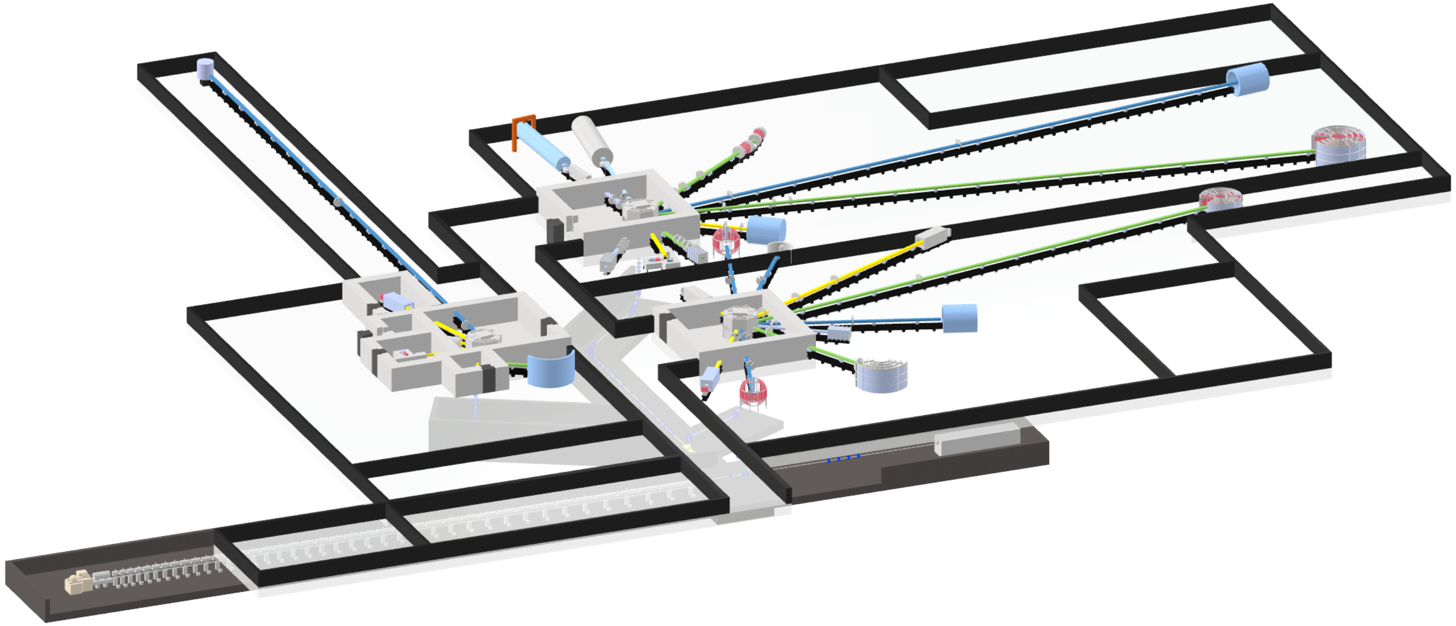


High Current Accelerator-based Neutron Sources – The HBS project for a next generation neutron facility

