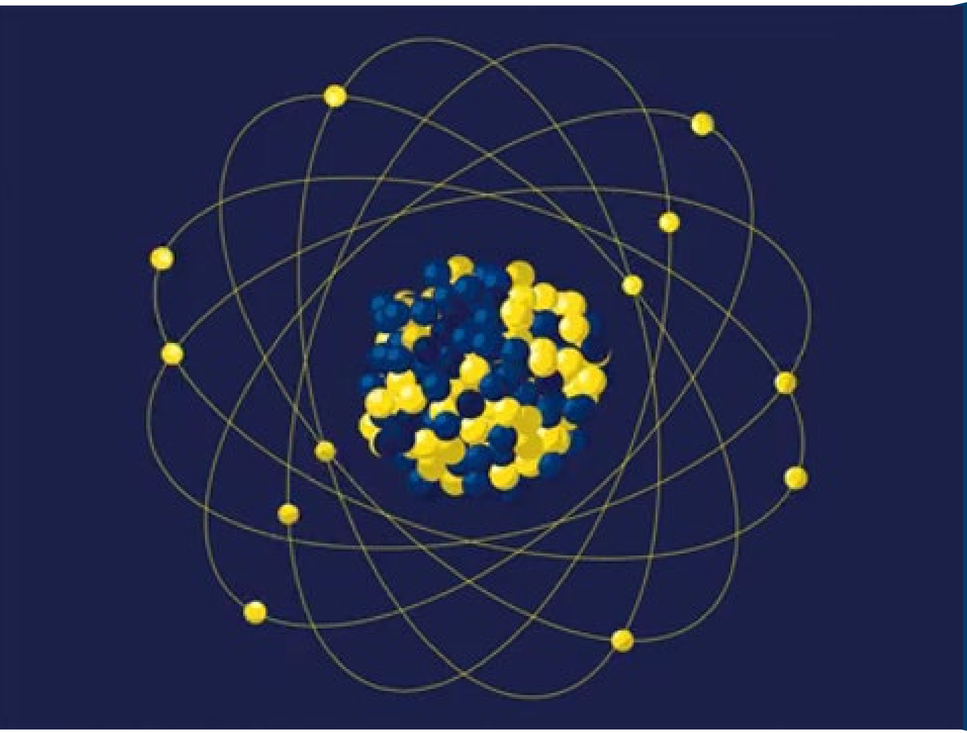
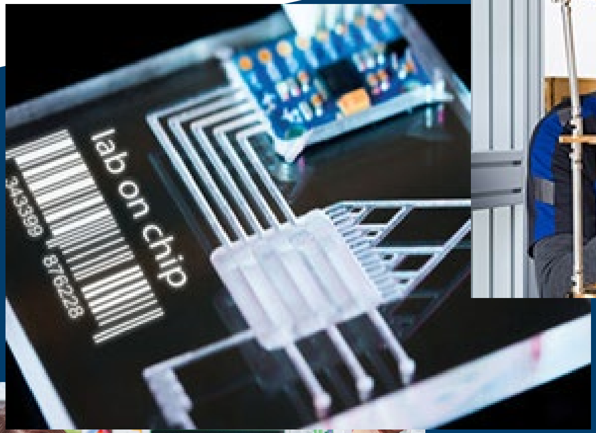
Neutrons for today and tomorrow

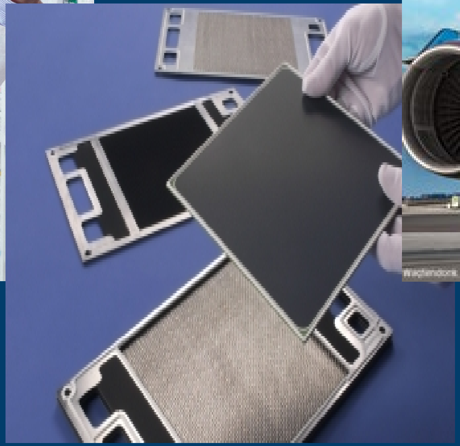
Next generation accelerator based neutron sources

Thomas Gutberlet, JCNS

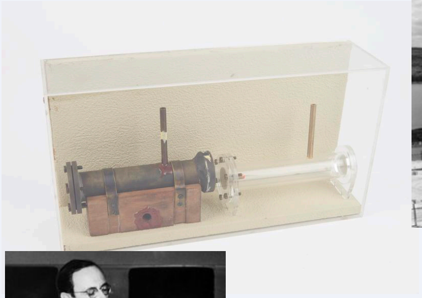
Science with Neutrons







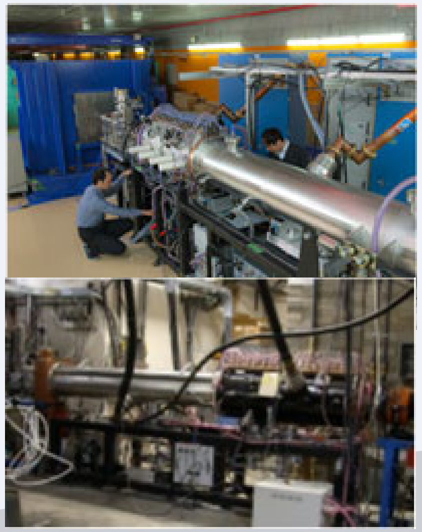
History of Neutron Sources



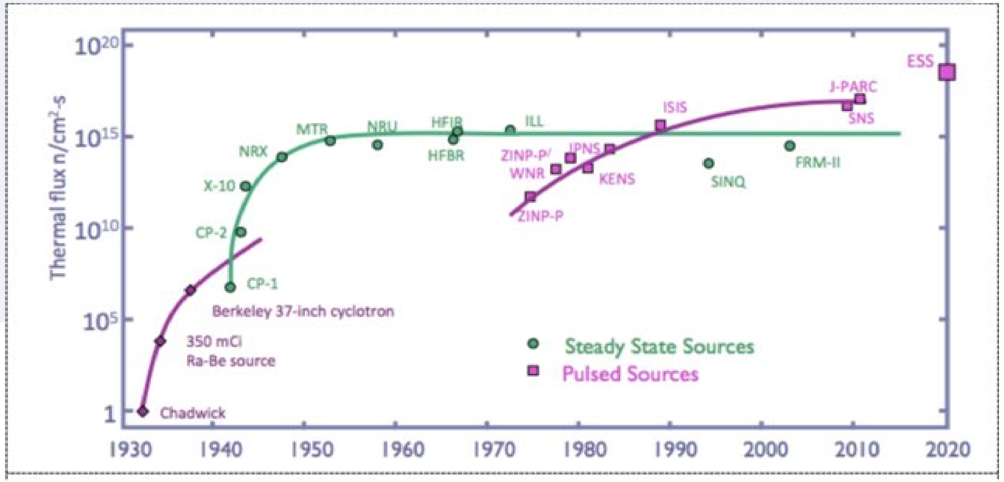

1930
neutron tube


1950
neutron reactor

1980
spallation source



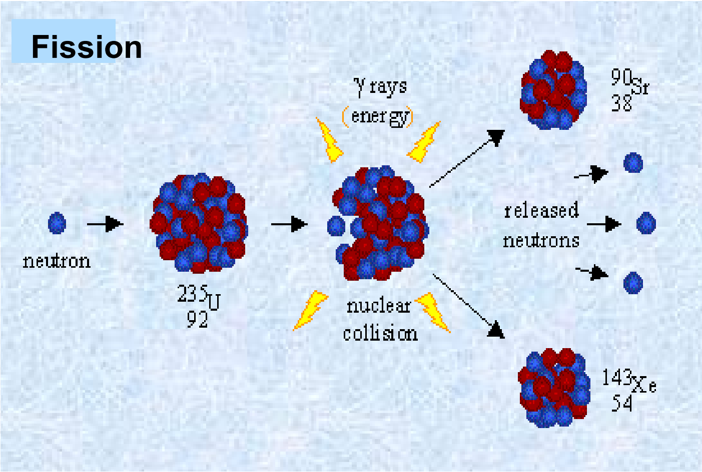
2010
CANS



K. Andersen et al., J.Phys.Conf.Ser. 746, 012030, 2016

Neutron Production

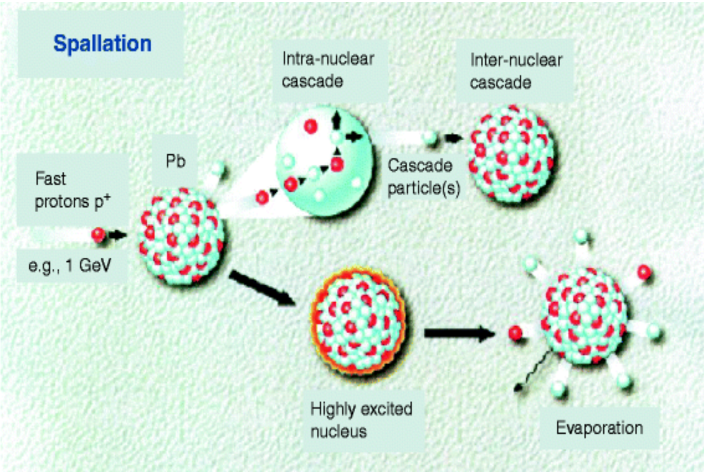
Nuclear fission



Reactor based neutron source

(ILL, FRM II, NIST, JINR, ANSTO a.m.m.)

Spallation

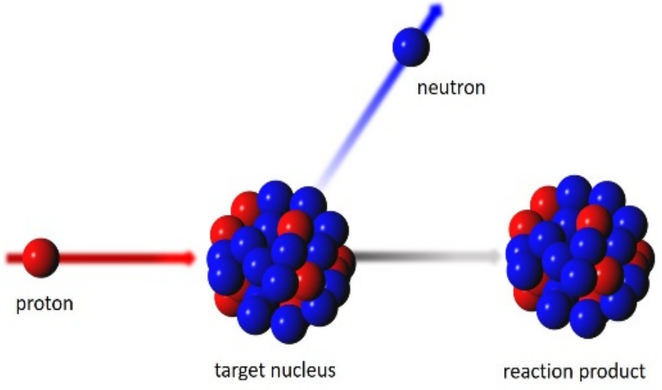


Spallation based neutron source

(ESS, ISIS, SINQ, SNS,

CSNS, J-PARC, KEK)

Nuclear processes



Accelerator based neutron source

(LENS, RANS, HUNS, NUANS, IREN

a.o.)

Neutron Production

Nuclear Process	Example	Neutron Yield	Heat Release [MeV/n]	Source
Spallation	800 MeV p on ^{238}U or Pb	27 n/p or 17 n/p	55 or 30	ISIS, SINQ, ESS
Nuclear fission	Fission of ^{235}U by thermal neutrons	1n/fission	180	MLZ, ILL
$^{9}Be(p,n:p,pn)$	11 MeV p on Be	4×10^{-5} n/d	2000	RANS, LENS
$^{9}Be(d,n)^{10}Be$	15 MeV d on Be	1.5×10^{-2} n/d	1000	
Nuclear photo effect from e-Bremsstrahlung	100 MeV e^- on ^{238}U	5×10^{-2} n/e^-	2000	HUNS, n-ELBE
Deuteron stripping	40 MeV d on liq. Li	7×10^{-2} n/d	3500	
D-T in solid target	400 keV d on T in Ti	4×10^{-5} n/d	10000	

Ref.: G. Mank, G. Bauer, F. Mulhauser, Accelerators for Neutron Generation and Their Applications, Rev. Accl. Sci. Tech 04, 219 (2011)

Neutron Production

Low energy nuclear processes

Nuclear process	E [MeV]	n/ion	n/(s mA)	n/(s kW)
p ⇒ Be	50	2.70%	1.68E+14	3.37E+12
d ⇒ Be	50	5.90%	3.69E+14	7.38E+12
p ⇒ Li	20	0.33%	2.08E+13	1.04E+12
p ⇒ V	50	5.08%	3.18E+14	6.35E+12
p ⇒ Ta	50	6.40%	4.00E+14	8.01E+12
p ⇒ W	50	6.95%	4.35E+14	8.70E+12

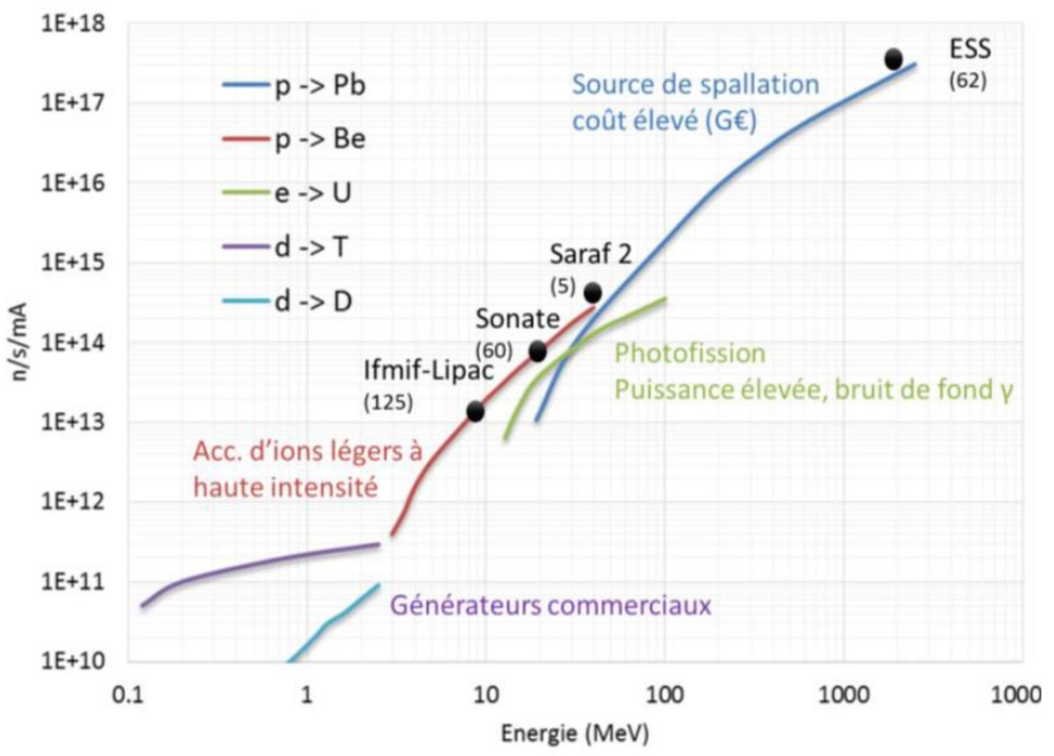


Figure 1: Neutron production using particle accelerators

Ref.: LLB – Compact Neutron Sources for Neutron Scattering

Accelerator Based Neutron Sources

Physics Reports 654 (2016) 1–58

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journal homepage: www.elsevier.com/locate/physrep

