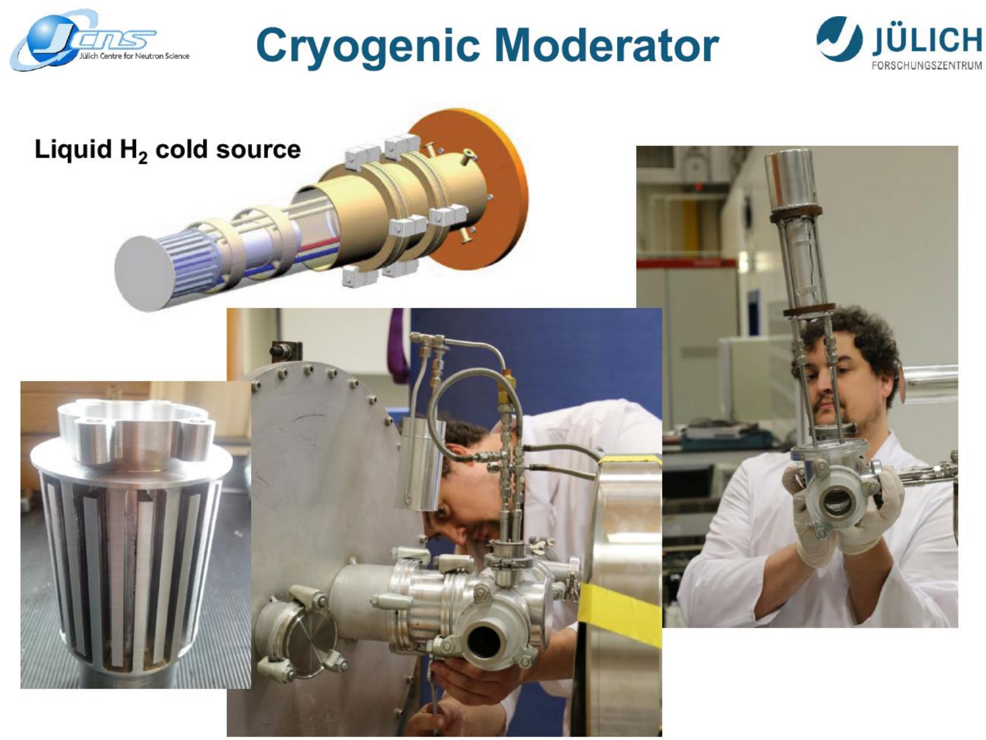
LENS, CPHS, RANS (methane)



JCNS

T. Cronert et al

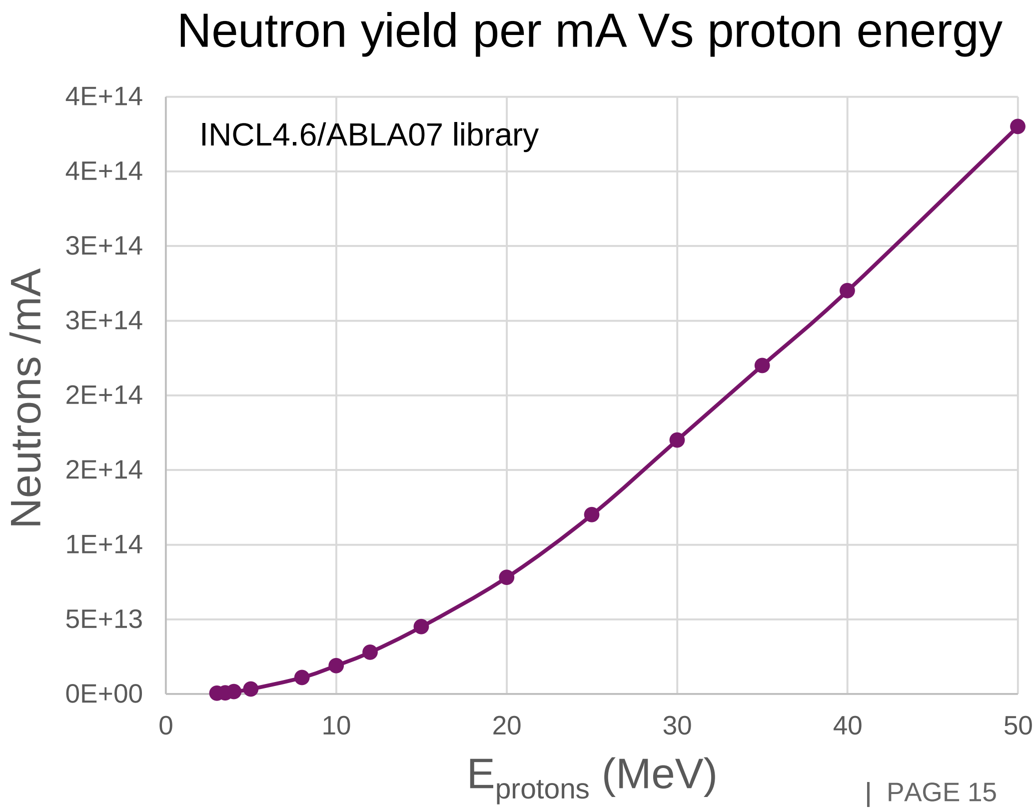
Journal of Physics: Conference Series **746** (2016) 012036



CHOICE OF THE DESIGN PARAMETERS

Starting point

- Maximum peak current : I = 100mA (hard limit)
- Operation in time-of-flight (Duty cycle <4%, ESS time structure)
- Beryllium target
- Choice of the proton energy
    - Neutron yield
    - Accelerator cost
    - Power on the target