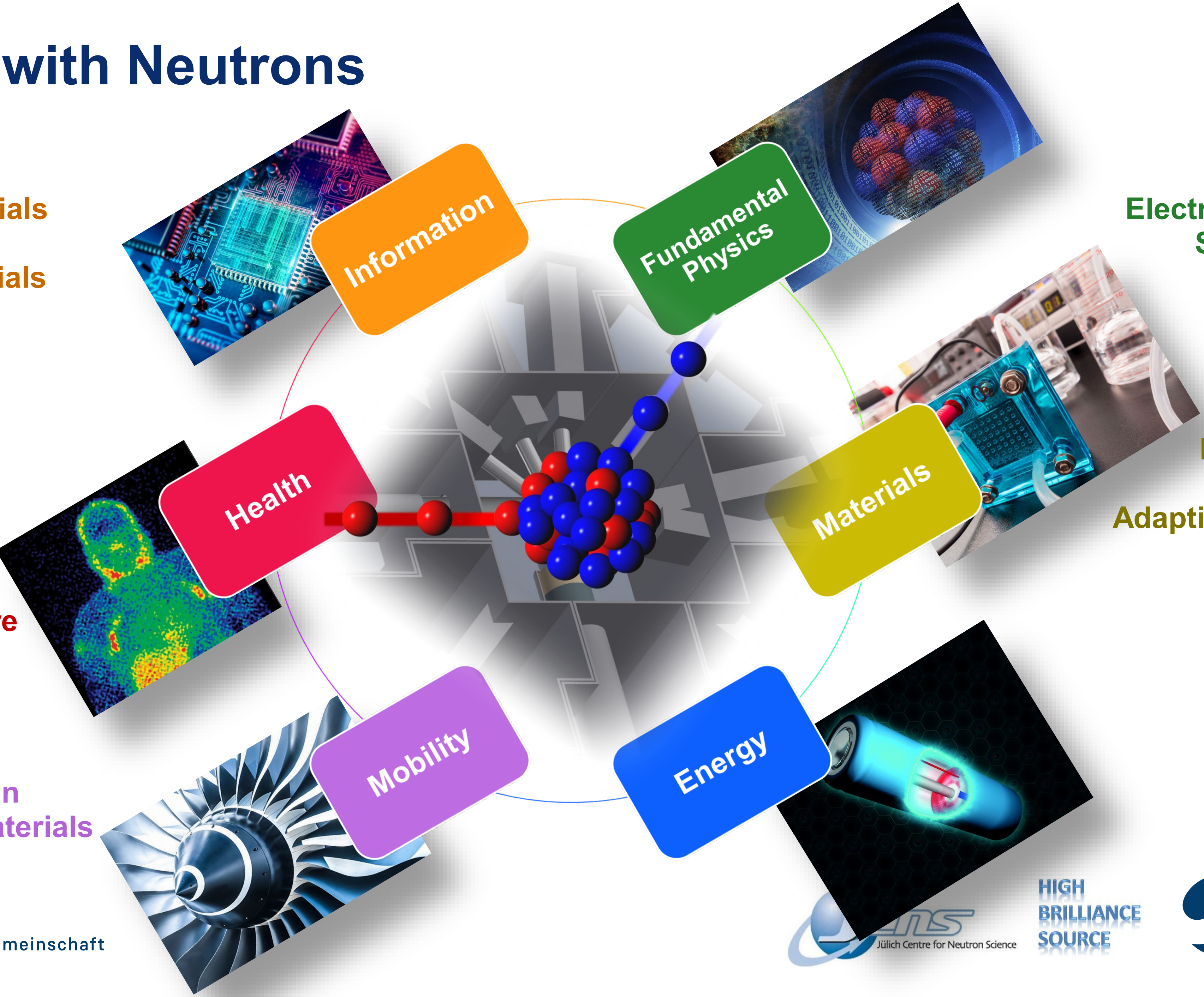
Thomas Gutberlet, JCNS

Science with Neutrons

Quantum materials
Spintronics
Magnetic materials

Radio isotopes
BNCT
Drug delivery
Protein structure

Stress and strain
Light weight materials
Ceramics
Corrosion



Electric dipole moment
Superconductivity

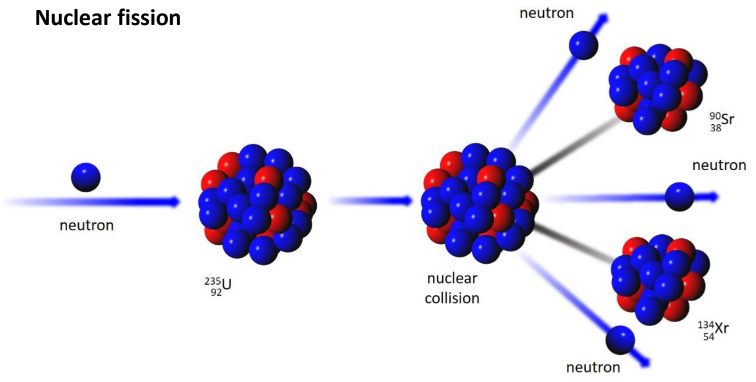
Fuel cells
Hydrogen storage
Green polymers
Adaptive manufacturing