ELSEVIER

Research opportunities with compact accelerator-driven neutron sources

CrossMark

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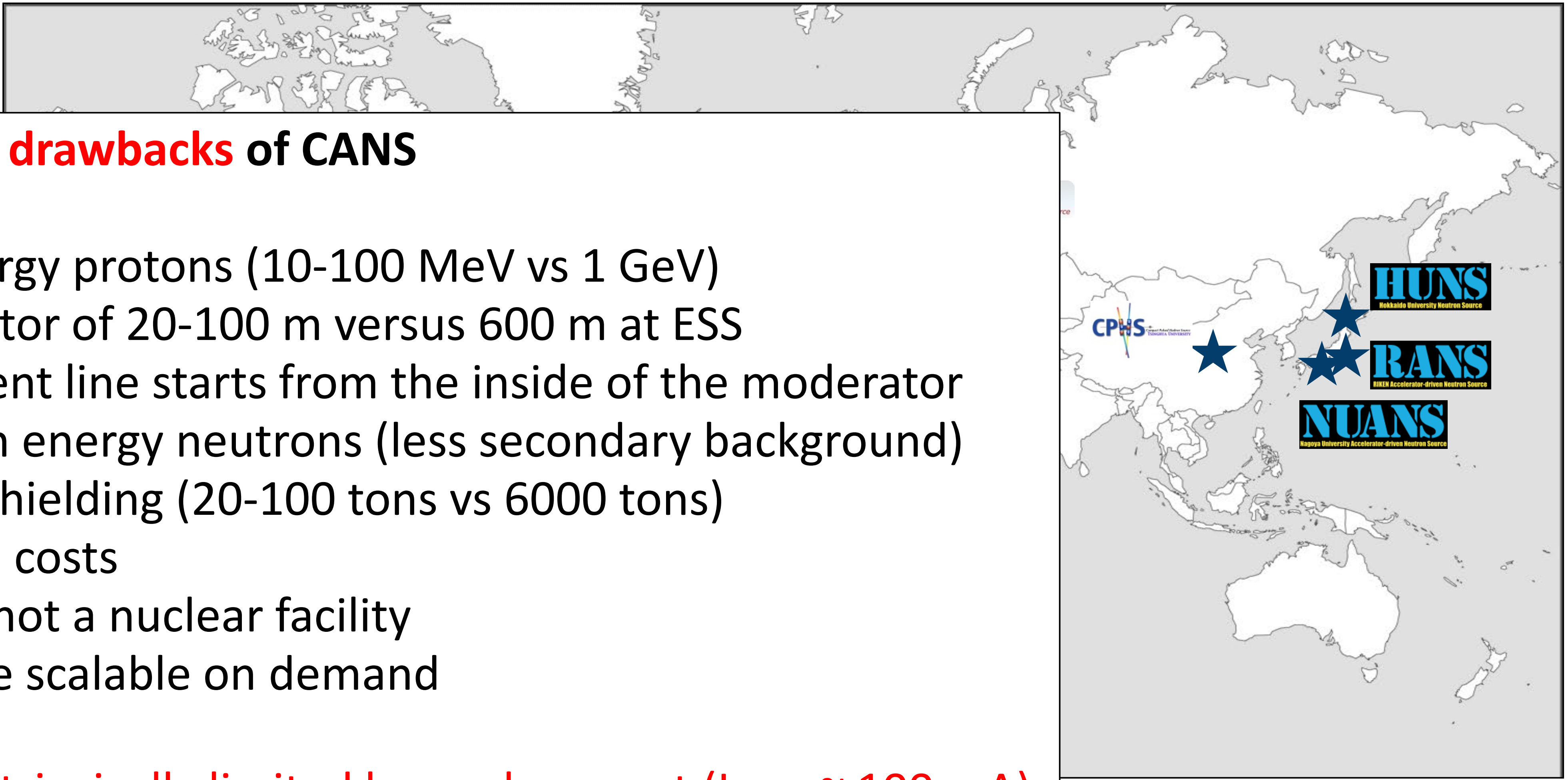
[g] Università degli Studi di Roma "Tor Vergata", Centro NAST, Via della Ricerca Scientifica 1, 00133 Roma, Italy

Accelerator Based Neutron Sources



Advantages / drawbacks of CANS

- Low energy protons (10-100 MeV vs 1 GeV)
- Accelerator of 20-100 m versus 600 m at ESS
- Instrument line starts from the inside of the moderator
- Less high energy neutrons (less secondary background)
- “Light” shielding (20-100 tons vs 6000 tons)
- Reduced costs
- CANS is not a nuclear facility
- CANS are scalable on demand

- Flux is intrinsically limited by peak current (I_{peak} ~ 100 mA)

Accelerator Based Neutron Sources

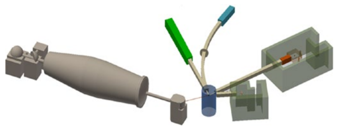
Scalable Neutron Sources – from CANS to LENF

CANS → LENF

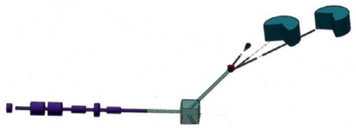
0.01 kW	0.1 kW	1 kW	10 kW	100 kW
0.001-0.01 mA	0.01-1 mA	0.5-5 mA	1-20 mA	50-100 mA
~10^{11} n/s	~10^{12} n/s	~10^{13} n/s	~10^{14} n/s	~10^{15} n/s

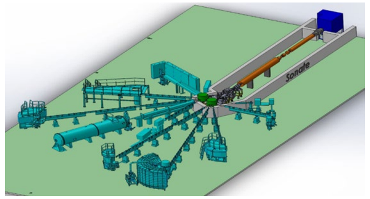
10 Mio EUR → 400 Mio EUR

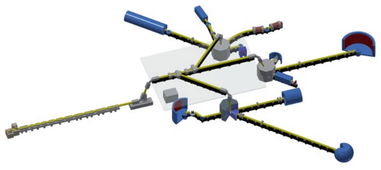
Prototype



NOVA ERA







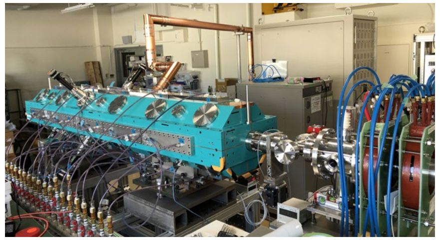
Accelerator Based Neutron Sources

RIKEN Accelerator-driven compact Neutron source RANS

Accelerator Based Neutron Sources

Compact Neutron Sources
Anytime, Anywhere

RANS: 15m, 25ton, MeV～meV
Cold source experiment from 2018



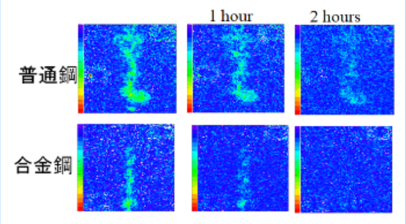
Transportable,
Floor standing

RANS2: ~5m, ~5ton, 500keV～meV

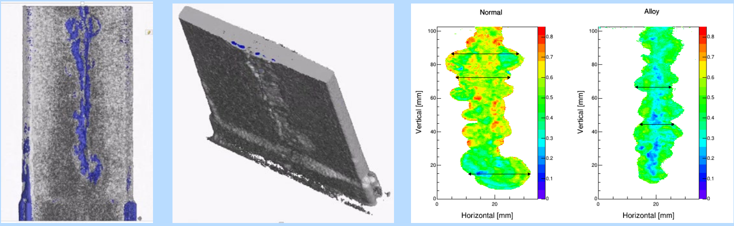
Iron and steel Corrosion visualization

Corrosion: 2~% of GDP is spent for anticorrosion

Visualization of the corrosion and its related water movement in painted steel

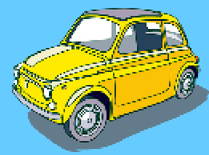


Averaged water content ratio



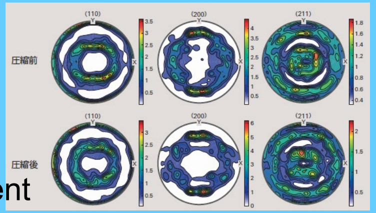
-> J-PARC experiment

Towards strength and formability

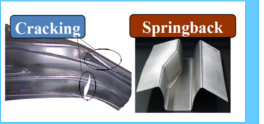


Retained austenite fraction measurement

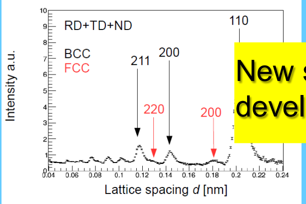
Texture evolution



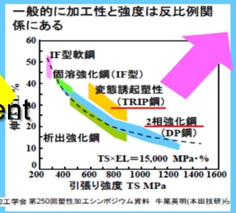
On-site use



1~2%agreement with J-PARC



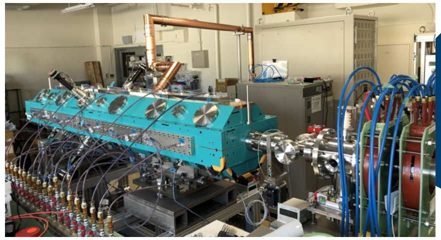
New steel development



Accelerator Based Neutron Sources

Compact Neutron Sources
Anytime, Anywhere

RANS: 15m, 25ton, MeV～meV
Cold source experiment from 2018

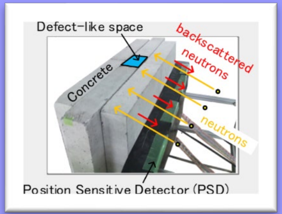


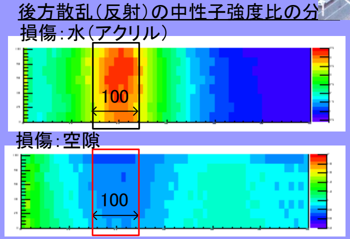
Transportable,
Floor standing

RANS2: ~5m, ~5ton, 500keV～meV

Non-destructive inspection infrastructure

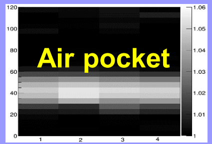
See through concrete
In the pavement :
reflected imaging

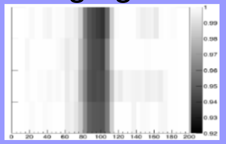




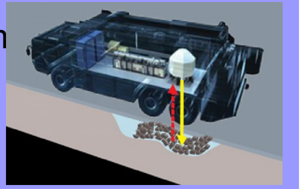
Visualization of degradation

Transmission imaging thicker than 30 cm





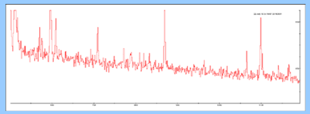
Reinforced steel bar



Salt detection of concrete

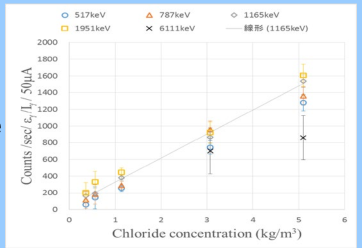
Prompt-Gamma Neutron Activation Analysis (PGAA)

Collapse of a bridge in USA



Salt Concentration Measurement of concrete

1.6～2kg/m^3
Japanese standards for concrete structures



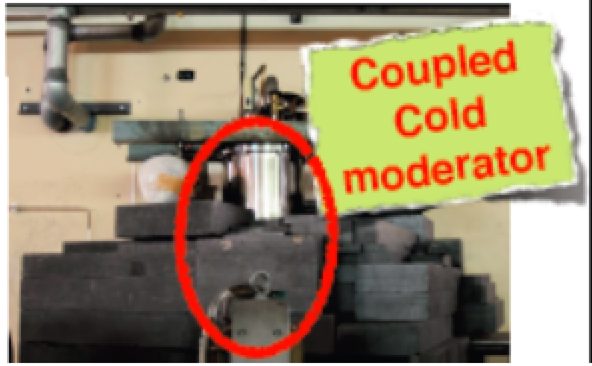
Accelerator Based Neutron Sources

Hokkaido University Neutron Source (HUNS)

Electron Linac

First beam: 1973

35 MeV, 30 μA, 50 pps : ~ 1 kW



Cold neutron source

W & Pb-Target

Solid methane cold moderator @17K

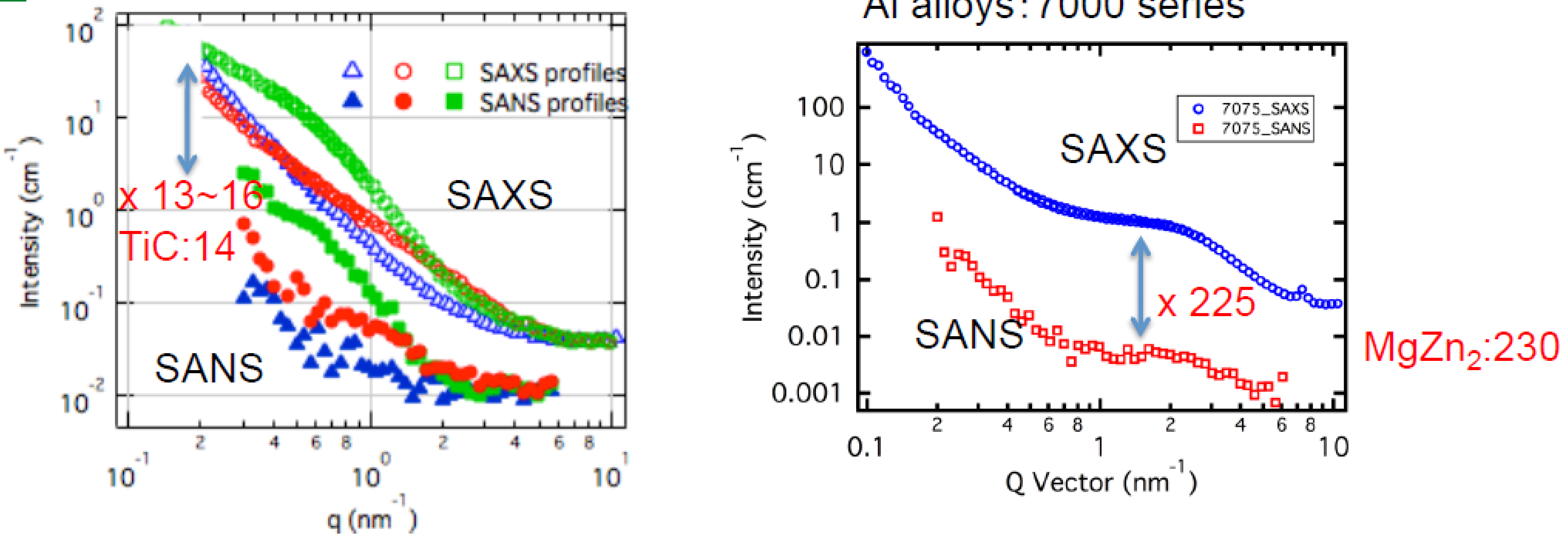
well know in Neutron Science
not in materials science..