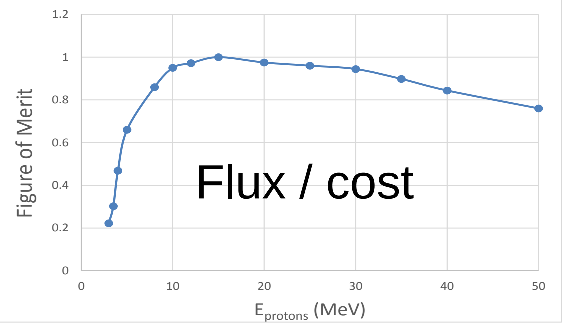


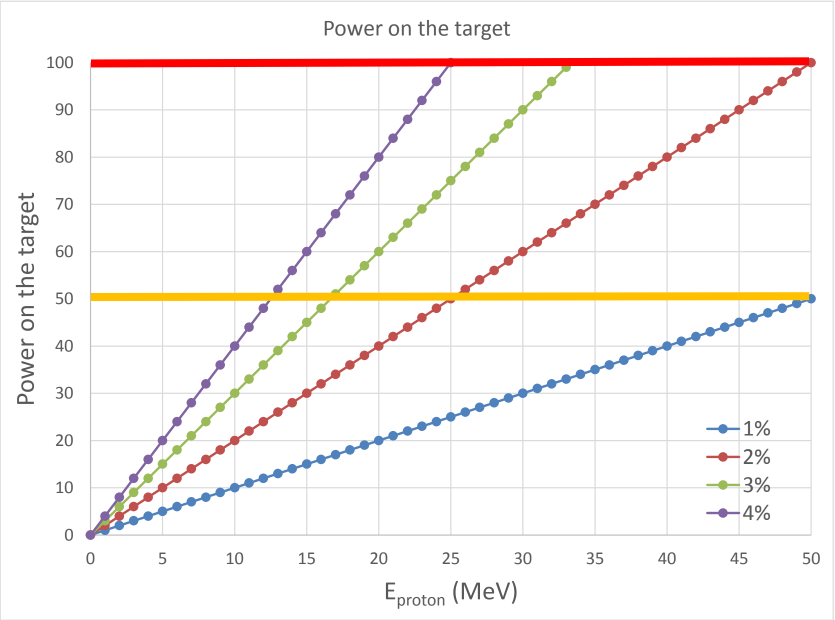
CHOICE OF THE DESIGN PARAMETERS

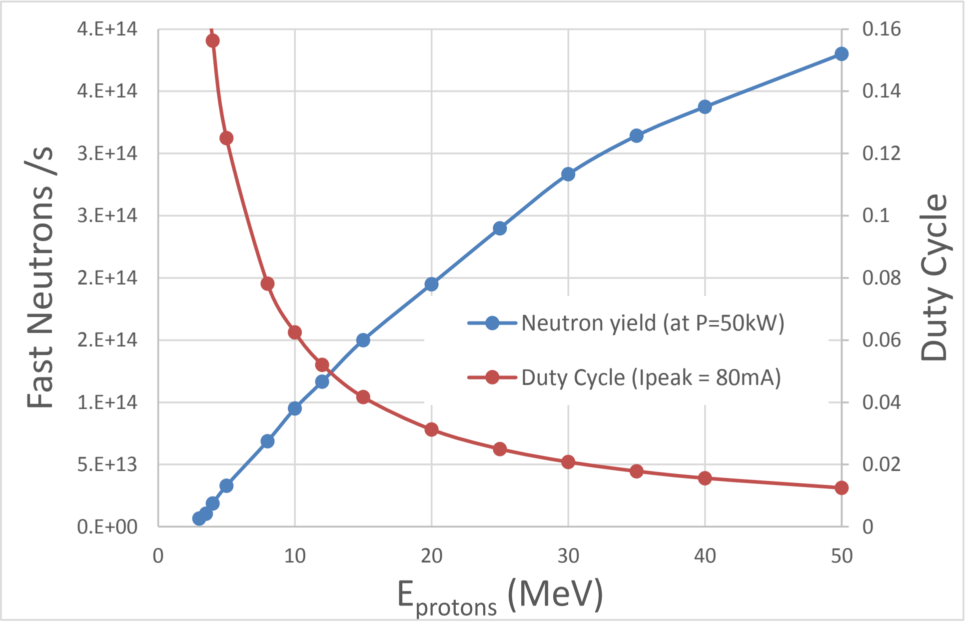
The moderator should be as compact as possible.

- The target should be as small as possible
  - Typical size <100cm²
  - Max power density 0.5-1 kW/cm²
  - Typical proton beam power ~50 – 100kW

- ESS
  - Long pulse - 2.86ms - 14Hz - 4% duty cycle







OPERATION PARAMETERS CHOICE

Proton beam energy choice

- Neutron yield : Y ~ 2 x E
- Power on target : P ~ E
- Lower energy fast neutron spectrum → moderation is more efficient
- Less high energy gamma background
- Smaller cost : C ~ 2 x E (very rough)

Figure of Merit difficult to define

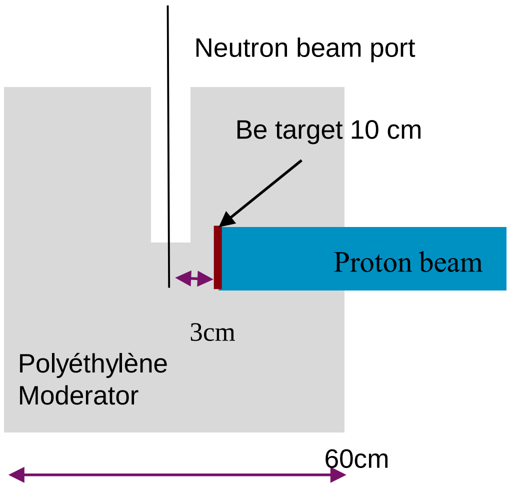
- 20 MeV – I_{peak} 100mA – 4% duty cycle – P = 80kW : Yield = 3.1×10^{14} n/s
- 40 MeV – I_{peak} 100mA – 2% duty cycle – P = 80kW : Yield = 5.4×10^{14} n/s

Reference designs

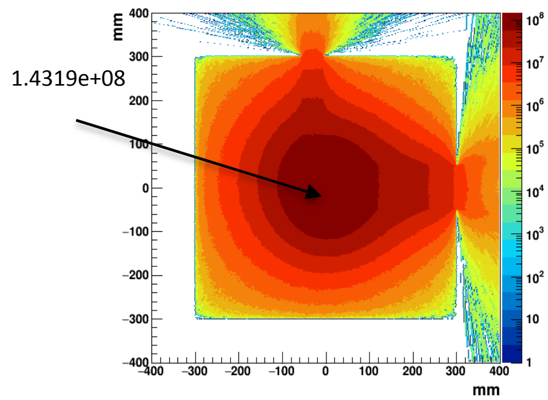
- SONATE (CEA)
  - Ep = 20MeV, I_{peak} = 100mA, duty cycle = 4%, P = 80kW, fixed Be target.
- HBS High Brillance Source (JCNS)
  - Ep = 50MeV, I_{peak} = 100mA, duty cycle = 2%, P = 100kW, fixed Be target

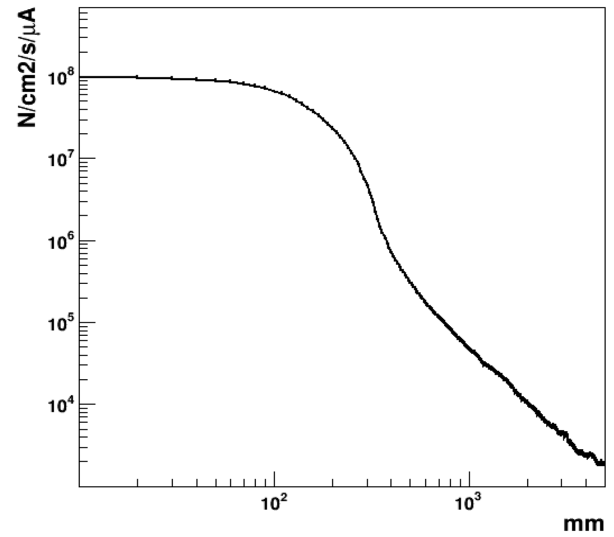
MONTE CARLO MODERATOR SIMULATIONS

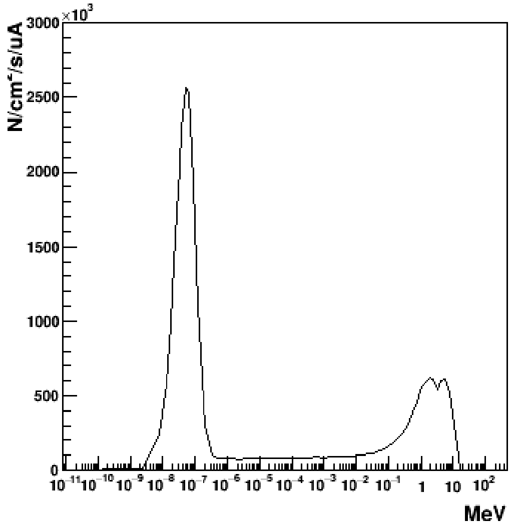
(a)

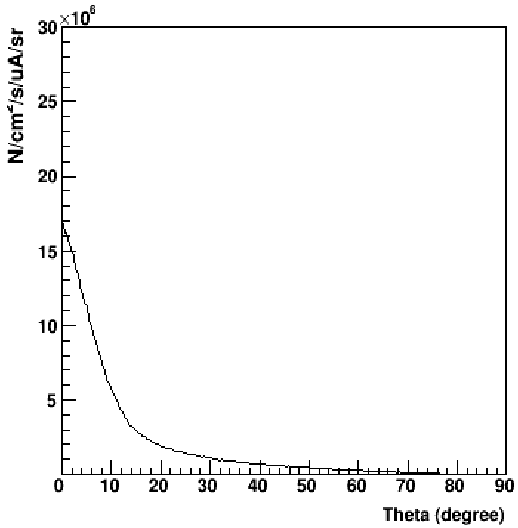


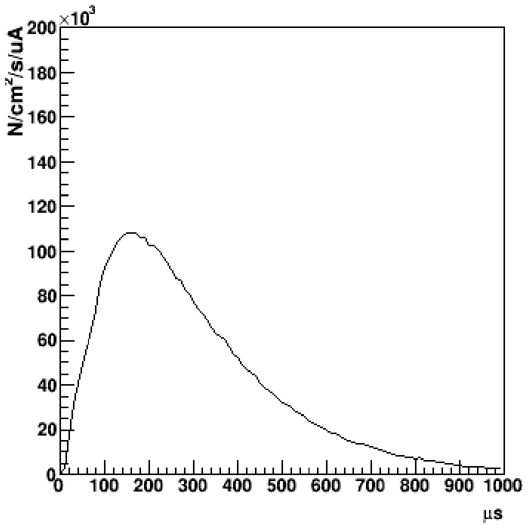
(b)