Batteries
Green hydrogen
Photovoltaics

Neutron Landscape – the global view

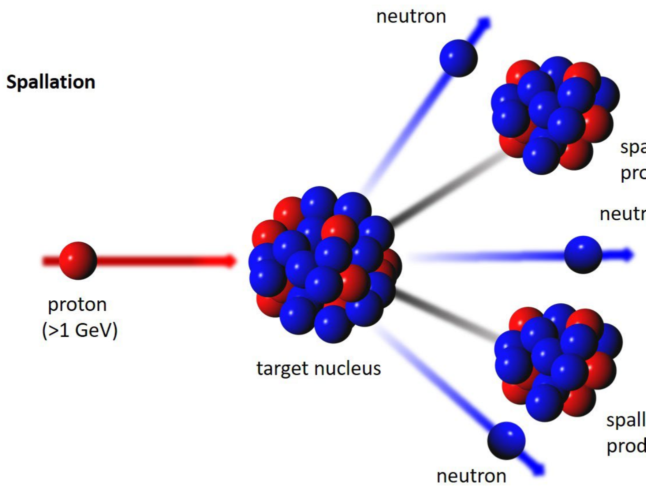
How to get neutrons

Nuclear fission



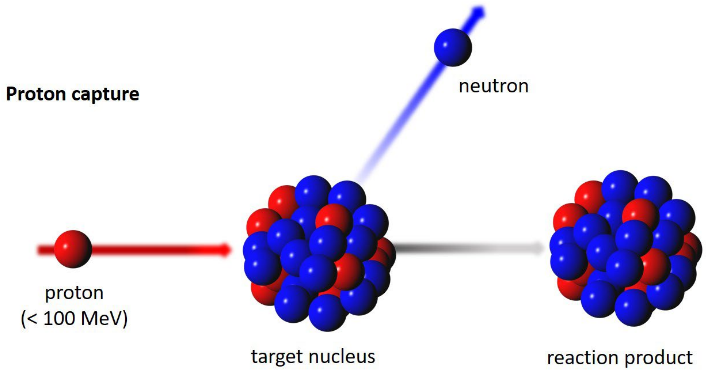
Reactor based
neutron source
(ILL, FRM II, NIST, JINR, ANSTO a.m.m.)

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.)