Accelerator Based Neutron Sources

Expand the value of iANS "Combination of SAXS & SANS"

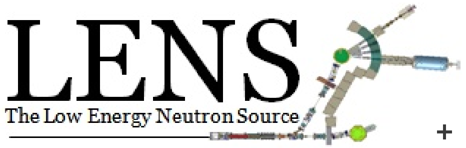
TiC precipitates in steels

Al alloys：7000 series

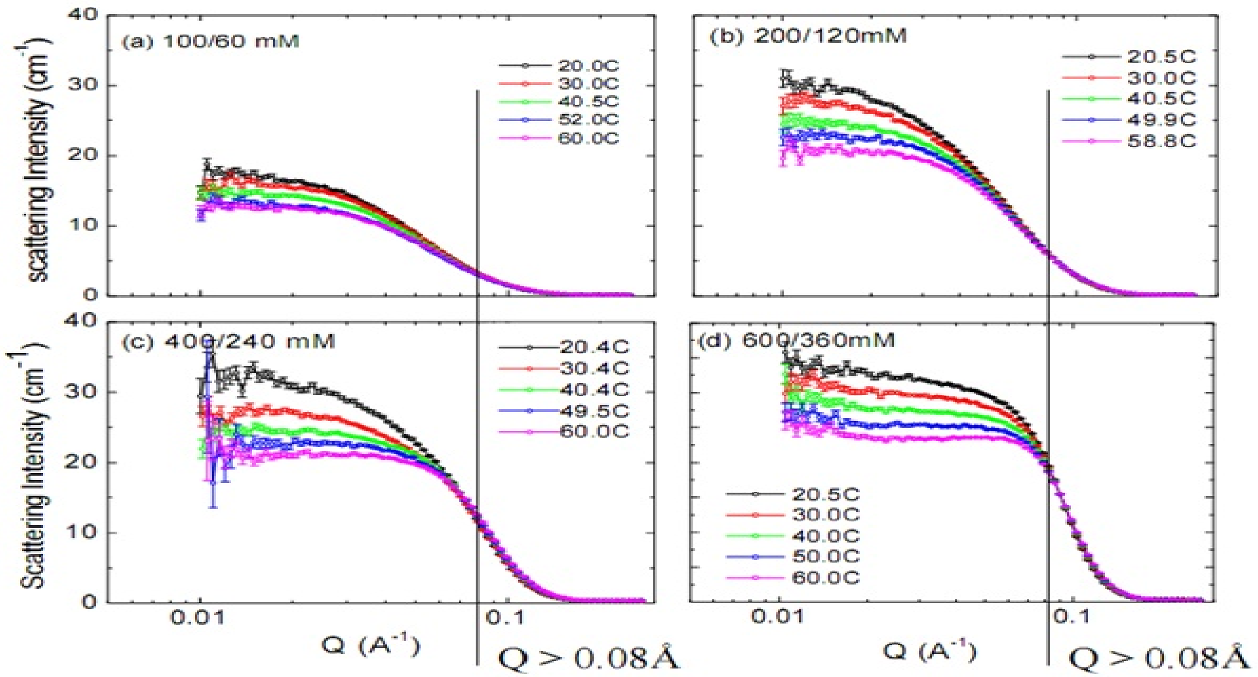


SAXS/SANS ratio can be evaluated only using in-house facilities

Accelerator Based Neutron Sources



- 13 MeV proton linac driver
- $^{9}Be(p,n)$ to produce neutrons
- Thermalization (polyethylene, solid CH_4@6.5 K)
- 100 n/(ms.cm^2)



Accelerator Based Neutron Source Projects

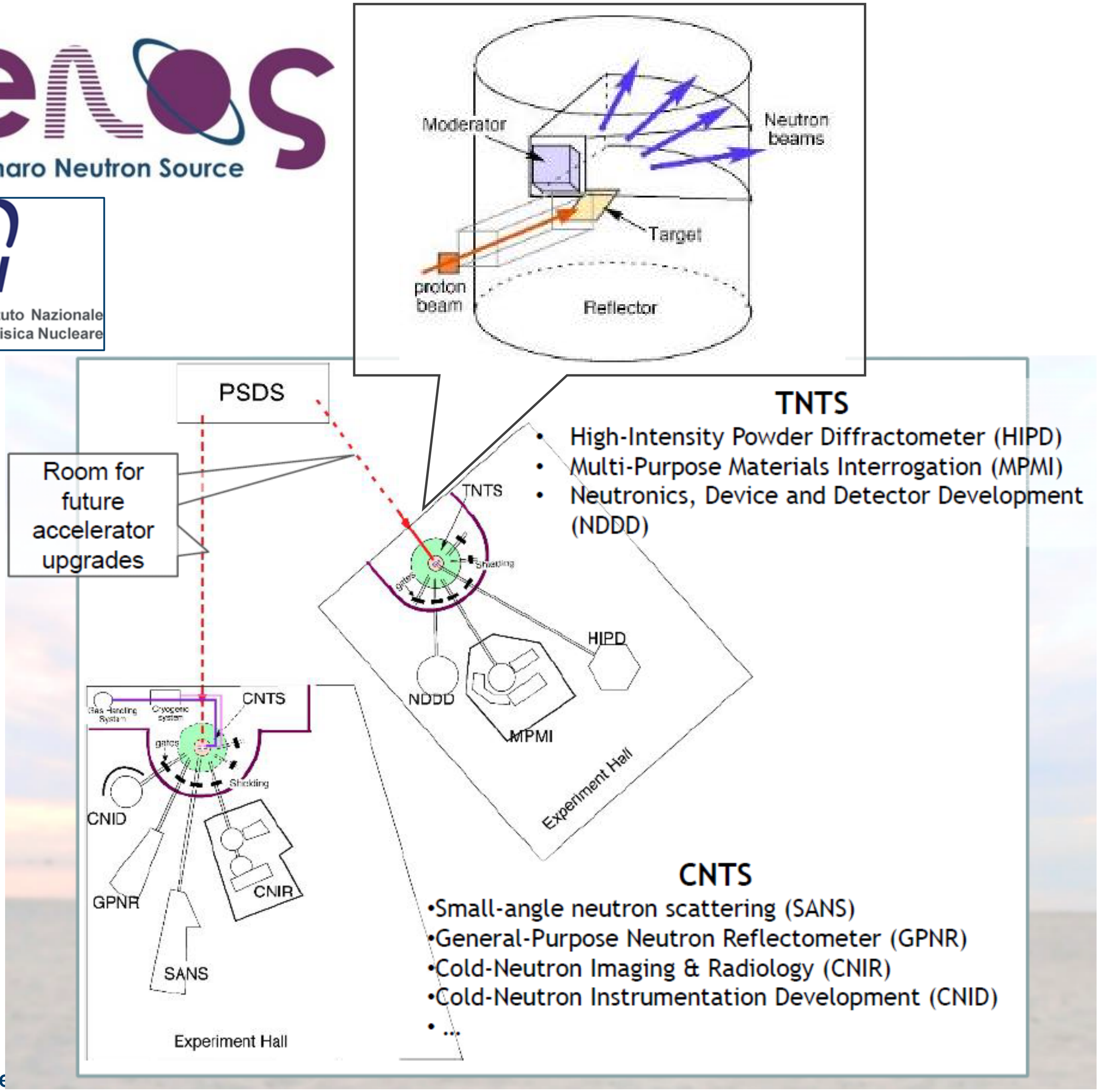
Martonvásár CANS

- CANS business plan:
  - Neutron instrumentation tests for own needs: saves 100 k€/y
  - Products and services for neutron source development
  - Beams for industrial applications
  - Beam for cancer therapy (BNCT)
  - Development of neutron source for > 2023 in Hungary

Specifications: accelerator

- $\geq$ 2.5 MeV, $\leq$ 20 mA, 50 kW CW capable H^+ beam
- Pulsed operation (5 % duty factor) for material diagnostics
- CW operation for irradiation (50 kW)
- 201.25 MHz (?) RF amplifier, solid state (?)
- Upgradable in energy

Accelerator Based Neutron Source Projects



Pulse Selection and **Distribution Station** (PSDS)

- CNTS (**Cold Neutron Target Station**)
  - Be target
  - Cryogenic moderator of solid methane
  - Reflector (graphite or water)
  - Up to 6 ports to expermental halls
- TNTS (**Thermal Neutron Target Station**)
  - Identical design to CNTS but with water (abient temperature) moderator
  - Initially three ports
- LENOS (astrophysics)

- **Modular** structure
- **Mild radioactivity** by low-energy protons ($\leq$ 5 MeV)
- Both **Short Pulse** (SP) and **Long Pulse** (LP) options
- Cryogenic and gas handling systems for hydrogenous moderator

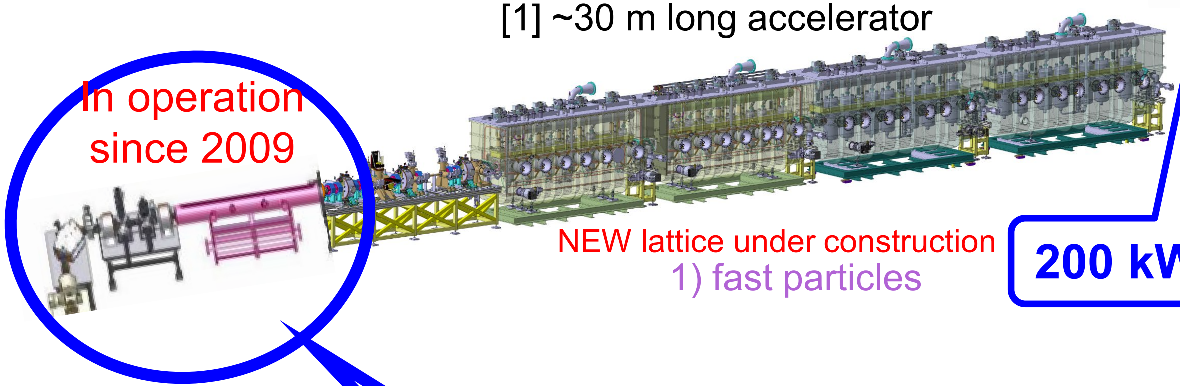
Accelerator Based Neutron Source Projects

SARAF concept and top level requirements

Soreq Nuclear Research Center

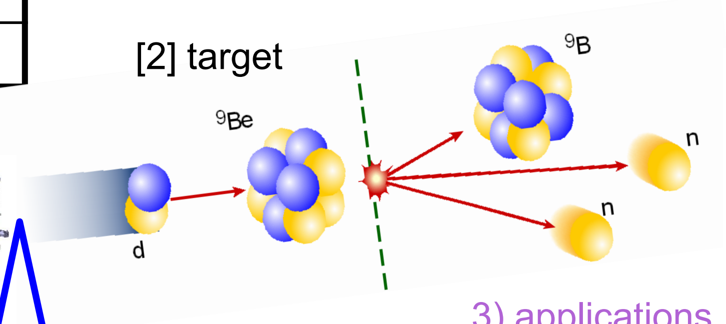
Parameter	Value	Comment
Ion Species	Protons/Deuterons	M/q ≤ 2
Energy Range	5 – 40 MeV	Variable energy
Current Range	0.04 – 5 mA	CW (and pulsed)
Maintenance	Hands-On	Very low beam loss

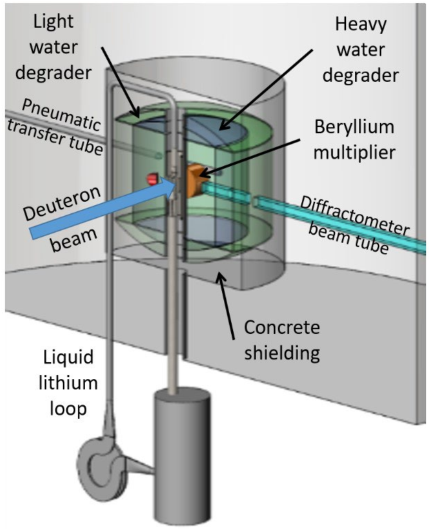
[1] ~30 m long accelerator



[2] target

[3] radiation and isotopes





3) applications

2) nuclear reaction

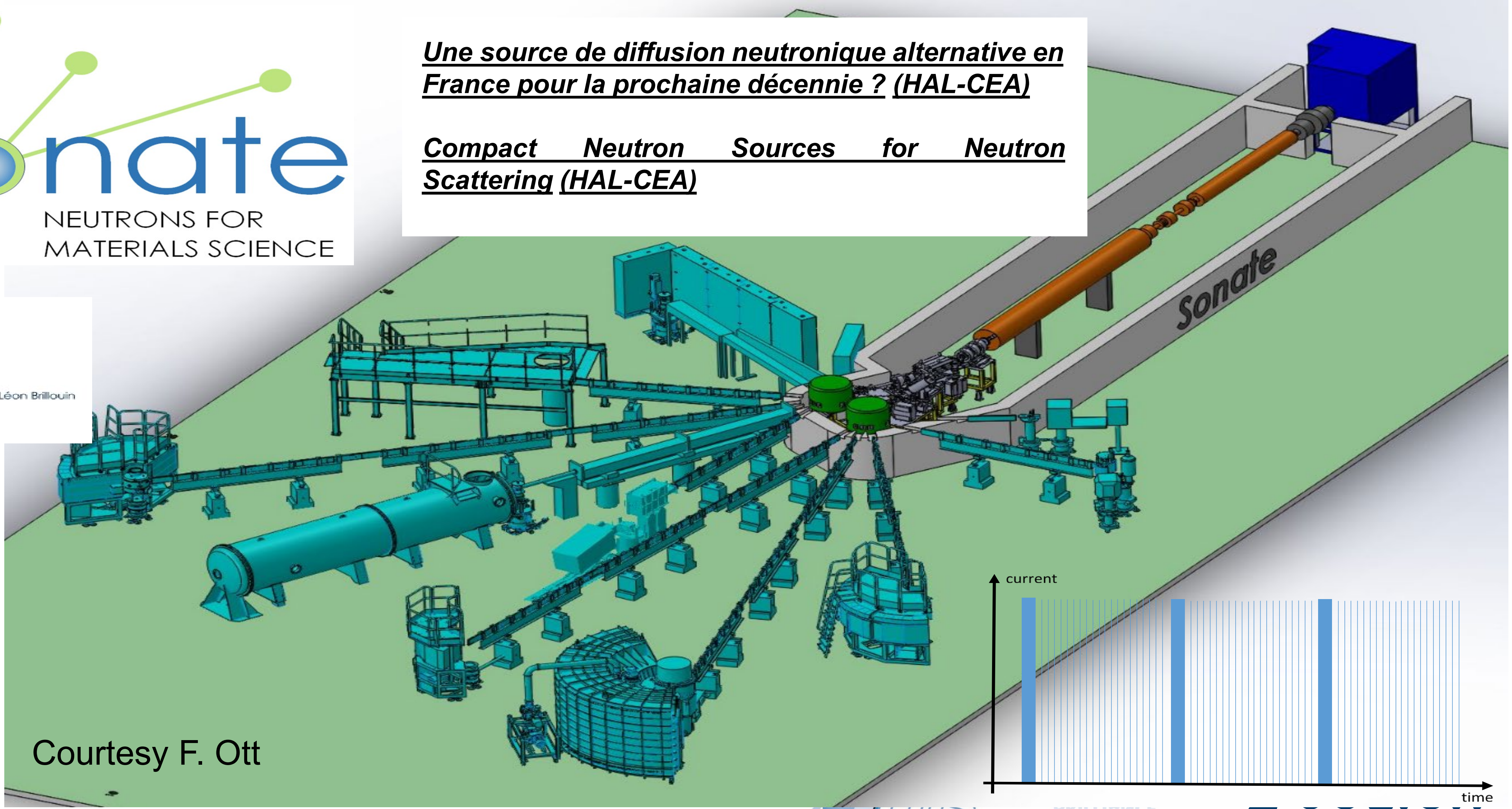
Planned for 2023

Phase-I in routine operation till last month, built to test characterize and prove the novel technologies

Accelerator Based Neutron Source Projects

Une source de diffusion neutronique alternative en France pour la prochaine décennie ? (HAL-CEA)

Compact Neutron Sources for Neutron Scattering (HAL-CEA)