MODERATOR BRILLANCE

Polyéthylène moderator + reflector

- Neutron brillance is $3x10^7$ n/cm²/s/µA/sr (at 20MeV) (GEANT4 Monte-Carlo simulations)
- In agreement with experimental values by (Allen, NIM A 1994) measured at 10MeV / 30µA using a PE moderator

Source brillance for an average current of 4mA

- 1.2×10^{11} n/cm²/s/sr

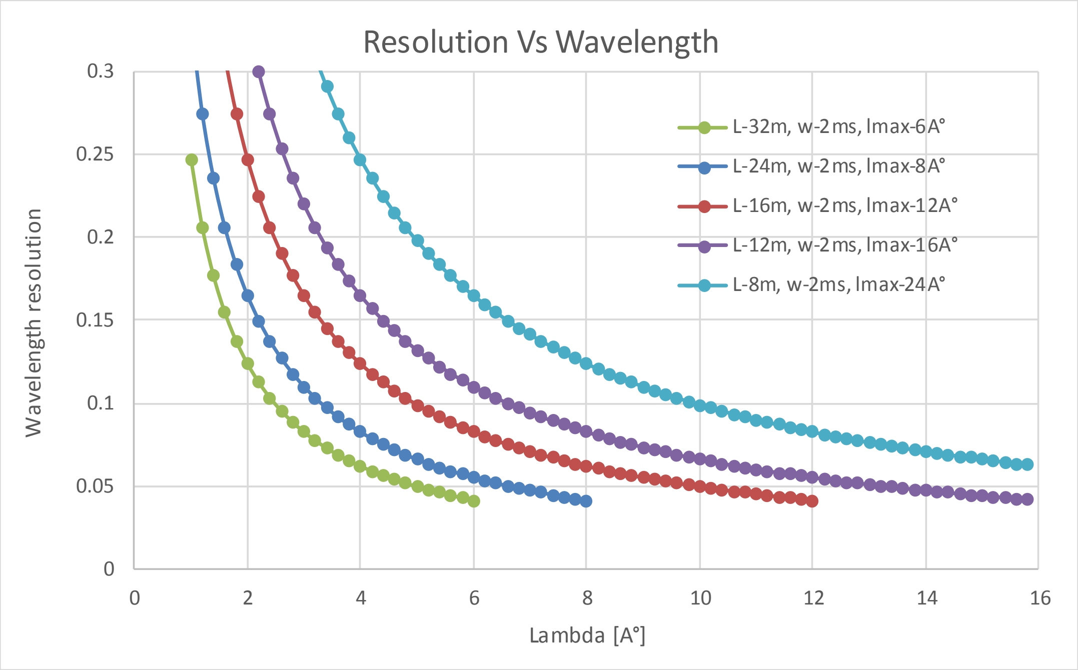
- This value was used for the source brillance in McStas Monte-Carlo simulations