How to get neutrons

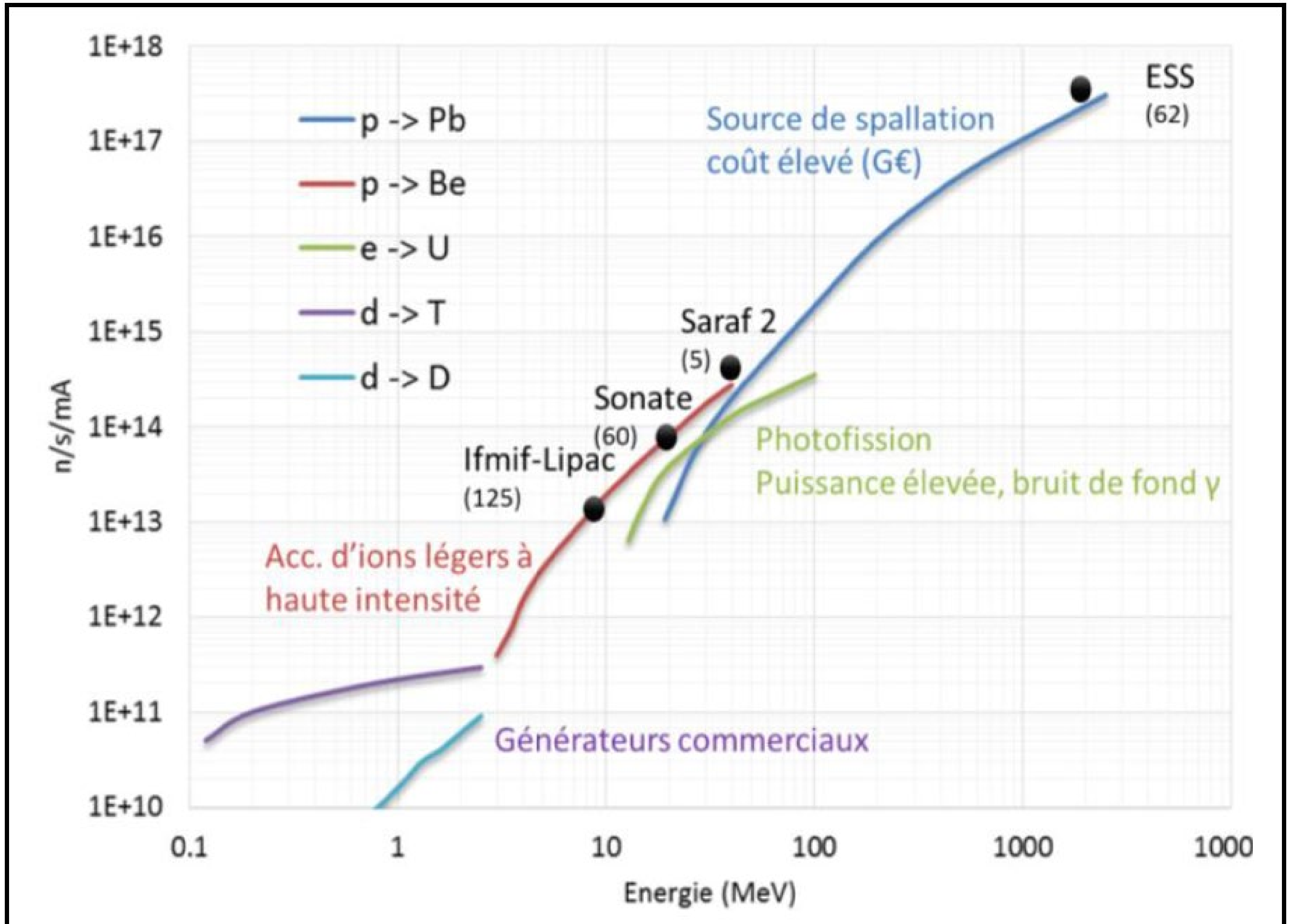
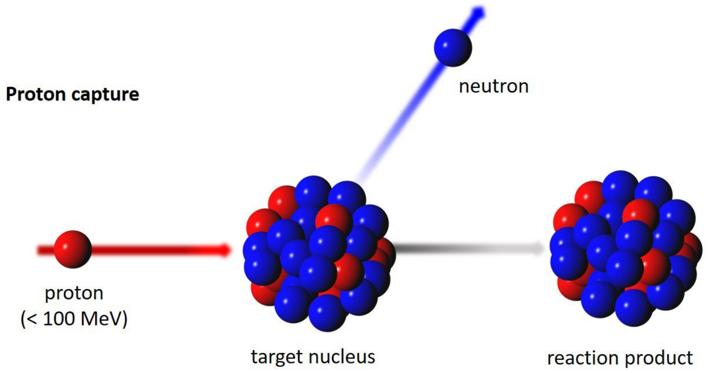


Figure 1: Neutron production using particle accelerators

Courtesy: A. Menelle, LLB

Ref.: LLB – Compact Neutron Sources for Neutron Scattering

Nuclear processes



Accelerator based neutron source

(LENS, RANS, HUNS, NUANS, IREN a.o.)