Courtesy F. Ott

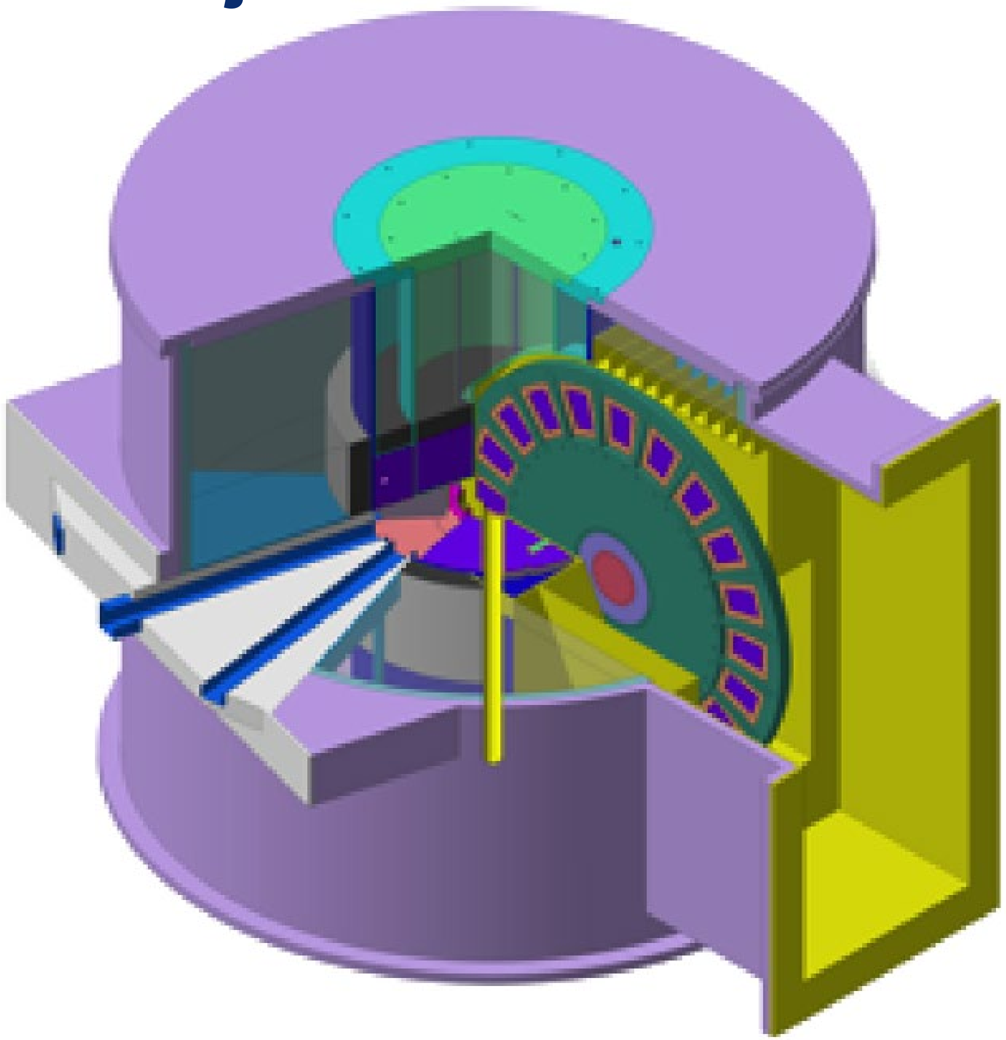
Accelerator Based Neutron Source Projects

ESS bilbao

Table 4.2.1
Parameters of the ESS-Bilbao project.

Proton linac
50 MeV, 16 kW 2.25 mA (average), 20 Hz Long pulse, width 1.5 ms

Target station	Major activities
Be(p, n) Solid methane with water premoderator $\sim 1 \times 10^{15}$ n/s (calc.)	SANS, moderator and neutron-scattering component testing



Accelerator Based Neutron Source Projects

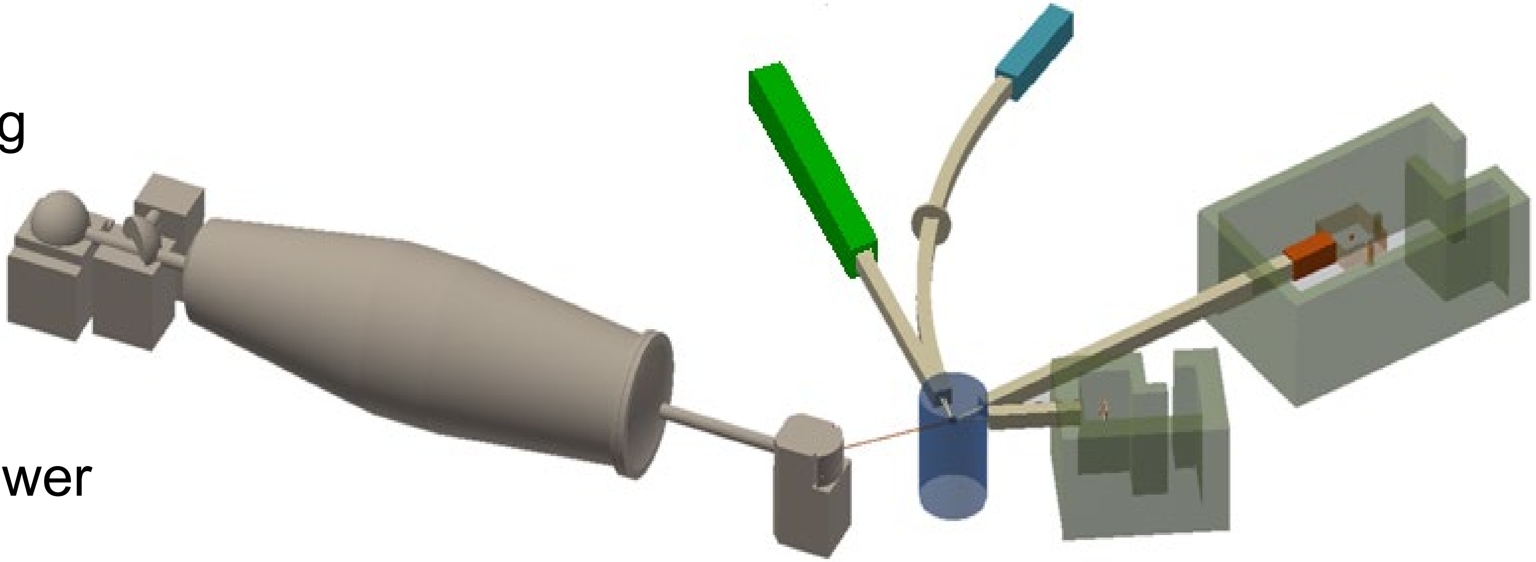
NOVA ERA (Design)

Laboratory facility: NOVA ERA

Workhorse instruments:
scattering / analytics / imaging

University / industry **laboratory**
Easy access, flexible use

Typical flux at sample position:
$10^3 – 10^5$ cm^{-2} s^{-1} at 400 W power



CDR NOVA ERA
FZJ Schriftenreihe, 2017
ISBN 978-3-95806-280-1

http://www.fz-juelich.de/SharedDocs/Downloads/JCNS/JCNS-2/EN/Conceptual-Design.pdf

Accelerator Based Neutron Source Projects

HBS project

High current linear accelerator

- 100 mA, 70 MeV pulsed proton beam
- Variable frequency

Several target stations

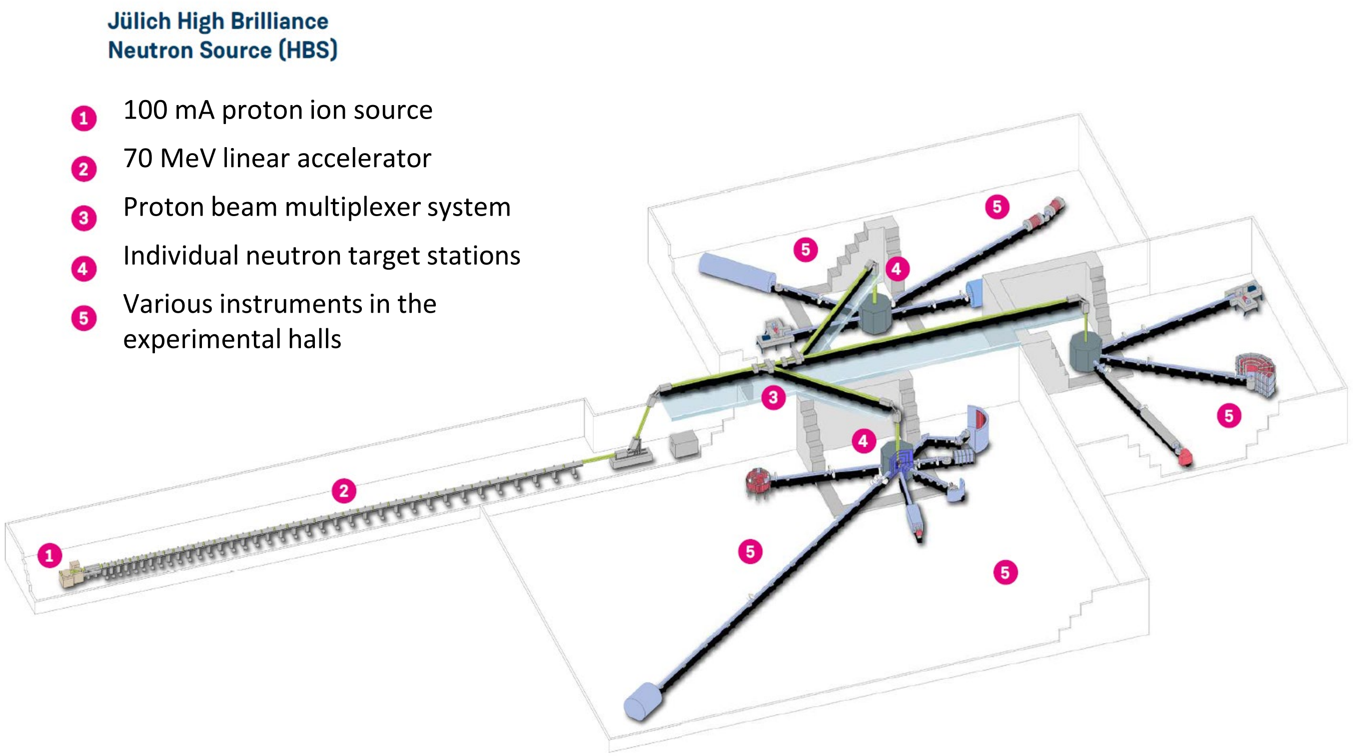
- Optimize pulse structure (length, rep. rate)
- Optimize thermal spectrum

Every beam port serves only 1 Instrument

- Optimize cold source spectrum
- Optimize geometry
- Integrate neutron optics with beam port

Small shielding

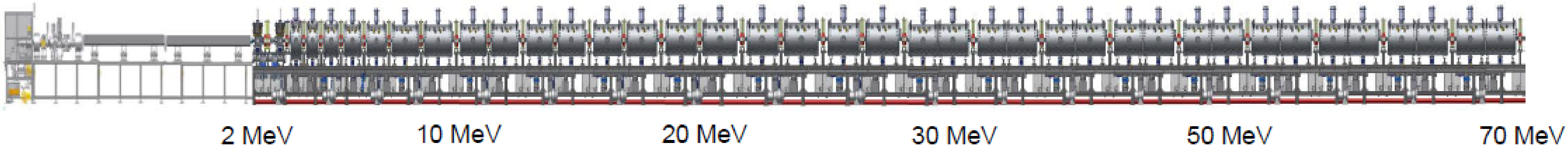
- Neutron guide around cold source
- Chopper at <1 m from target



www.fz-juelich.de/jcns/jcns-2/EN/Forschung/High-Brilliance-Neutron-Source/_node.html

Accelerator system

Concept of the HBS-Accelerator



Beam current: 10-100 mA
Duty factor beam: up to 10%
Duty factor RF: up to 20%

For all beam currents, duty factors and energies (above 5 MeV) the DTL layout is the same.

This allows scalability for CANS with an average beam power between 1 kW to 1 MW.

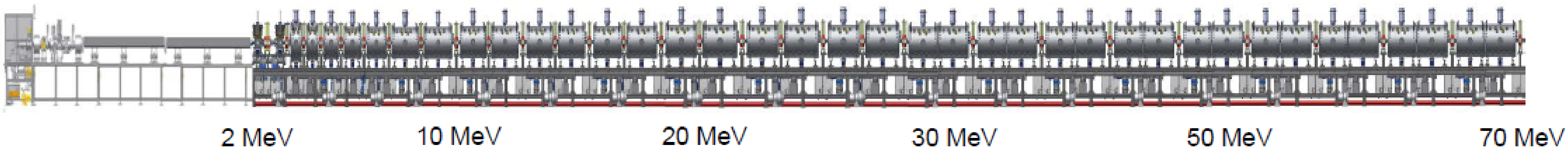
H. Podlech et al., Proc. IPAC'19 (2019)

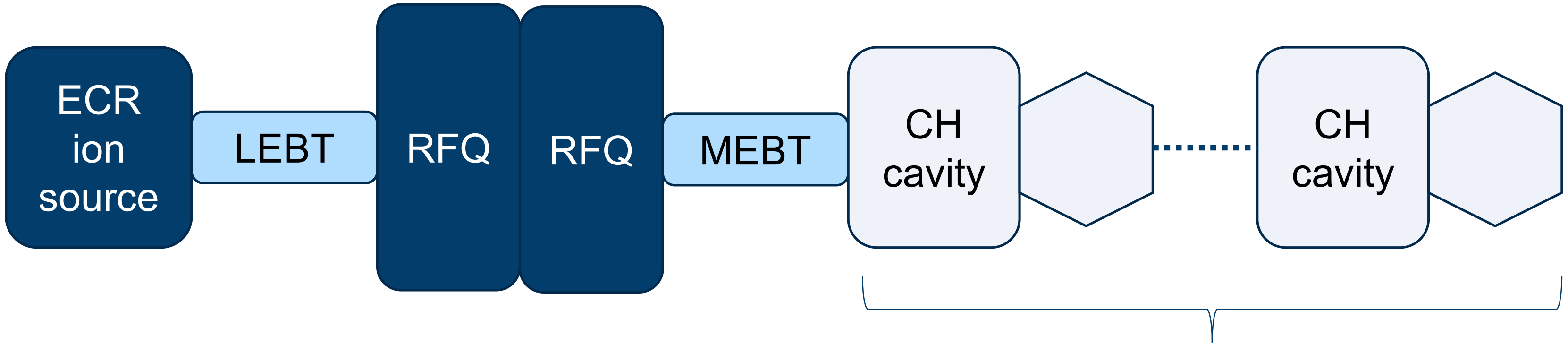
Accelerator system

Concept of the HBS-Accelerator

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

IAP Institut für Angewandte Physik





100 mA
proton source

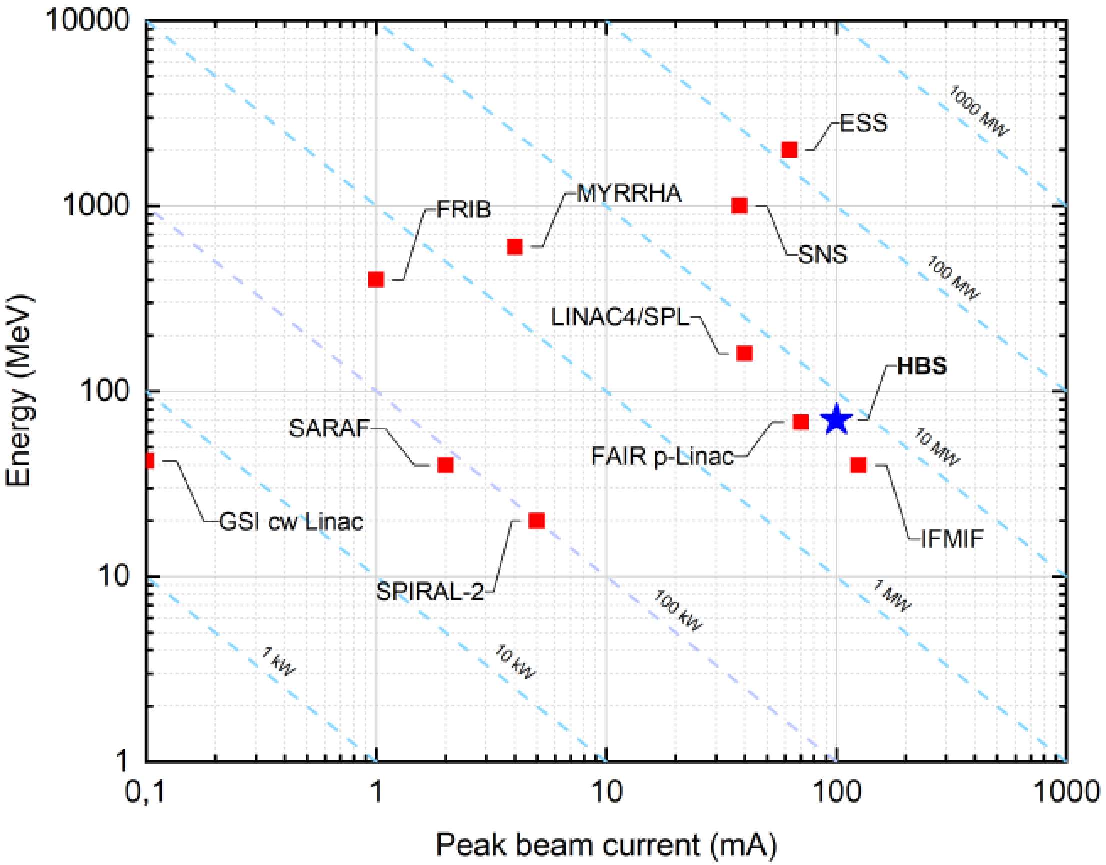
175 MHz
(2-4 m, ~5 MeV each)