- Repetition rate and pulse length as adjustable parameters
  - Duty cycle < 4%

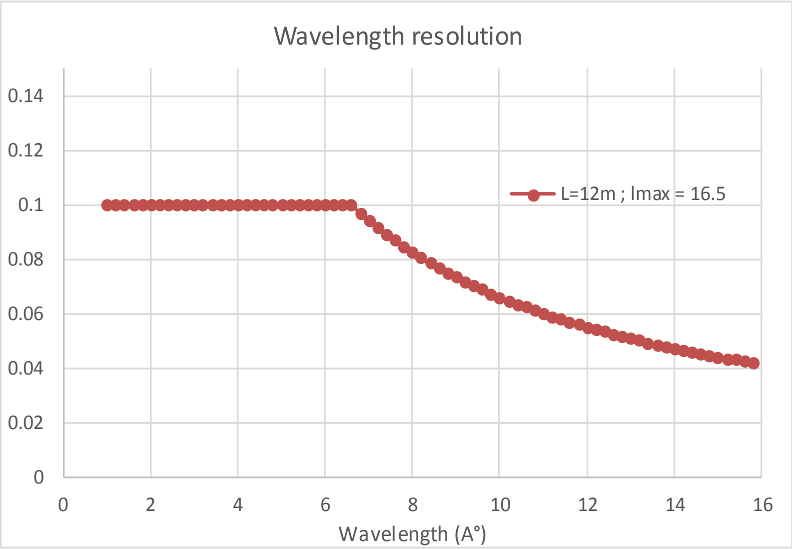
REFLECTOMETRY

Aim for a low resolution instrument : dQ/Q ~10%
Assume f = 20Hz, w = 2ms

Wavelength resolution Vs length L

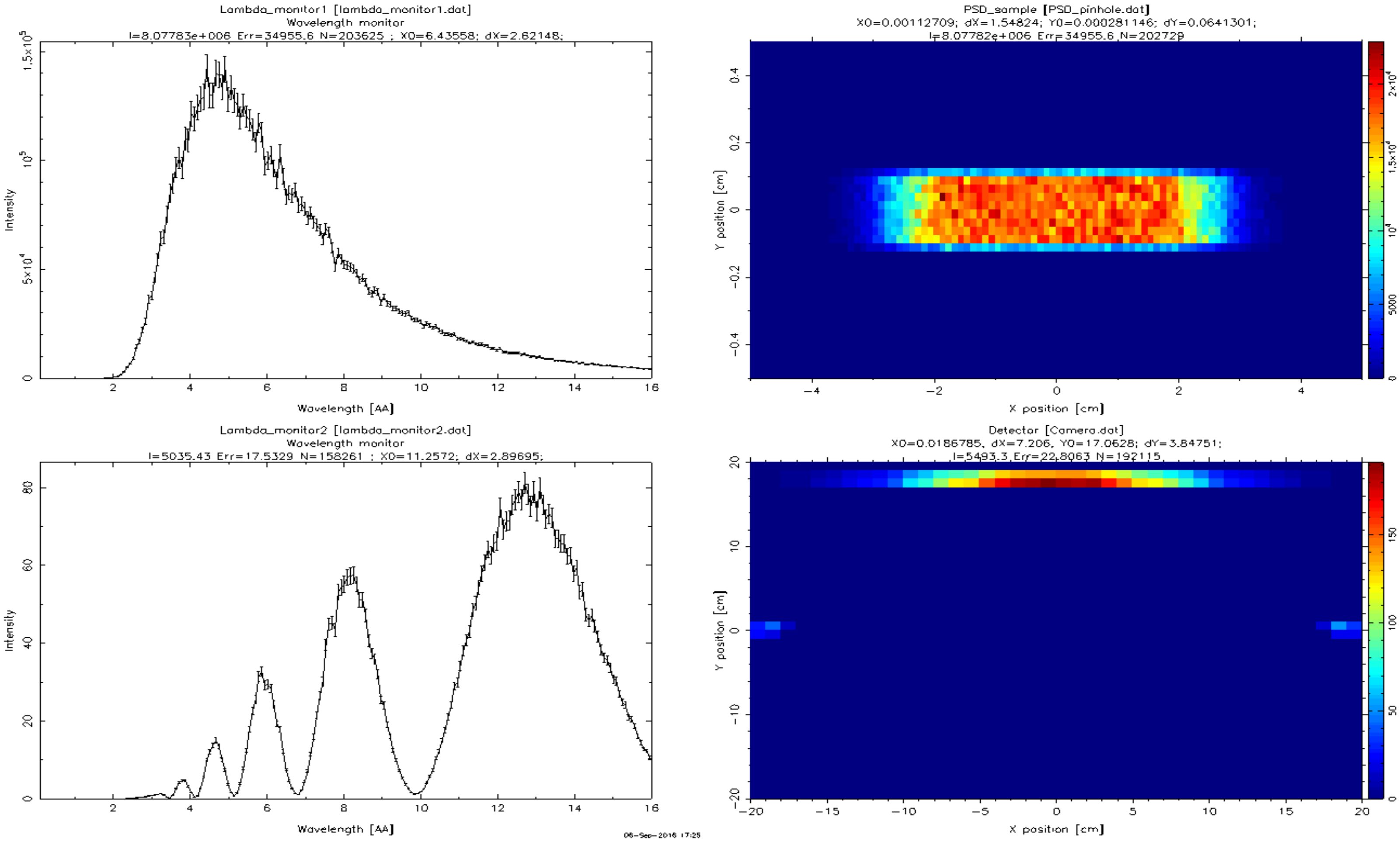


Wavelength resolution for L=12m with double disk chopper



REFLECTOMETRY

McStas simulations : Ni 20nm//Si at an incidence angle of 3°

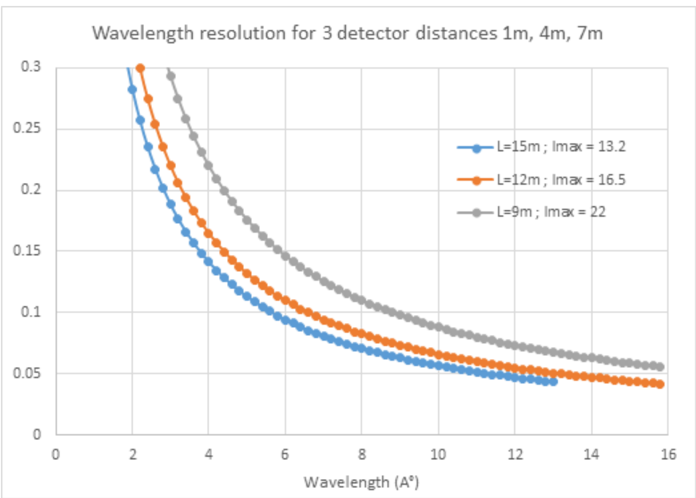


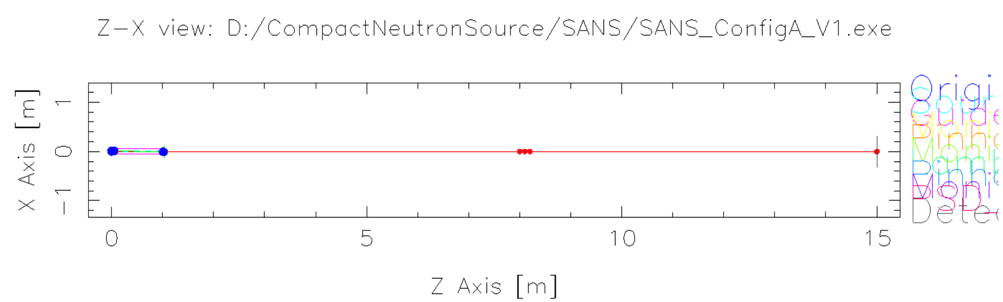
Flux at sample position

- HERMES@LLB design
  straight guide of length 8m with m = 4, cross section 100x50mm²; a 2 m long collimator with F1 = 2 mm and F2 = 2 mm and a side guide with m = 4; a detector at 2 m from the sample position.
- the neutron flux at the sample position is 8×10^6 n/cm²/s
- on the order of CRISP@ISIS and HERMES@LLB (10^7 n/cm²/s)

Reference design

- Cold source / w = 2ms / f = 20Hz
- Source – sample distance = 8m.
- Sample – detector distance = 1 to 7m (PAXY@LLB)
- Total flight path L from 9 to 15m
- Useful bandwidth : 3A° to 16A° (depends on the total instrument length)





Configuration	L_g (m)	L_1 (m)	L_2 (m)	L_{tot} (m)	D_1 (mm)	D_2 (mm)	Flux (n/cm²/s)
Low Q	1	7	7	15	20	16	0.7×10^6
Medium Q	4	4	4	12	20	16	2.2×10^6
High Q	6	2	1	9	20	16	6.7×10^6
PAXE@LLB	6	2.5	2.5	11	12	8	0.7×10^6 (low Q)

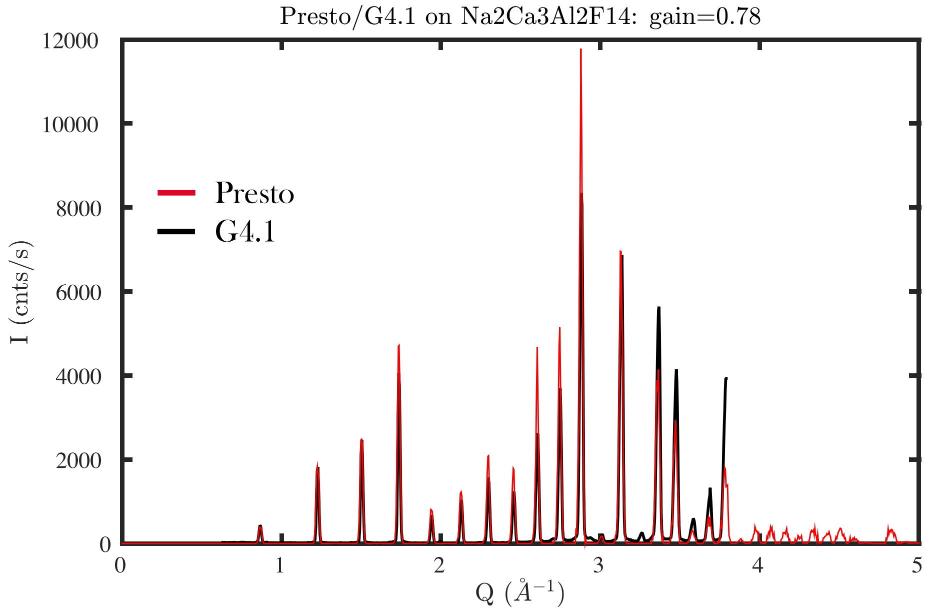
POWDER DIFFRACTION : PRESTO

Reference design (transposition of MAGIK@ESS) (X. Fabrèges)

- Cold source / w = 250µs / f = 40Hz (1% duty cycle)
- Source – sample distance = 52m.
- Sample – detector distance = 1 m
- Total flight path L = 53 m
- Useful bandwidth : 1.4A° to 3.3A°
- $\Delta\lambda/\lambda$: 1.3% to 0.5%

Comparison with G4.1@LLB :

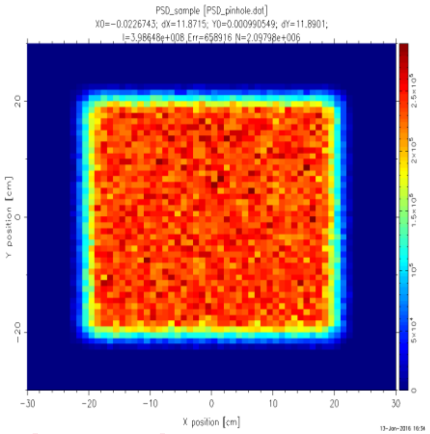
- G4.1:
  - Flux = 4E6 n/cm²/s
  - Divergence: div_h=0.3°, div_v=3°
  - Detector: 80°x3° (35% eff.)
- PRESTO:
  - Flux: 2E6 n/cm²/s
  - Divergence: div_h = div_v = 0.6°
  - Detector: 80°x3° (35% eff.)
  - Gain: x0.7
  - Detector: 120°x20° (90% eff.) (7C2@LLB)
  - Gain: x20



RADIOGRAPHY

Radiography usually performed on continuous source

- A pulsed source is handicaped



Design 1: Short instrument L/D = 250

- Flux 1.5 x 10^6 n/cm²/s
  Counting times remain low (10-60s)
- Limitation set by the experiment kinetic

Design 2 : Long instrument (50m) for Bragg edge imaging

- textures – strain (IMAT@ISIS, ODIN@ESS)
- Drawback : very long instrument

Technique	Flux on sample	Reference spectrometers
Imaging (white beam)	1.5x10^6 n/s/cm² (for L/D = 240) 1.3x10^7 n/s/cm² (for L/D = 80)	ICON@PSI 1x10^7 n/s/cm² CONRAD@PSI 1x10^7 n/s/cm² (for L/D = 240)
Imaging (time resolved)	10^5 n/s/cm² (for L/D = 500) dl/l = 1%	ANTARES@FRM2 5x10^5 n/s/cm² (1% resolution)

SPECTROSCOPY

- Only rough estimates performed at the LLB

J. Voigt (JCNS) performed « clean » estimates

- Key ingredient: source tuning → fast repetition rates (100 - 400 Hz)
- J. Voigt et al, NIM A **884** (2018) 59–63

Jülich Centre for Neutron Science

JÜLICH FORSCHUNGSZENTRUM

HBS Spectrometer

For a medium flux HBS with 100 kW beam power, 100 mA peak current and 50 MeV deuteron energy

	Backscattering	Cold ToF	Thermal ToF
$E_{i,f}$ (meV)	1.84	5	45
$\frac{\Delta E_i}{E_i}$ (%)	1	2	5
$\Delta\theta(^\circ)$	4	2	0.75
$\Delta t(\mu s)$	120	50	18
Rep. rate (Hz)	200	100	400
Flux ($cm^{-2}s^{-1}$)	2.5×10^7	1.3×10^5	1×10^5
Reference instrument	OSIRIS	LET	MERLIN
Flux reference ($cm^{-2}s^{-1}$)	2.7×10^7	5×10^4	6×10^4

Spin-Echo uses a broad wavelength band (~20%)

- Very efficient on a reactor (continuous source)

Reference design (S. Longeville)

  - Straight guide L_g = 4m ; m=4 ; section 100x100mm²
  - Collimator L_1 = 4.6m with 40mm pin-holes (angular divergence ~1°)
  - Detector at 3m from the sample
  - Total length 12m.