Accelerator Based Neutron Sources

From CANS* to HiCANS**

(***C**ompact **A**ccelerator based **N**eutron **S**ource , ** **Hi**gh-**C**urrent **A**ccelerator based **N**eutron **S**ource)

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

Running CANS facilities:

- LENS, Indiana University (USA)
- HUNS, Hokaido University (Japan)
- RANS, RIKEN (Japan)
- NUANS, Nagoya University (Japan)
- CPHS, Tsinghua University (China)
- IREN, JINR Dubna (Russia)

HiCANS projects:

- **HBS, JCNS (Germany)**
- SONATE, CEA LLB (France)
- ARGITU, ESS Bilbao (Spain)
- LENOS, INFN LNL (Italy)
- SARAF, SOREQ (Israel)

ELENA
European Low Energy accelerator-based Neutron facilities Association

https://elena-neutron.iff.kfa-juelich.de/

Accelerator Based Neutron Sources

From CANS* to HiCANS**

Advantages / drawbacks of HiCANS

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

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

100 kW
50-100 mA
~10^{15} n/s

400 Mio EUR

rojects:

Germany)

A LLB (France)

Bilbao (Spain)

N LNL (Italy)

EQ (Israel)

IREN, JINR Dubna (Russia)

CANS and HiCANS projects world-wide

Europe

Germany	JCNS HBS
France	LLB Icone
Italy	LNL Legnaro
Spain	ESS Bilbao
Hungary	Mirrotron
Sweden	U Uppsala
Israel	SOREQ

North & South America

Canada	U Windsor
USA	ORNL
Argentina	CNAE Bariloche

Asia

Japan	RIKEN
	U Nagoya
	U Kyoto
	AIST
	U Hokaido
Korea	KAERI
Taiwan	INER
China	CIAE
	U Xi'an Jiatong
	U Tsinghua
	U Peking
	INEST CAS

HBS project: A HiCANS facility

Project rationale

- Accelerator driven pulsed neutron source (-> HiCANS)
- Optimized for neutron scattering on small samples
- National medium flux neutron facility
- Reasonable investment and operational costs

HBS project: A HiCANS facility

Project rationale

High current linear accelerator

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

Several target stations

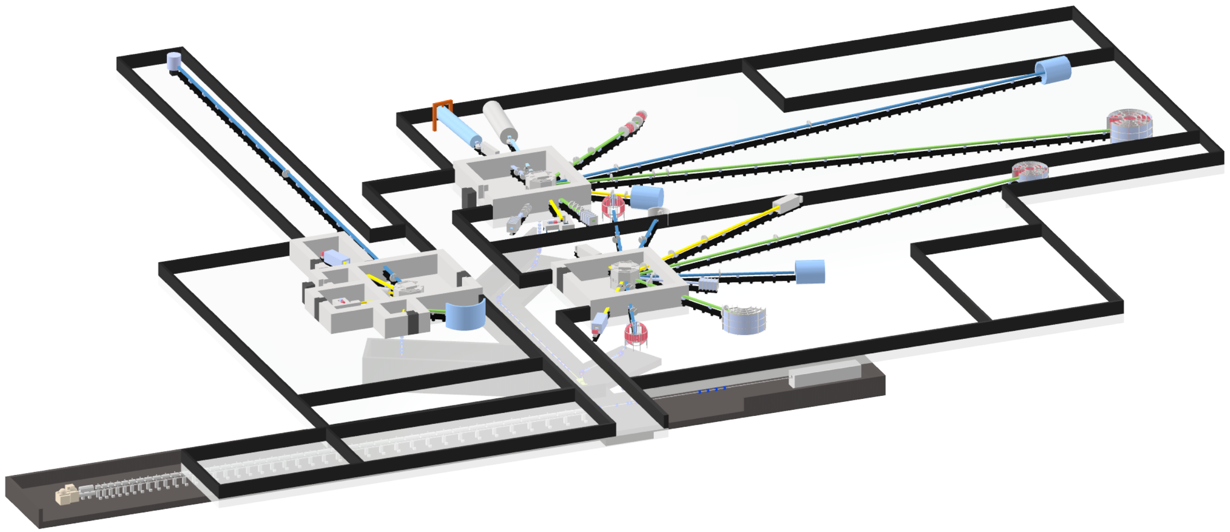
- Optimize pulse structure (length, rep. rate)
- Optimize thermal spectrum