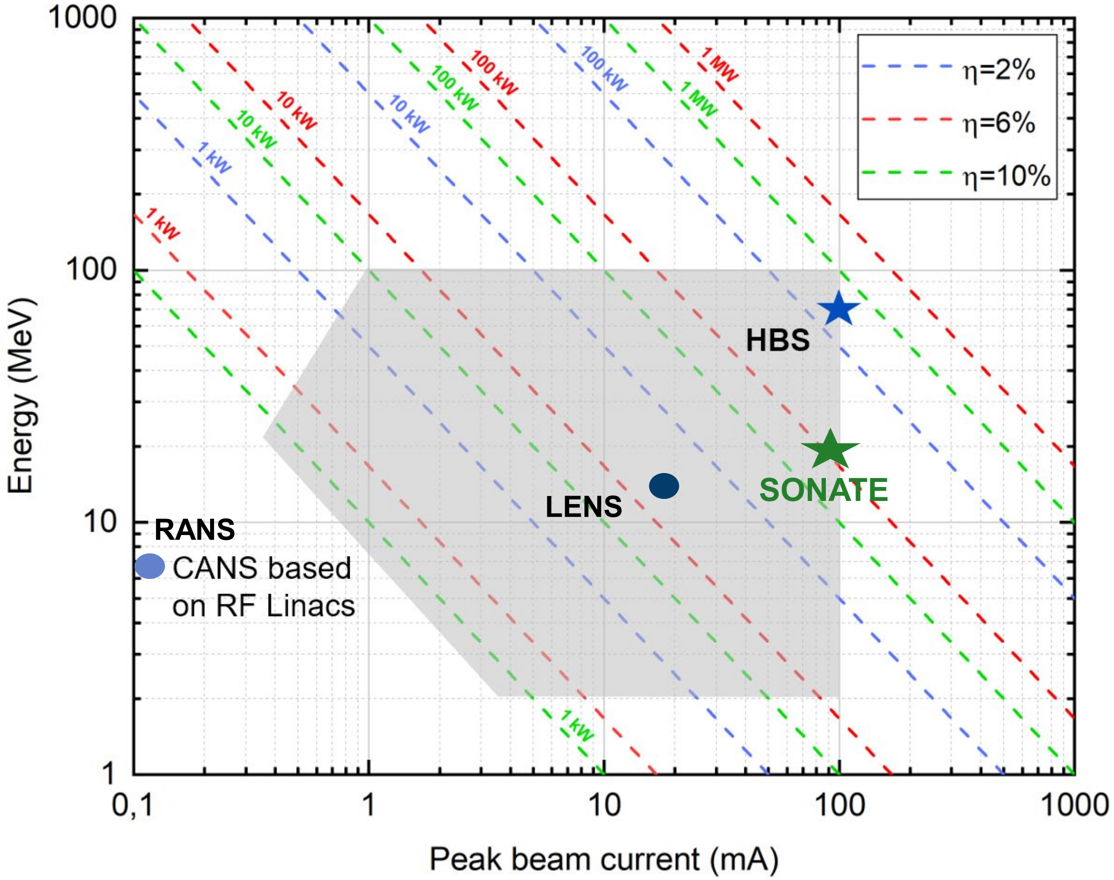
normal conducting CH cavities and
quadrupole dublets
(~2.5 m, ~2 MeV each)

H. Podlech et al., Proc. IPAC'19 (2019)

Accelerator system

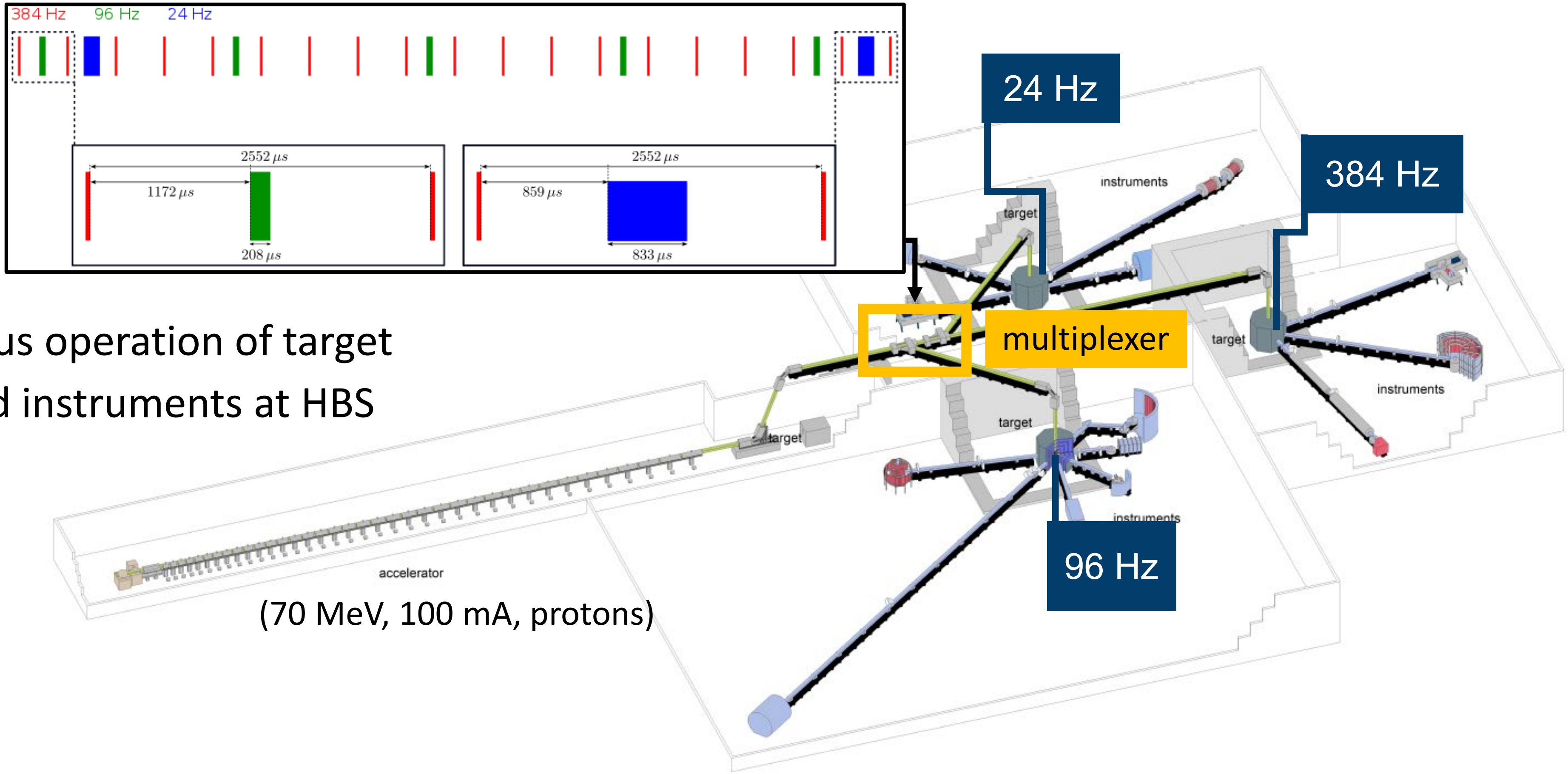
Peak beam power and average beam power levels of proton linacs





Accelerator system

Multiplexer

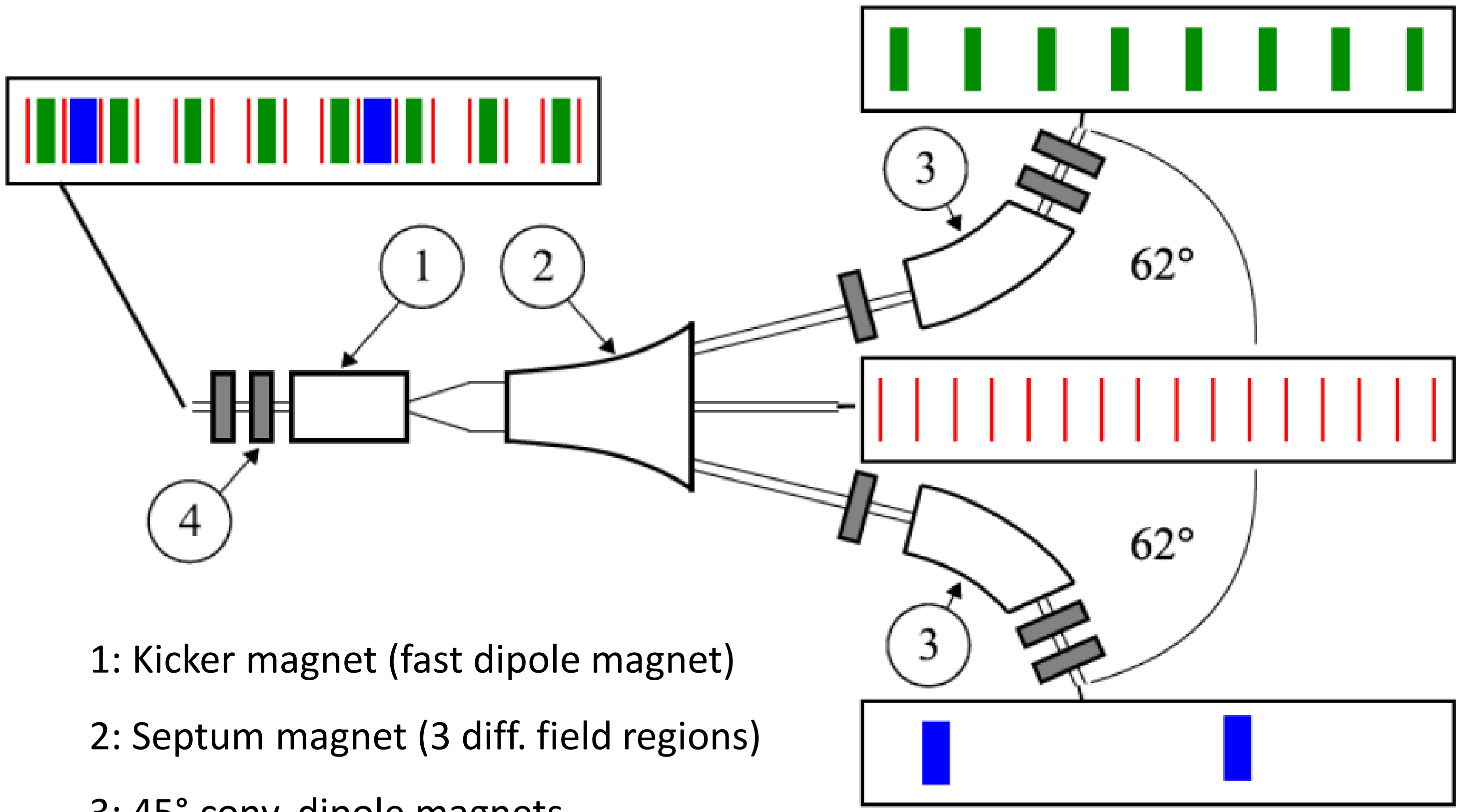


- simultaneous operation of target stations and instruments at HBS

(70 MeV, 100 mA, protons)

Accelerator system

Multiplexer



1: Kicker magnet (fast dipole magnet)

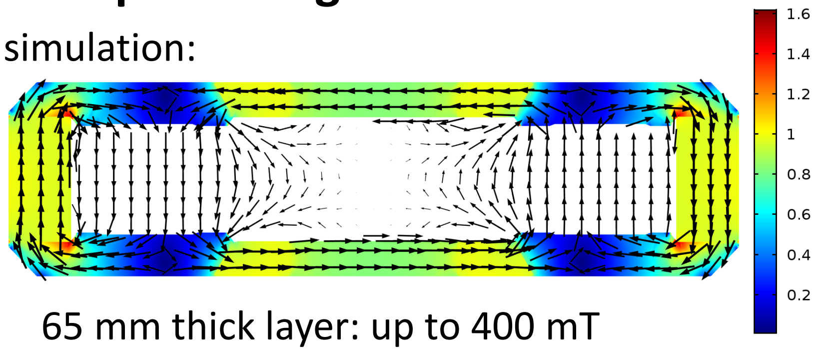
2: Septum magnet (3 diff. field regions)

3: 45° conv. dipole magnets

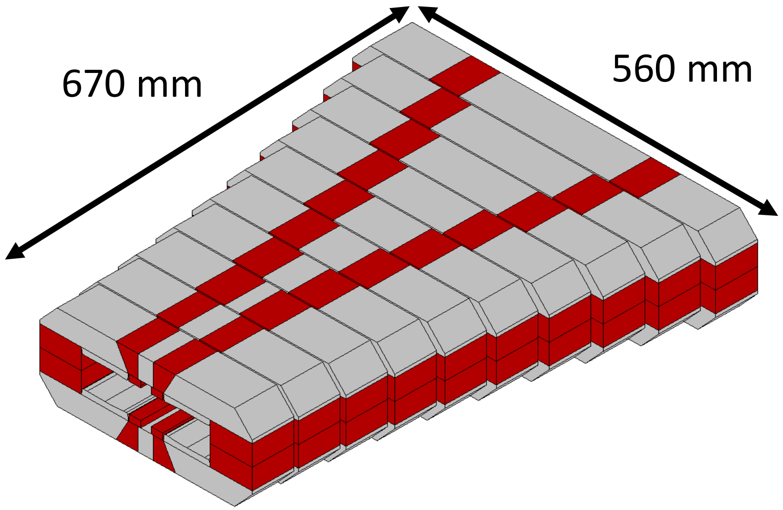
4: conv. Quadrupole magnets (in grey)

Septum magnet

simulation:



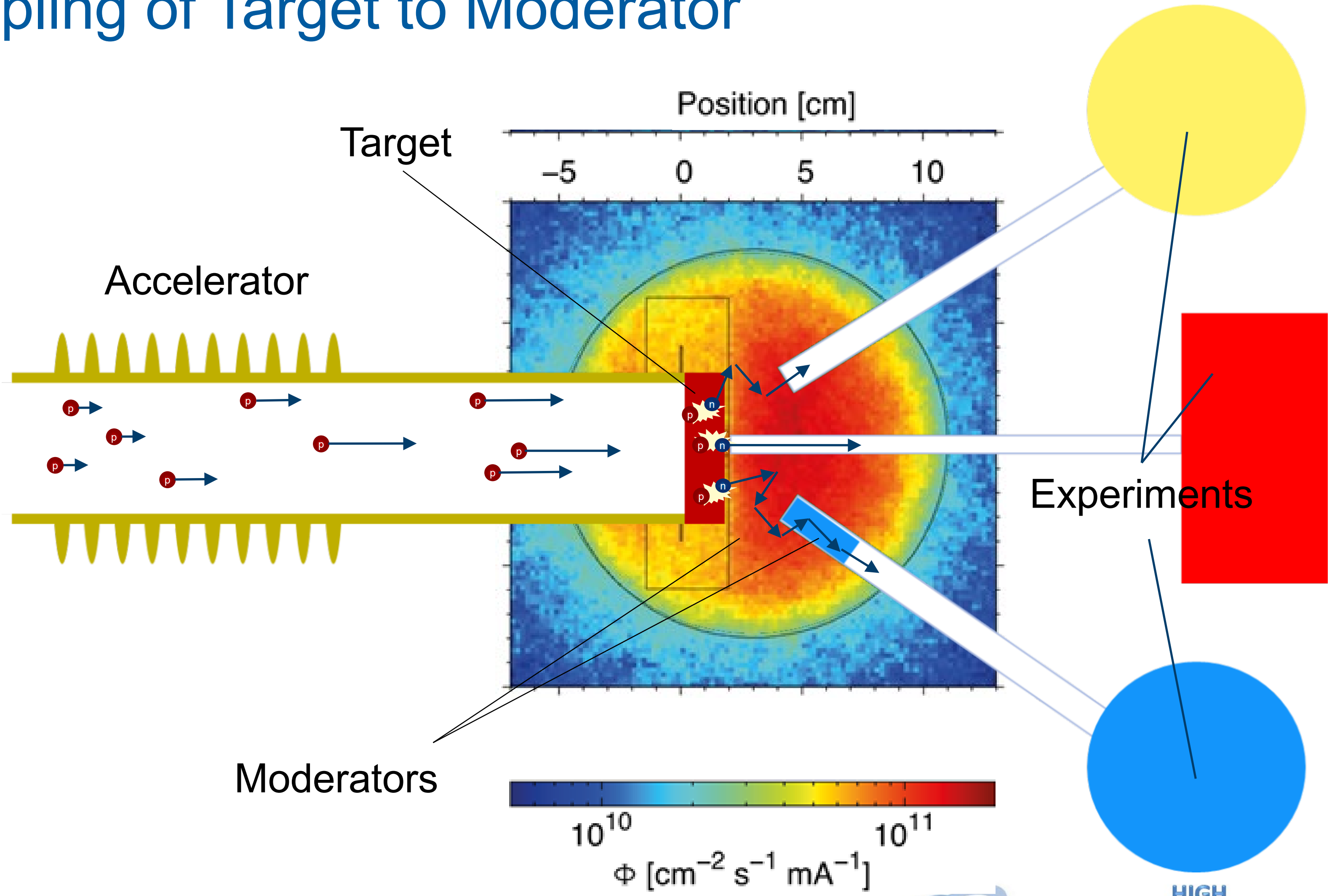
65 mm thick layer: up to 400 mT



Rimmler et al., EPJ Web of Conf. 231, 02002 (2020)

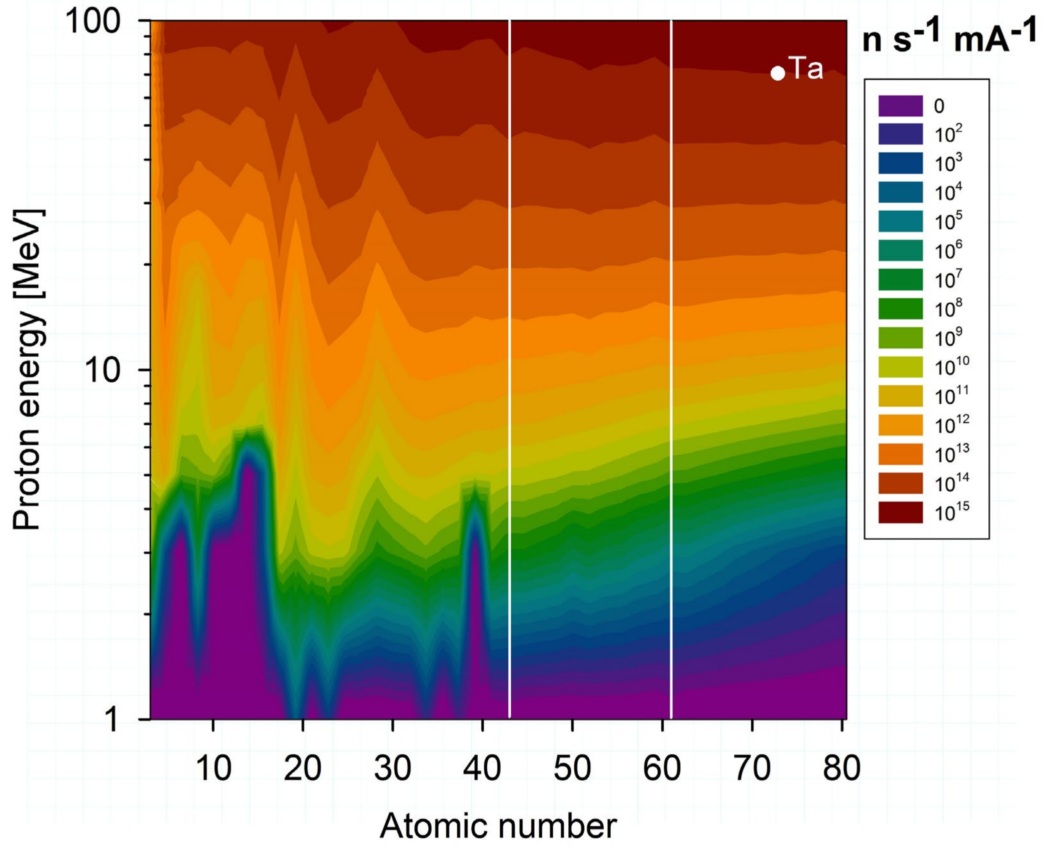
Target system

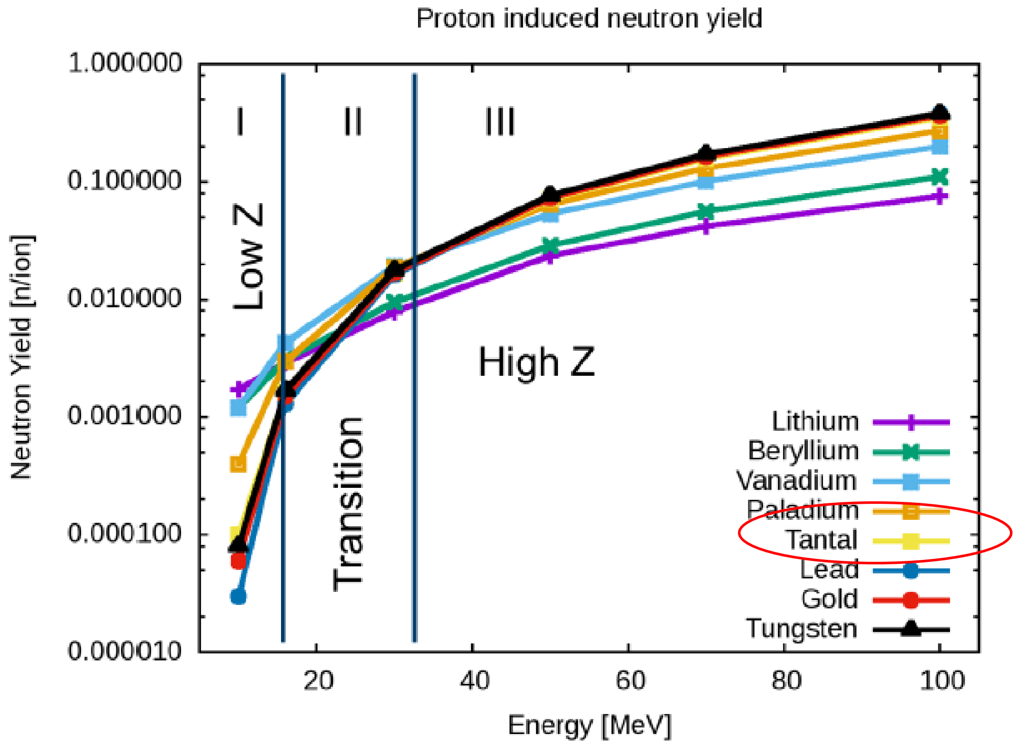
Efficient Coupling of Target to Moderator

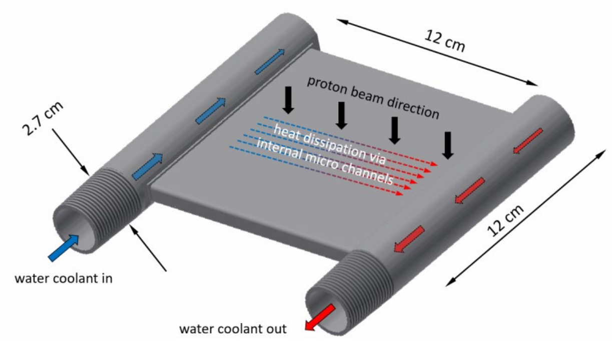


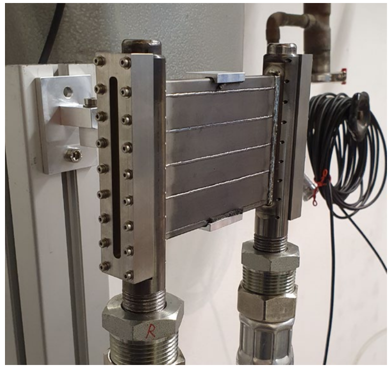
Target system

Target material and design





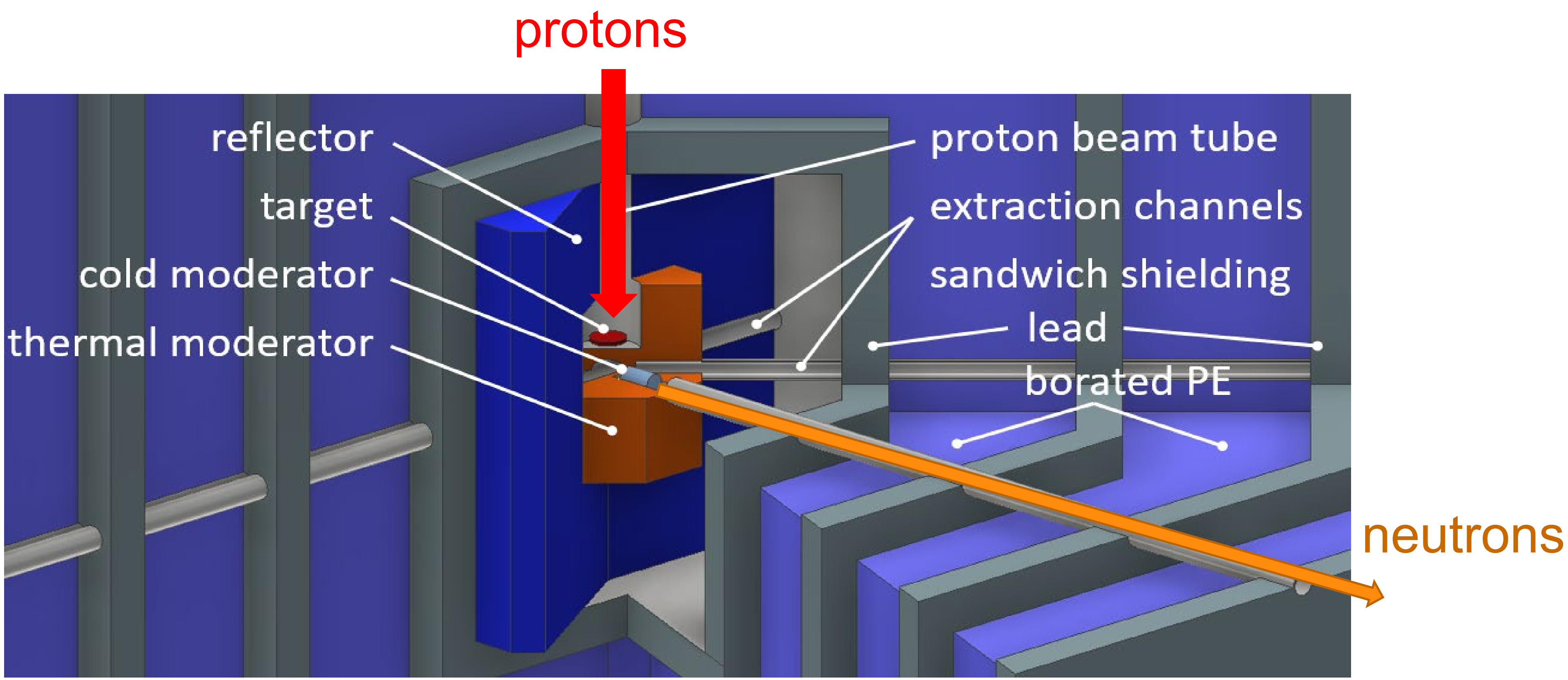




Zakalek et al. EPJ Web of Conf. 231, 03006 (2020)