Flux (polarised) on the sample : $2x10^6$ n/cm²/s

- To be compared with $2x10^7$ n/s/cm² at 5Å on MUSES@LLB = 10% of MUSES
- Possible upgrade : multi-MUSES : gain x70
- One may still imagine having an instrument 10x more efficient that the current MUSES

Use Very Cold Neutrons ?

- Moderator at 4K
- Very low heat load
  - 1.5W on cryogenic components
  - 3.3mW/cm3 on methane
- Not demonstrated yet

WORKSHOP ON APPLICATIONS OF A VERY COLD NEUTRON SOURCE (Argonne, 2005) (170 pages!)

	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}

SUMMARY

Technique	Flux on sample	Reference spectrometers	Potential gains
Reflectivity	0.8×10^7 n/s/cm²	HERMES@LLB 1×10^7 n/s/cm² POLREF@ISIS ~1×10^7 n/s/cm²	ESTIA@ESS concept x10 Advanced Deconvolution x3
SANS	0.7×10^6 n/s/cm² (low Q) 2.2×10^6 n/s/cm² (med Q) 6.7×10^6 n/s/cm² (high Q)	PAXY@LLB (low Q) 0.7×10^6 n/s/cm² SANS2D@ISIS 1×10^6 n/s/cm²	Slit setup x10 Focusing optics for VSANS (small Q) x10
Powder diffraction	2×10^6 n/s/cm²	G41@LLB 2×10^6 n/s/cm²	Large solid angle detector (7C2 type) x20
Imaging (white beam)	1.5×10^6 n/s/cm² (for L/D = 240) 1.3×10^7 n/s/cm² (for L/D = 80)	ICON@PSI 1×10^7 n/s/cm² CONRAD@HZB 1×10^7 n/s/cm² (for L/D = 240)	MCP detectors x5 Coded Source Imaging x10
Imaging (time resolved)	1×10^5 n/s/cm² (for L/D = 500) dl/l = 1%	ANTARES@FRM2 5×10^5 n/s/cm²	
Direct TOF	1×10^5 n/s/cm² (thermal) 1.3×10^5 n/s/cm² (cold)	MERLIN@ISIS 6×10^4 n/cm²/s LET@ISIS 6×10^4 n/cm²/s IN5@ILL 6.8×10^5 n/cm²/s	MUSHROOM (LETx70 on single crystals)
Back scattering	2.5×10^7 n/cm²/s	OSIRIS@ISIS 2.7×10^7 n/cm²/s	
Spin-Echo	2×10^6 n/s/cm²	MUSES@LLB 2×10^7 n/s/cm² (at 5A°)	Multi-MUSES (x70)

MODULARITY

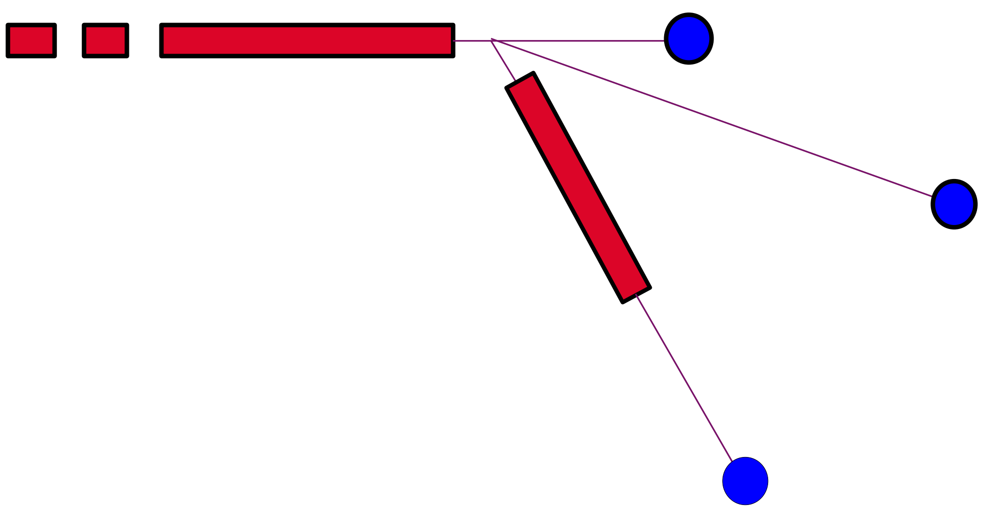
Possibility to install several targets

- Cold / low repetition rate target
- Thermal / high repetition rate target
- One cold source per instrument

If the finances allow it it might be possible to boost the protons energy from 20 to 40 or 60 MeV