Every beam port serves only 1 Instrument

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

Small shielding

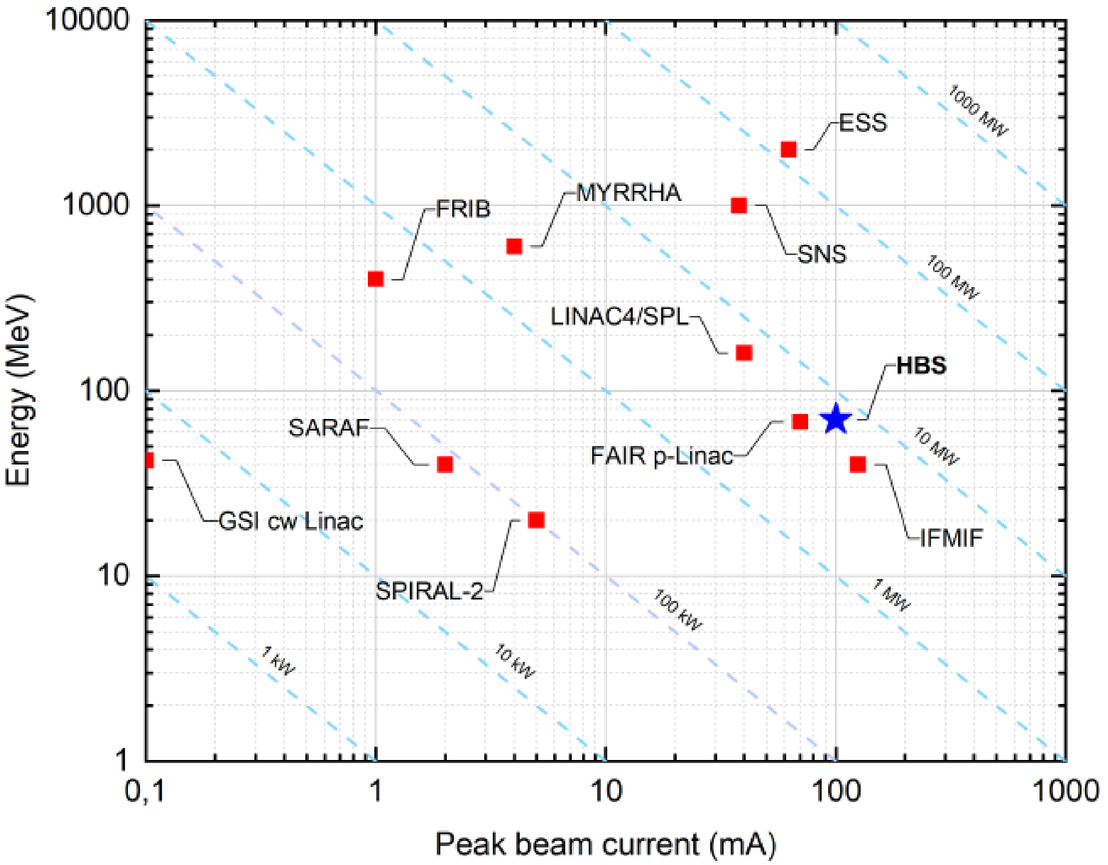
- Neutron guide around cold source
- Chopper at <2 m from target