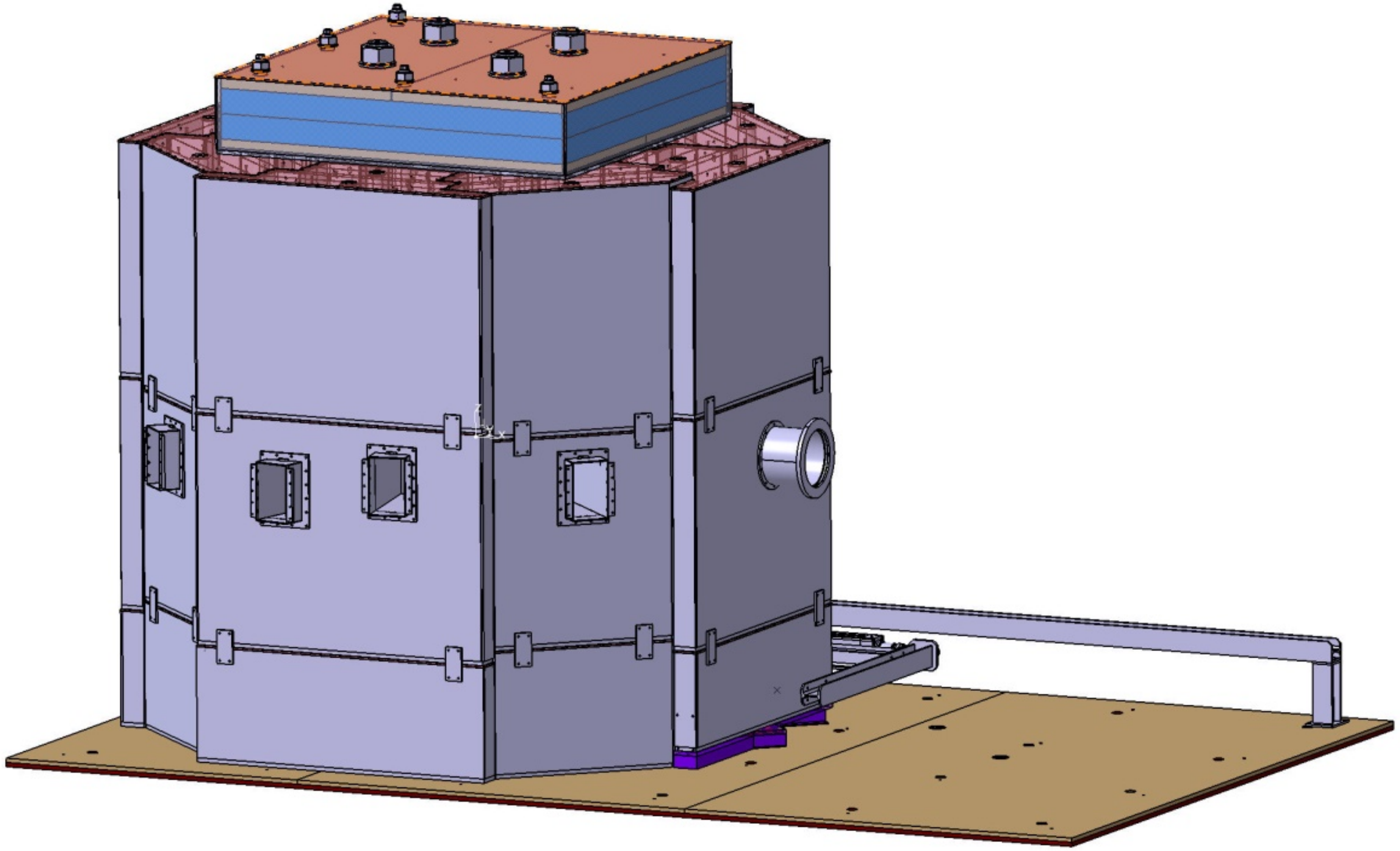
Target system

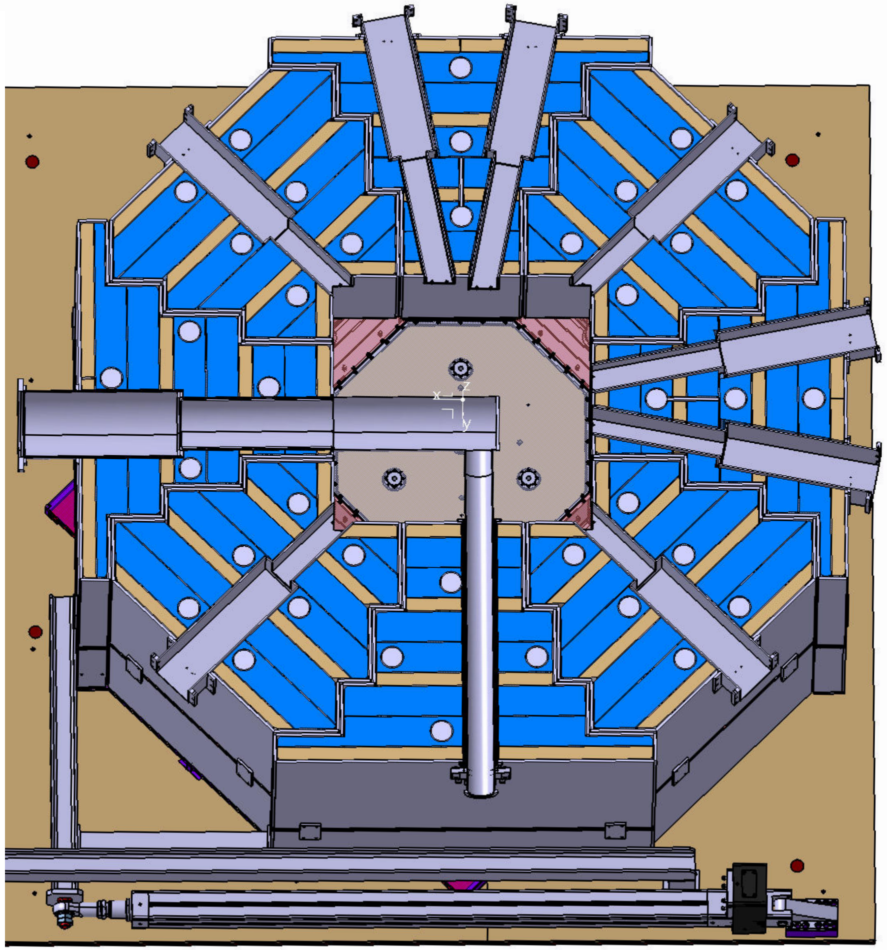
Target-Moderator-Reflector unit



Target system

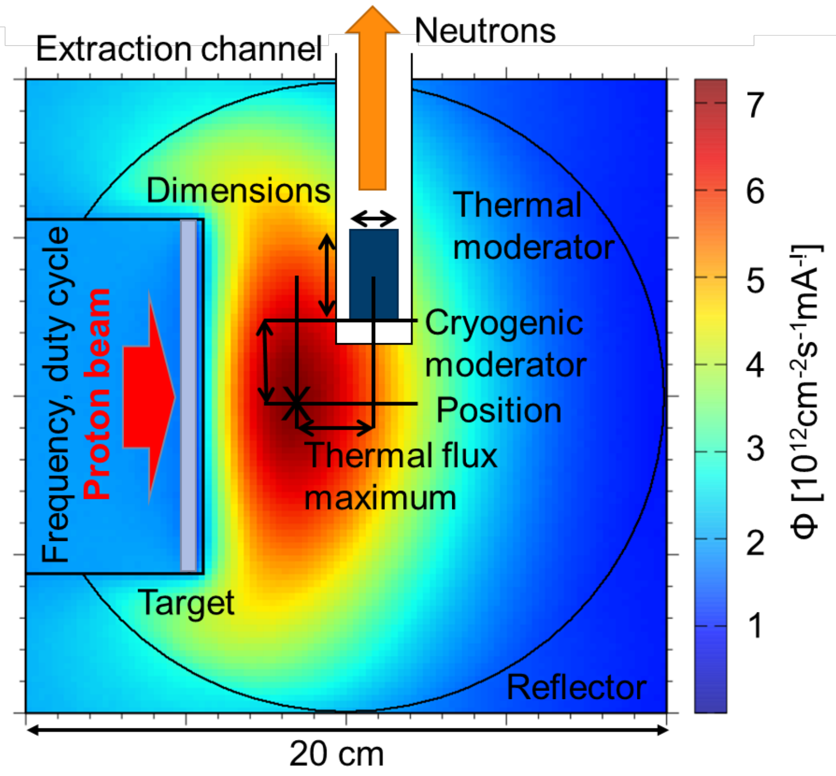
Target-Moderator-Reflector unit



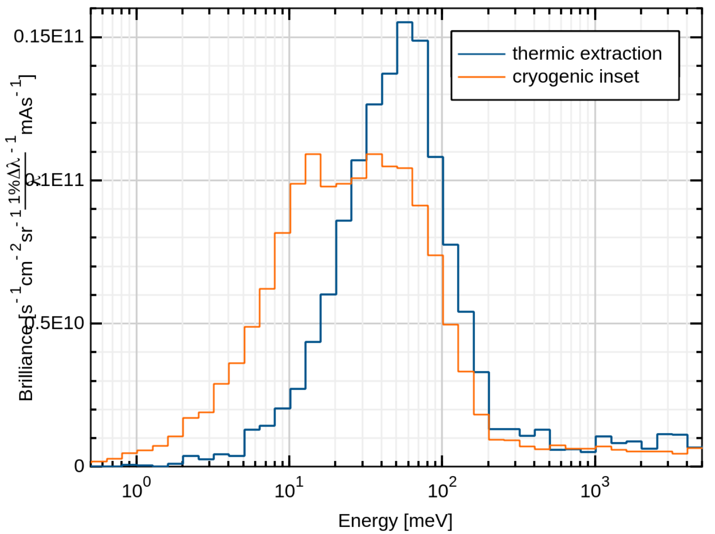


Target system

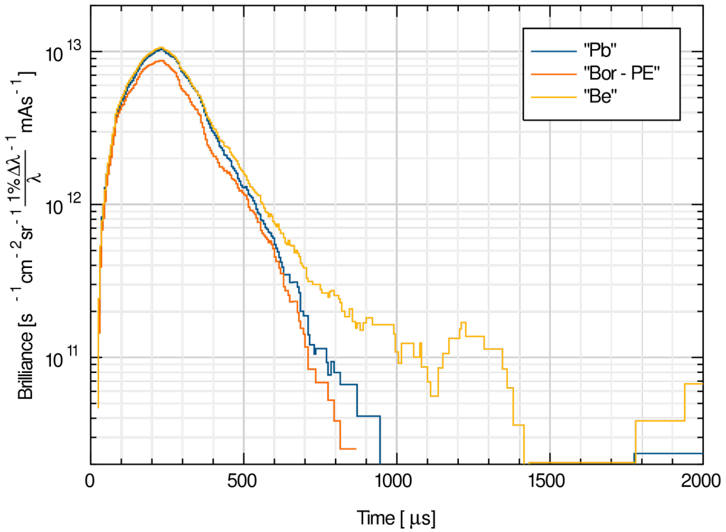
Neutron moderation

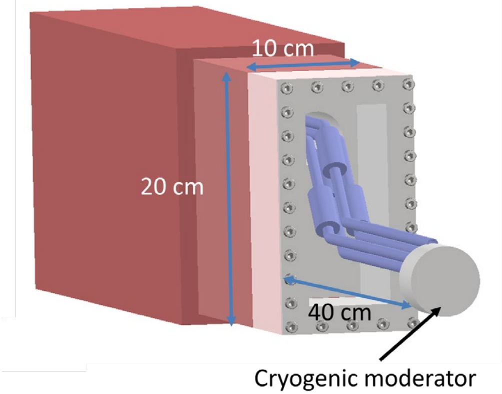


Thermal/cold neutron spectrum

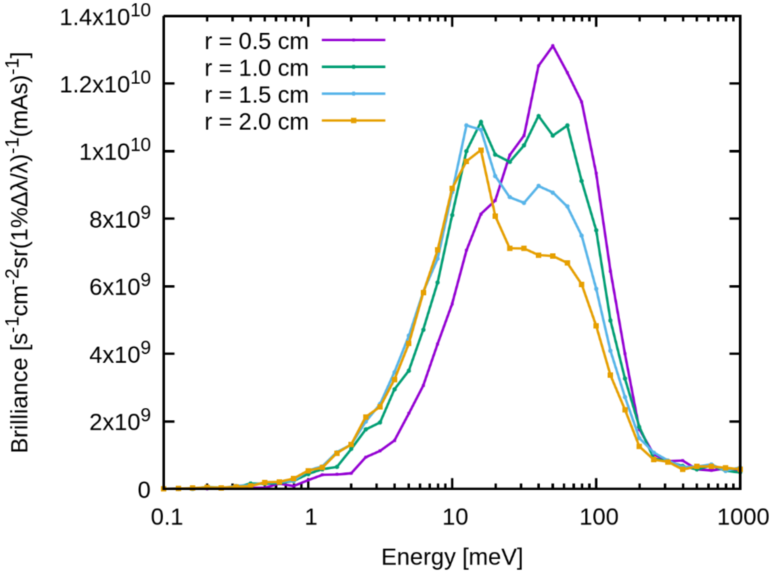


Neutron emission of PE/reflector materials





Cold moderator dimensions

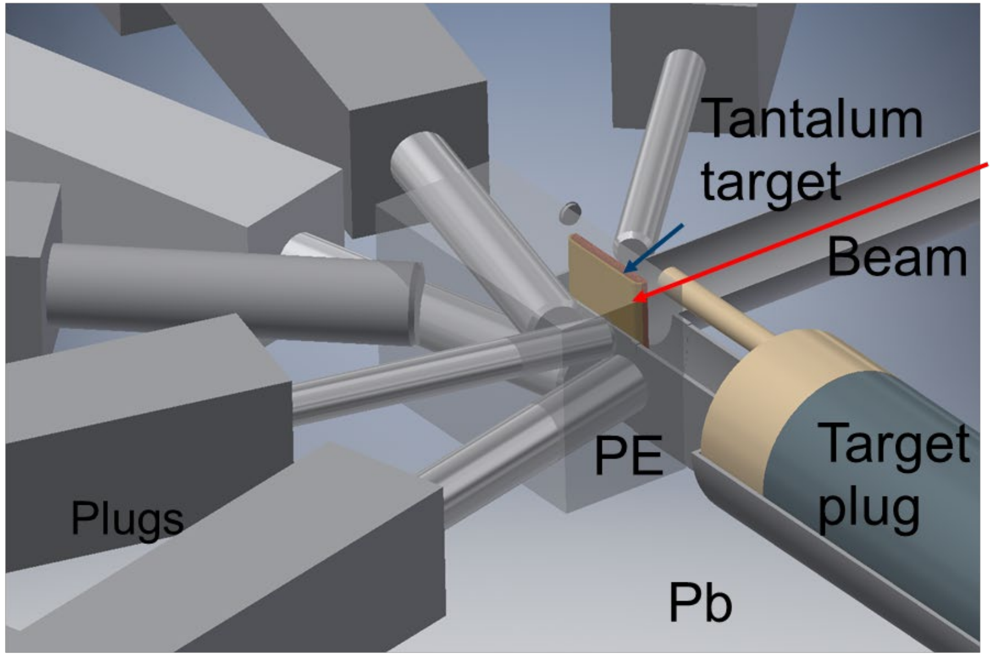


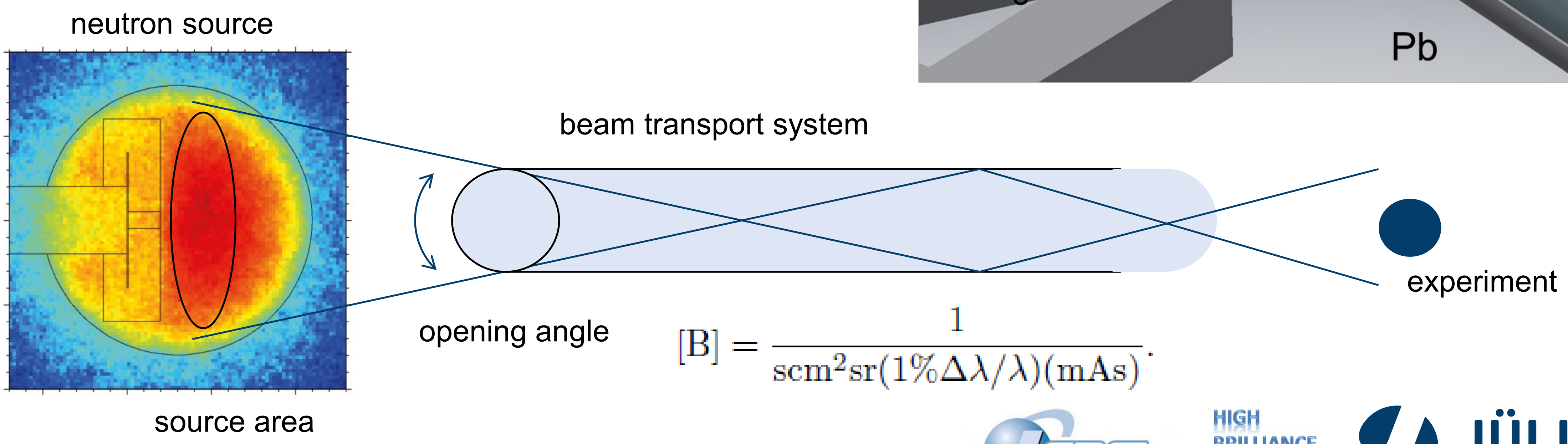
Instrumentation

Extraction / beam parameters

- Efficient beam extraction in combination with modern beam transport system
- Maximize accessible phase-space volume