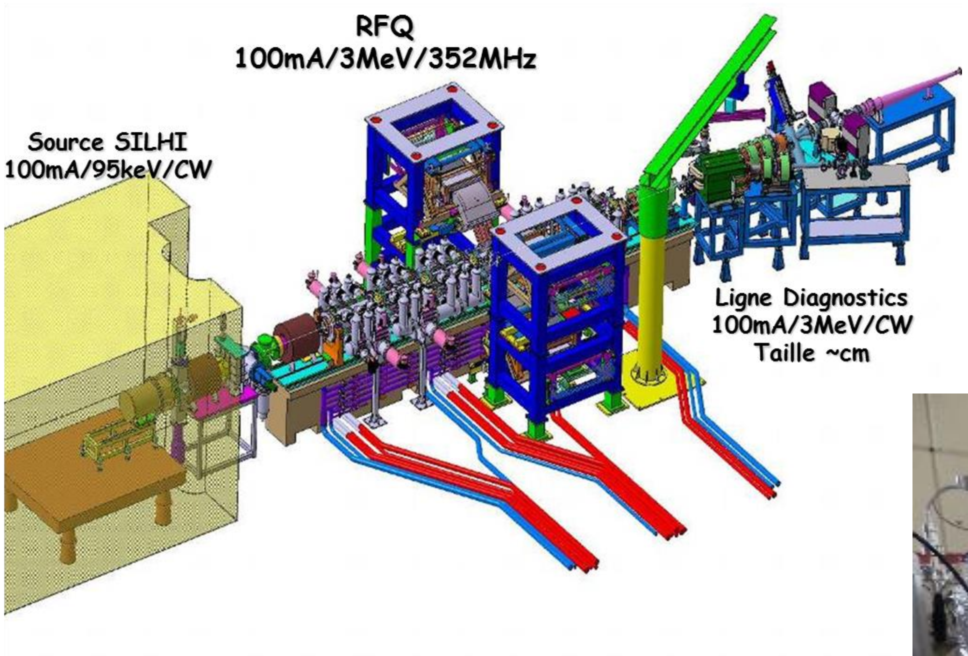
- Beware : the RFQ should be oversized

An accelerator source is a lot more versatile than a reactor

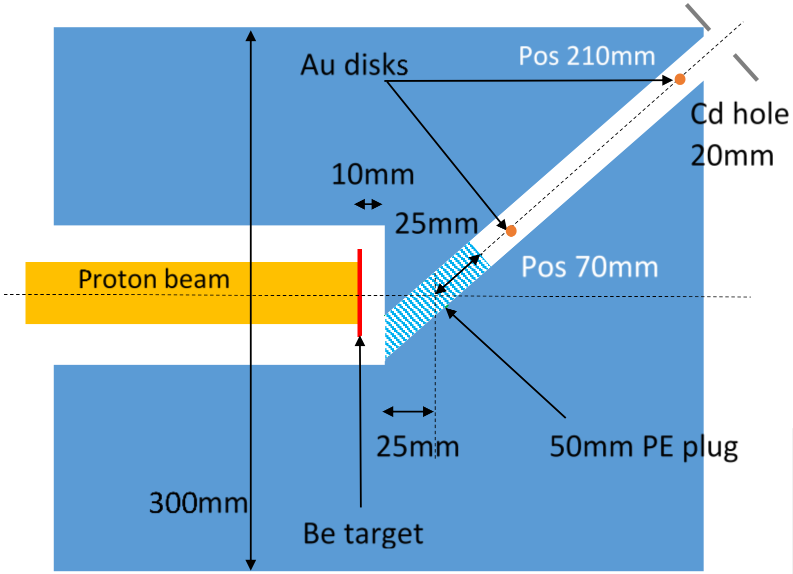


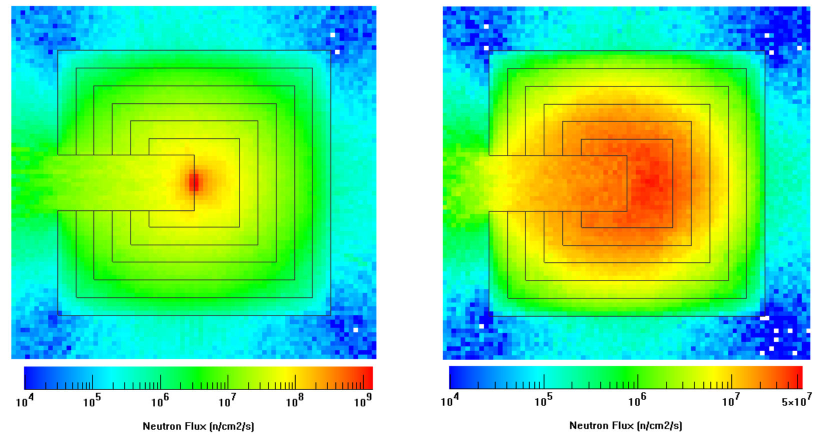
FIRST TESTS A SACLAY

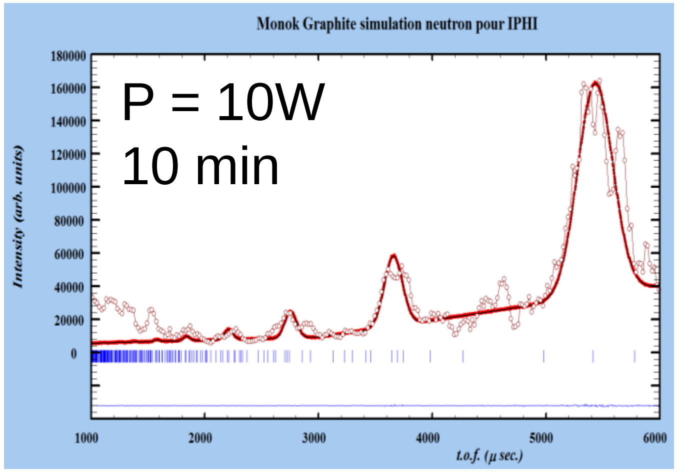
Accelerateur IPHI@Saclay: 3MeV - 100mA peak

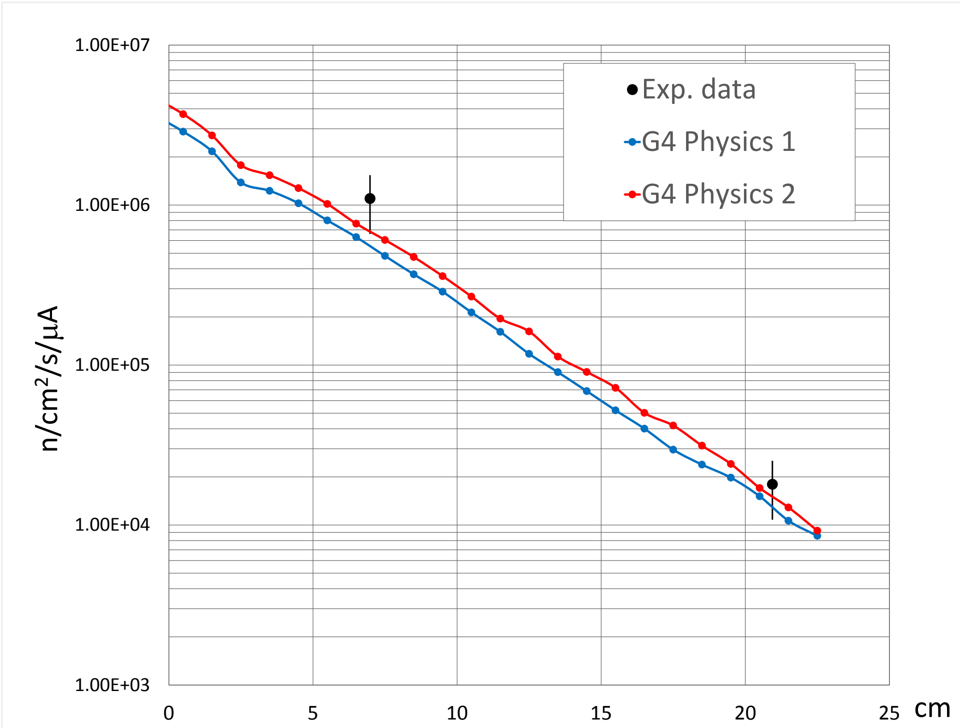


Opération at 10W
Avoid producing too many neutrons


Au disks
Pos 210mm
Cd hole
20mm
10mm
25mm
Pos 70mm
Proton beam
25mm
50mm PE plug
300mm
Be target