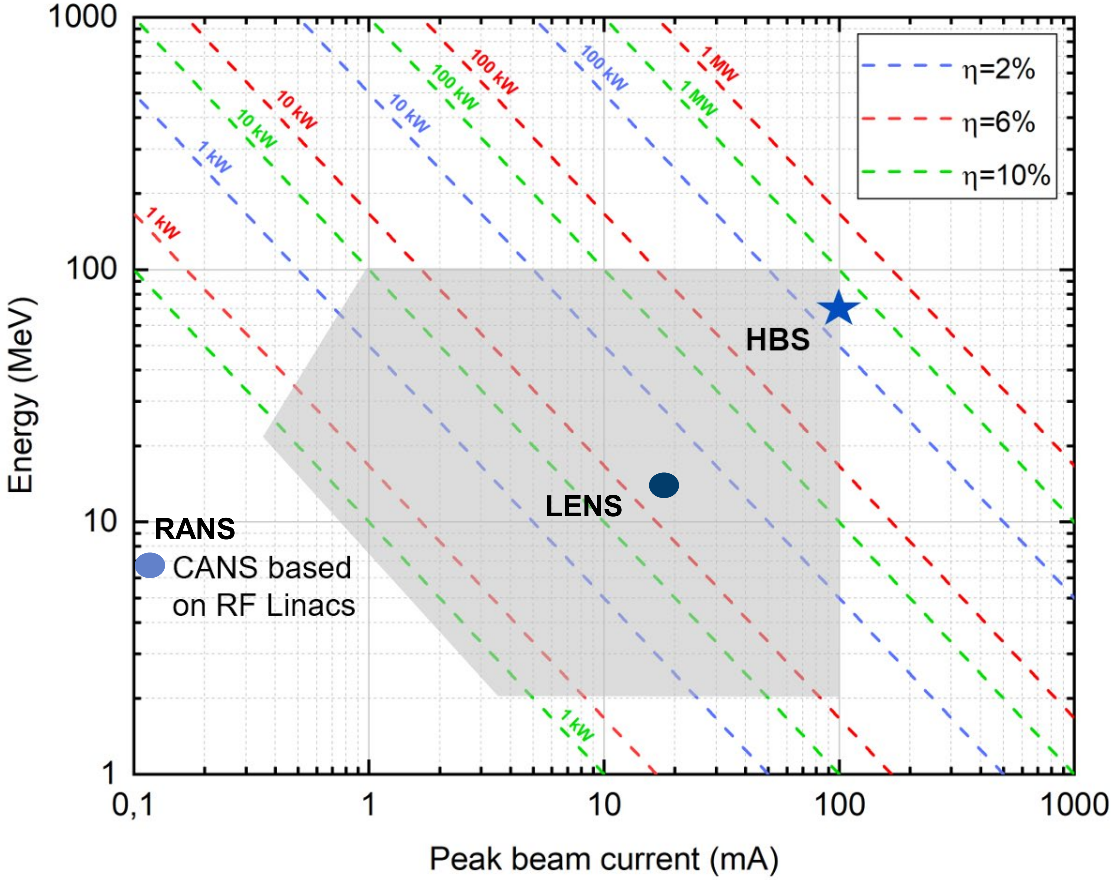


www.fz-juelich.de/jcns/jcns-2/EN/Forschung/High-Brilliance-Neutron-Source/_node.html

HBS Accelerator

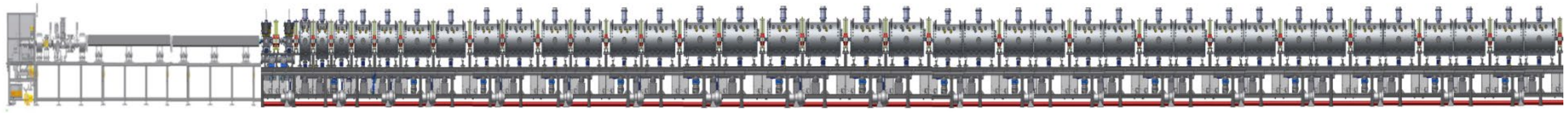
Peak beam power and average beam power levels of proton linacs