Extraction channels



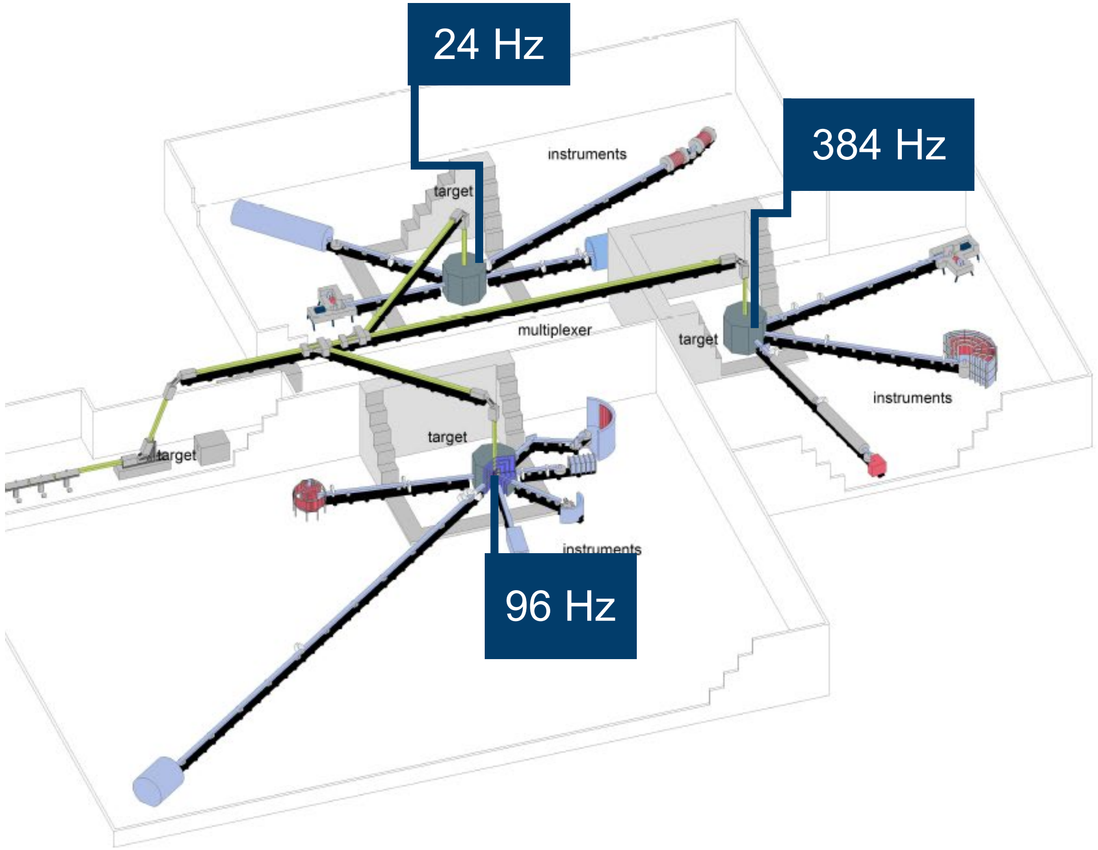


$$[B] = \frac{1}{\text{scm}^2\text{sr}(1\%\Delta\lambda/\lambda)(\text{mAs})}.$$

Instrumentation

Calculated instrument neutron flux

	Length [m]	Resolution	Bandwidth	Flux [cm^{-2} s^{-1}]	Frequency [Hz]
SANS	20.0	5% $\Delta\lambda/\lambda$	2.0-9.0 Å	9.4×10^7	24
Reflectometer	22.0	4% $\Delta\lambda/\lambda$	1.3-8.0 Å	1.7×10^7	24
Thermal powder diffr.	100.8	0.0061-0.014 $\Delta\, d/d$	0.75-2.4 Å	1.5×10^8	24
Cold neutron imaging I	6.0	2.0-10.0%	1.0-15.0 Å	3.0×10^8	96
Disordered material diffr.	61.0	0.016-0.028 $\Delta\, d/d$	0.5-1.2 Å	1.9×10^7	96
Macromolecular diffr.	12.5		2.0-4.0 Å	4.0×10^7	96
Cold chopper spectr.	18.5		1.6-10.0 Å	3.4×10^5	96
Backscattering spectr.	102.5	3.0-20.0 μeV	6.05-6.0 Å	7.0×10^6	96
Epithermal neutron imaging	37.0		25-80 meV	5.0×10^9	384
High energy chopper spectr.	28.5	4% ΔE/E	0.5-2.5 Å	9.0×10^4	384
PDGNAA-2	21.0	50%	0.6 eV - 10 MeV	2.7×10^7	384



HBS project

High current linear accelerator

- 100 mA, 70 MeV pulsed proton beam
- Variable frequency

Several target stations

- Optimize pulse structure (length, rep. rate)
- Optimize thermal spectrum

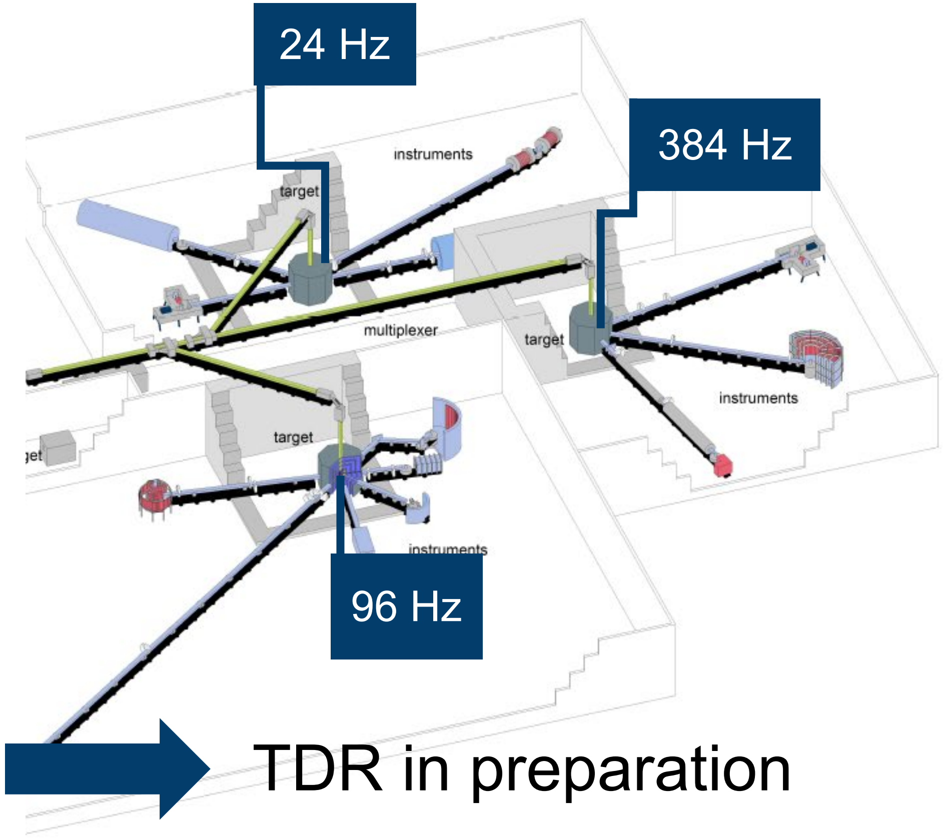
Every beam port serves only 1 Instrument

- Optimize cold source spectrum
- Optimize geometry
- Integrate neutron optics with beam port

Small shielding

- Neutron guide around cold source
- Chopper at <1 m from target

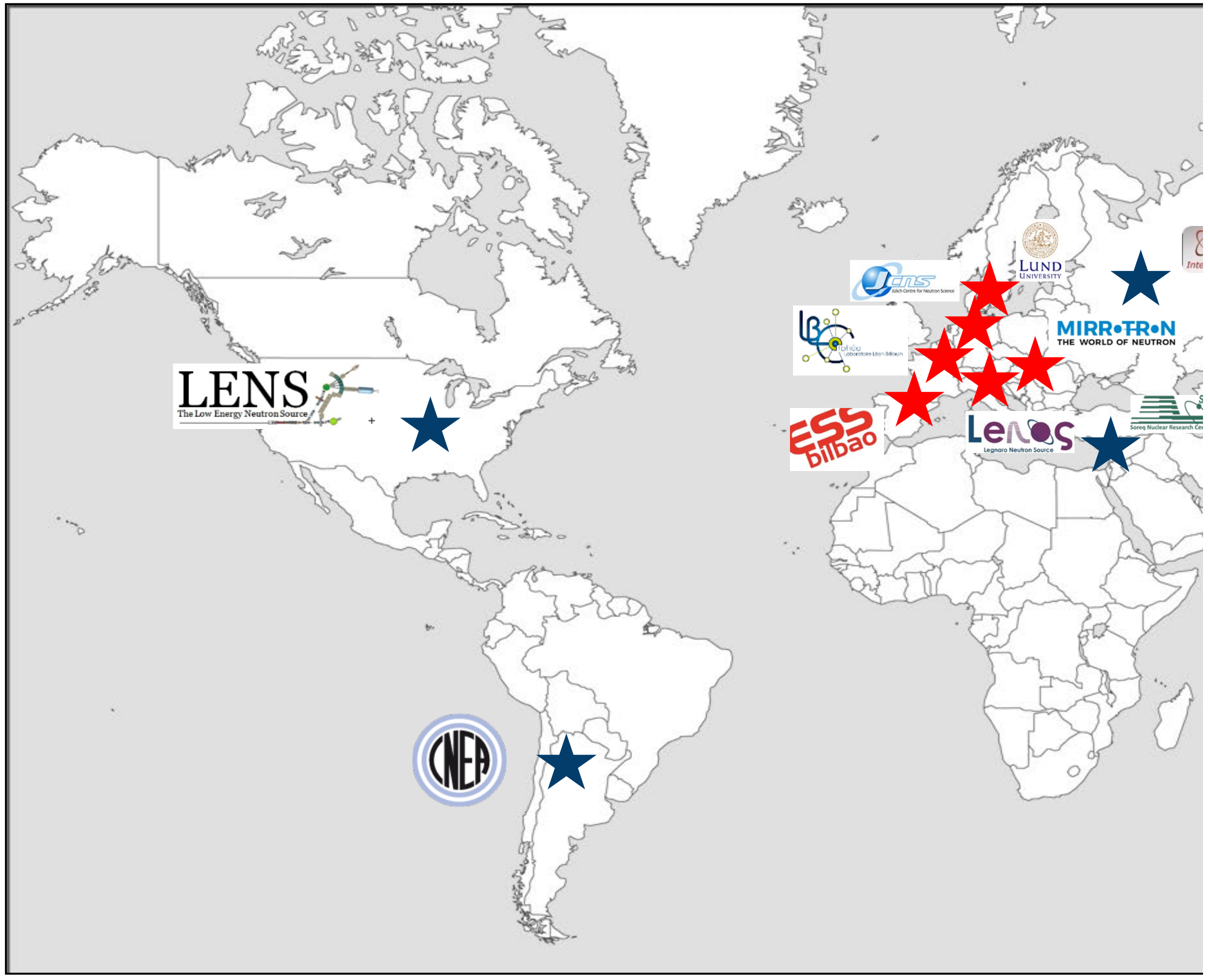
HBS CDR



TDR in preparation

www.fz-juelich.de/jcns/jcns-2/EN/Forschung/High-Brilliance-Neutron-Source/_node.html

Accelerator Based Neutron Sources



www.elena-neutron.eu

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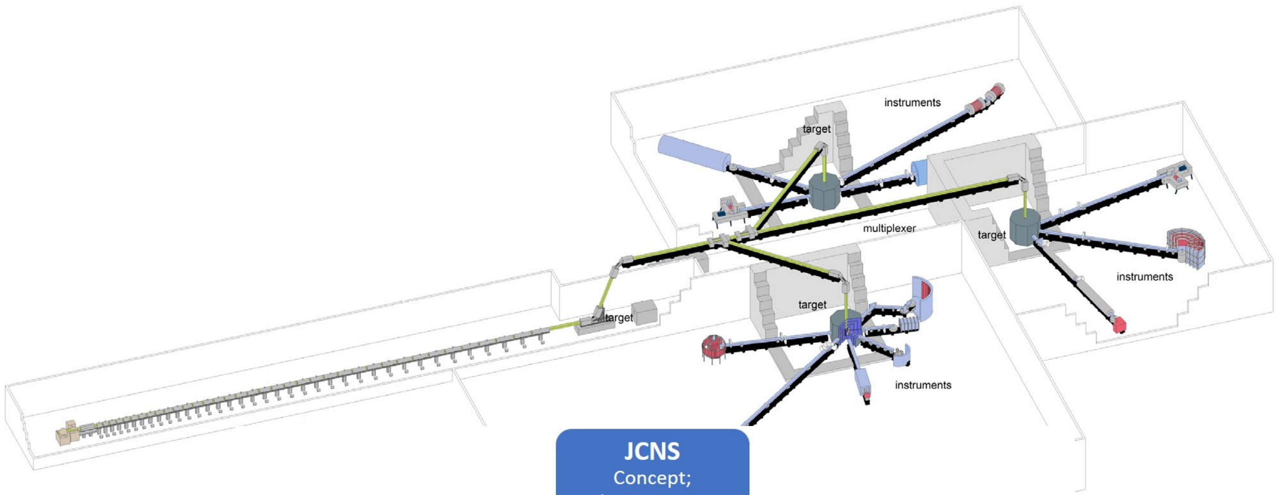
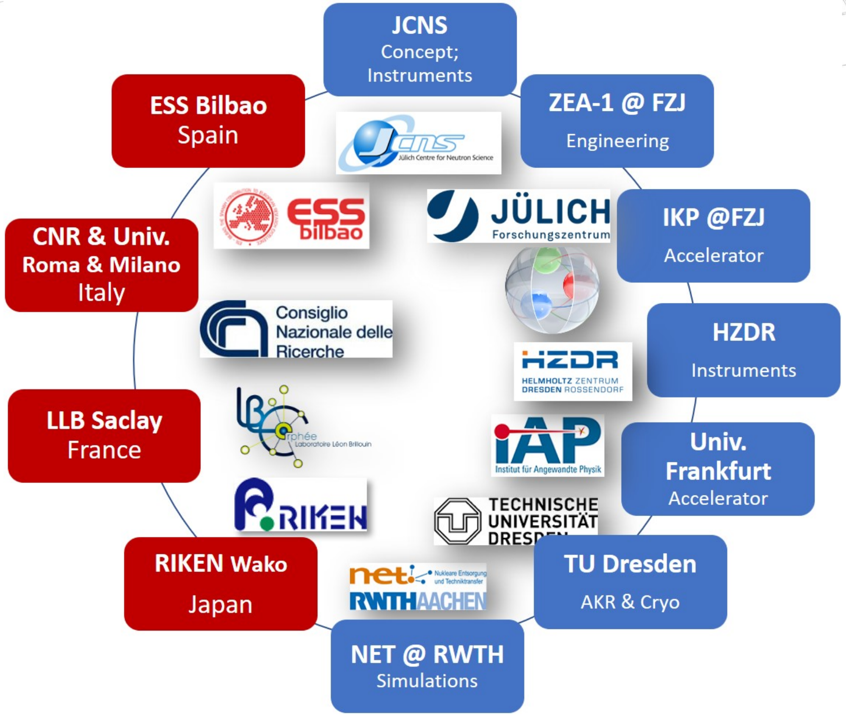
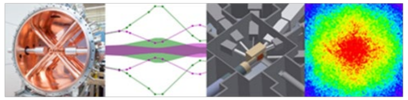




HBS Innovationpool Project



FB Matter: MML, MT

Federal Ministry of Education and Research

HIGH BRILLIANCE SOURCE