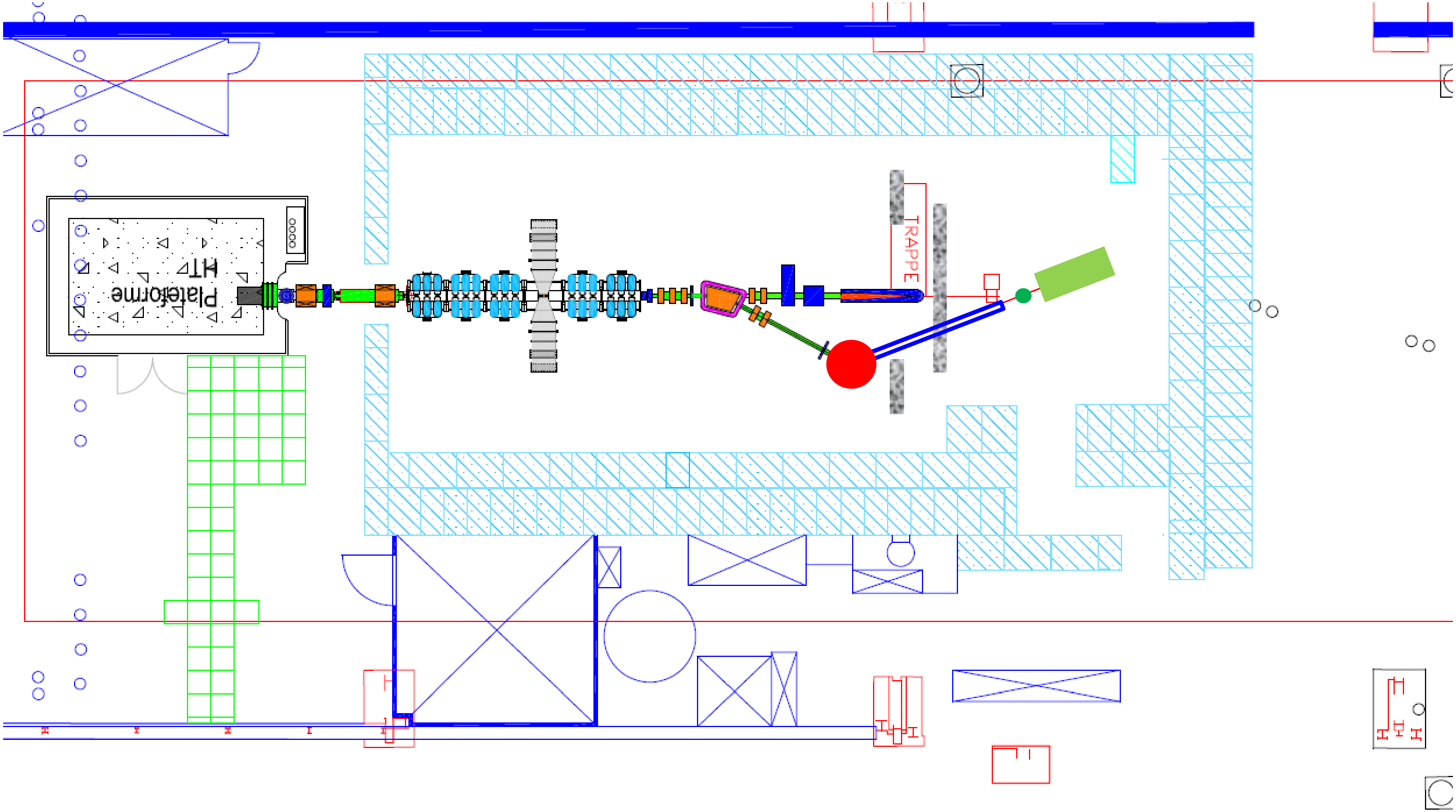

Neutron Flux (n/cm2/s)
Neutron Flux (n/cm2/s)


Monok Graphite simulation neutron pour IPHI
P = 10W
10 min
Intensity (arb. units)
t.o.f. (μ sec.)


Exp. data
G4 Physics 1
G4 Physics 2
n/cm²/s/μA
cm
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
0
5
10
15
20
25

2019

IPHI - Neutrons



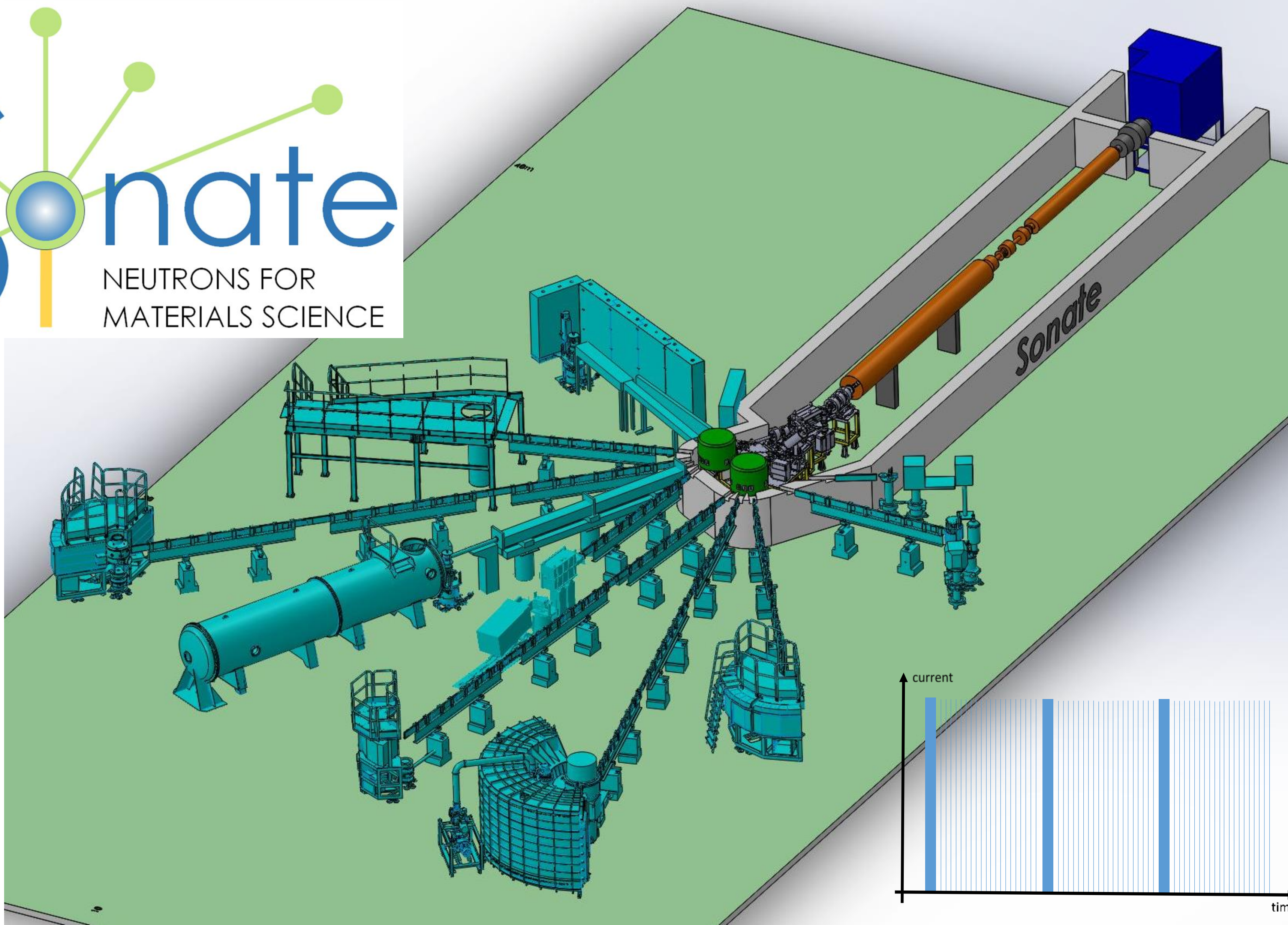
1 « generic » instrument : SANS, réflectomètre, imagerie, diffraction

Measurements on samples – Proof of concept – Performances validation

Orphée Laboratoire Léon Brillouin

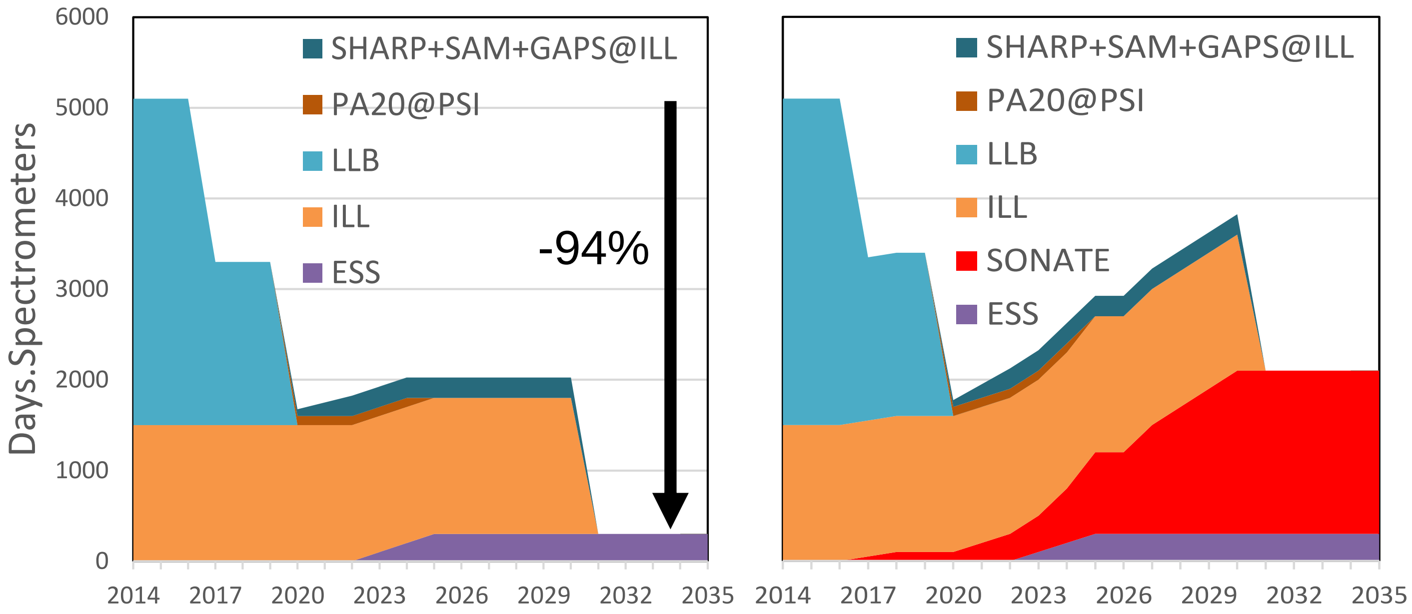
2030: 10 INSTRUMENTS AROUND 2 TARGETS

Sonate
NEUTRONS FOR MATERIALS SCIENCE



LANDSCAPE IN FRANCE

Neutron provision for the French community users over the period 2015 to 2035



COSTS

	Coût	Existing Capital
Source construction	40	Source (4M€) RFQ (IPHI) (10M€) Bâtiments (5M€)
Spectrometer construction (x10)	30	20 (LLB + CRG +ILL)
TOTAL	**70**	39

Source Operation (180 Jours / 4 shifts)	0.75	
Operations of 10 instruments (40 people)	3.2	
TOTAL	**4**	

Facility	ILL	ISIS	MLZ	SINQ	ESS	LLB	SONATE TS1 + TS2
First Neutrons	1971	1994	2004	1998	2023	1981	2025-2030
Replacement value (M€)	2000	800	600	750	1847	400	70
Operating costs (M€)	95	62	55	30	140	30	3.65
Instrument-day (k€)	11.9	16.7	9.2	12.5	35.3	7.9	2
Operation cost / replacement value	4.75%	7.75%	9.2%	4%	7.6%	6.7%	5.2%

HARD POINT

Beryllium target

- High power density : ~< $1kW/cm^2$
- Embrittlement: fragilization due to the formation of hydrogen bubbles

Fig. 8 Multiple Target Failures at 7 MeV

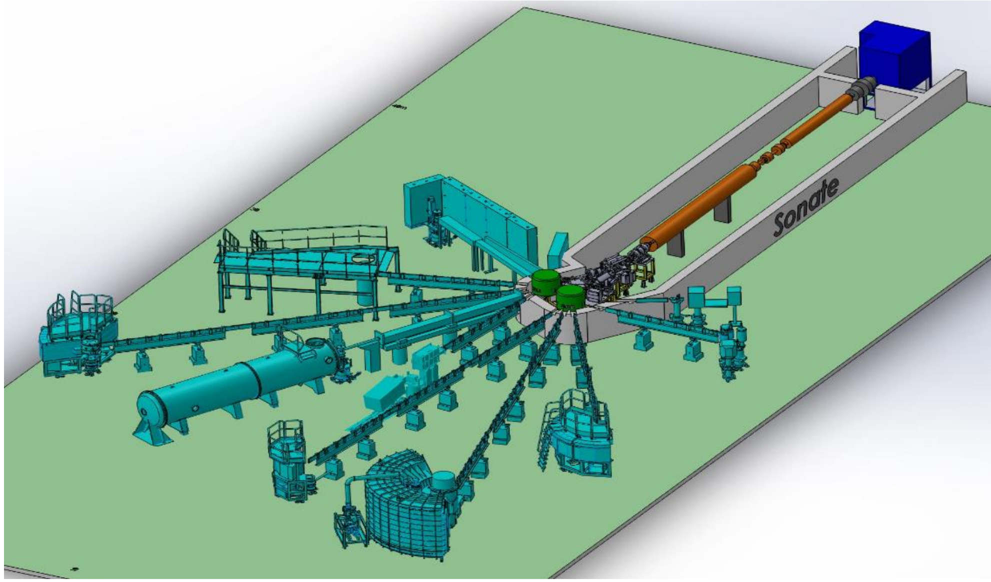
Various strategies under study

- Be: LENS, RANS, JCNS, ESS-Bilbao, CEA…
- Li: SARAF, Nagoya, various BNCT facilities in Japan

CONCLUSION

The performances of a high end compact source are potentially equivalent to a medium power nuclear reactor for neutron scattering

- Reduced cost / not a nuclear facility



Technologically

- Accelerator OK
- Target → CMR50
- Moderator OK / can be improved
- Instruments OK

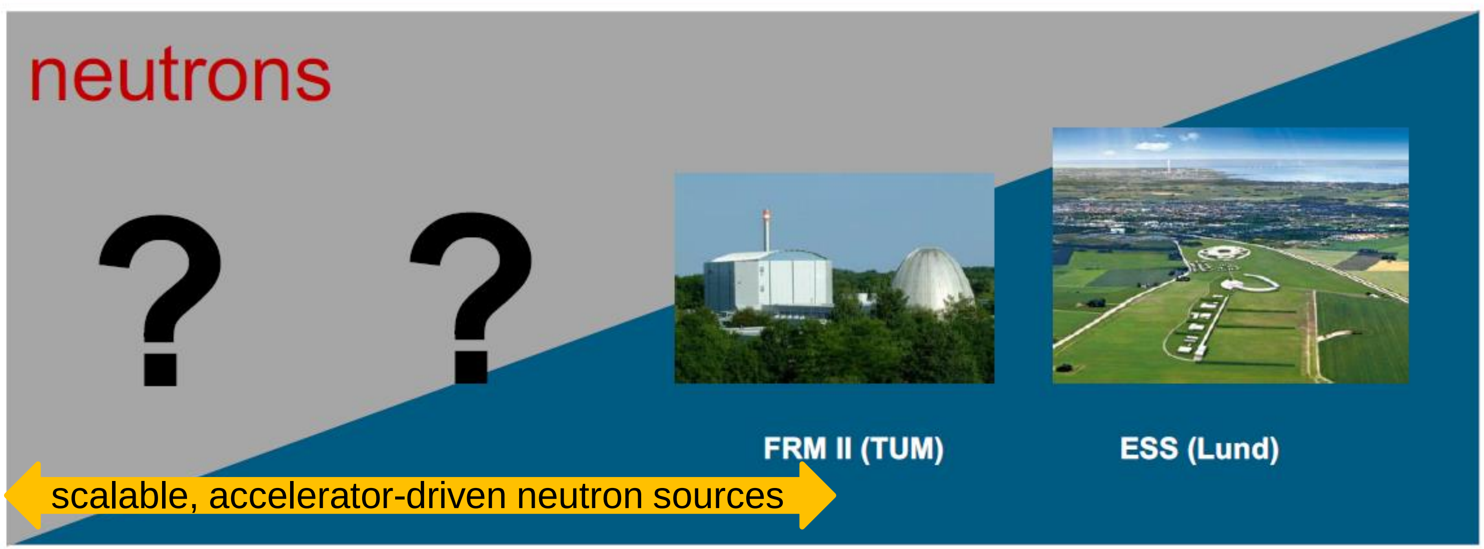
Possiblity to benefit from the French ecosystem

- Scientific and technical expertise at the LLB and ILL
- Broad user base (~1500)
- Possibility to reuse efforts deployed for ESS
  - Instrument designs
  - Detectors developments
  - Data reduction and processing
- Existing instrumental suite

SONATE **a "Neutrons for Materials Science" platform**

TABLE-TOP TO FLAGSHIP

Adapted from Thomas Brückel (FZ Jülich)



Monte-Carlo simulations

- H.N. Tran (IRFU/SPhN) (post-doc)
- A. Marchix (IRFU/SPhN)
- A. Letourneau (IRFU/SPhN)
- J. Darpentigny (IRAMIS/LLB)
- CEA/SPR (shielding / activation)
- TechnicAtome
- DEN/SERMA

IPHI

- J. Schwindling (IRFU/SACM)
- N. Chauvin (IRFU/SACM)
- IPHI personnel
  B. Pottin, G. Perreu …

Instruments simulations

- X. Fabrèges (IRAMIS/LLB)
- A. Menelle (IRAMIS/LLB)
- F. Ott (IRAMIS/LLB)

Target - moderateur

- N. Sellami (IRFU/SIS)
- B. Annighöfer (IRAMIS/LLB)
- P. Permingeat (IRAMIS/LLB)

Technical support

- K. Jiguet (IRAMIS/LLB)
- W. Josse (IRAMIS/LLB)
- B. Homatter (IRAMIS/LLB)
- P. Lavie (IRAMIS/LLB)
- J.-L. Meuriot (IRAMIS/LLB)
- F. Prunes (IRAMIS/LLB)
- …

Strategic support

- C. Alba-Simionesco (IRAMIS/LLB)
- R. Duperrier (IRFU/SACM)
- A. Leservot (DRF/DCEPI)