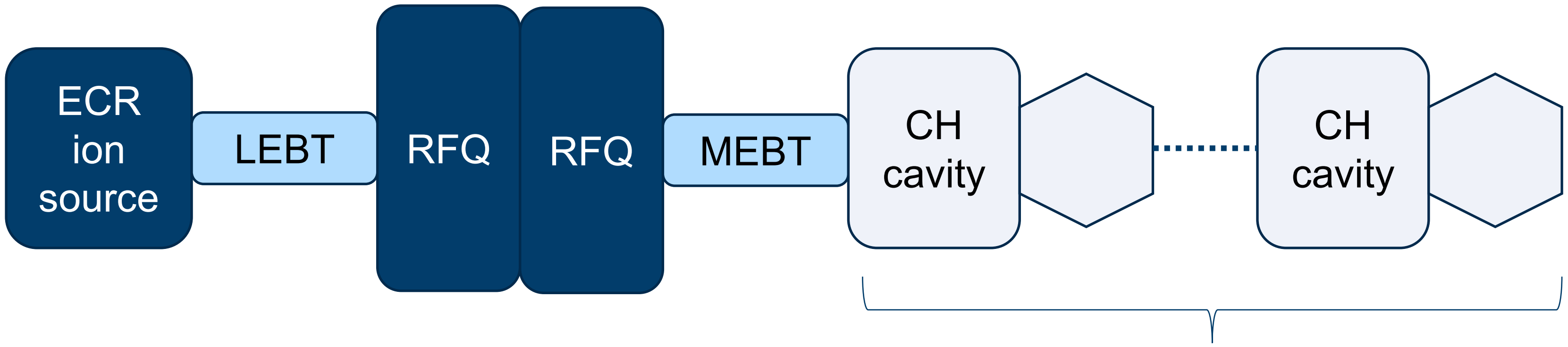


HBS Accelerator

Concept



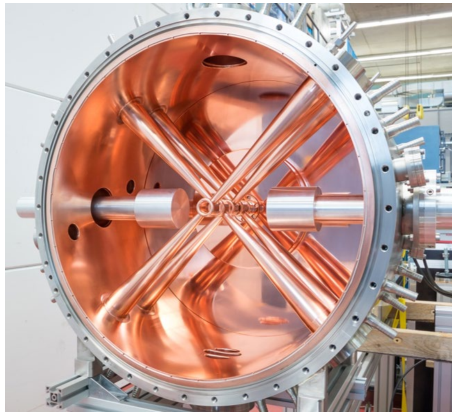
100 mA, 70 MeV pulsed proton linac, ~75 m

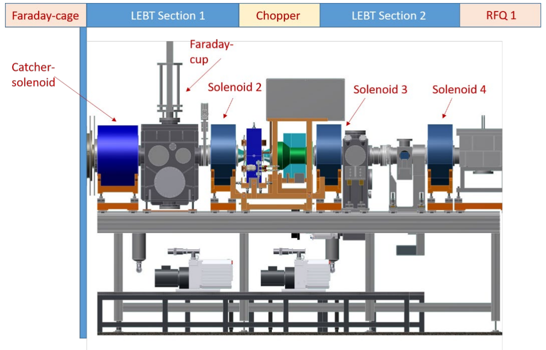


>100 mA
proton source

175 MHz
(2-4 m, 1.2 -> 2.5 MeV)

normal conducting CH cavities and quadrupole dublets
(~2.5 m, 2.5 -> 70 MeV each
4.8 % dc, 96/96/24 Hz)





HBS Accelerator
Room Temperature Solution

- Much simpler technology
- Easy access to all components
- No cryo-plant: less cost
- No cryo-modules: less operation cost
- Beam losses less severe (quenches): more reliable...
- Easier beam dynamics
  (no additional drifts due to cold-warm-transitions)
- Already available technology

Peak beam power: 7 MW

Peak RF power: ≈12 MW

A room temperature linac is the most
reasonable and safe solution

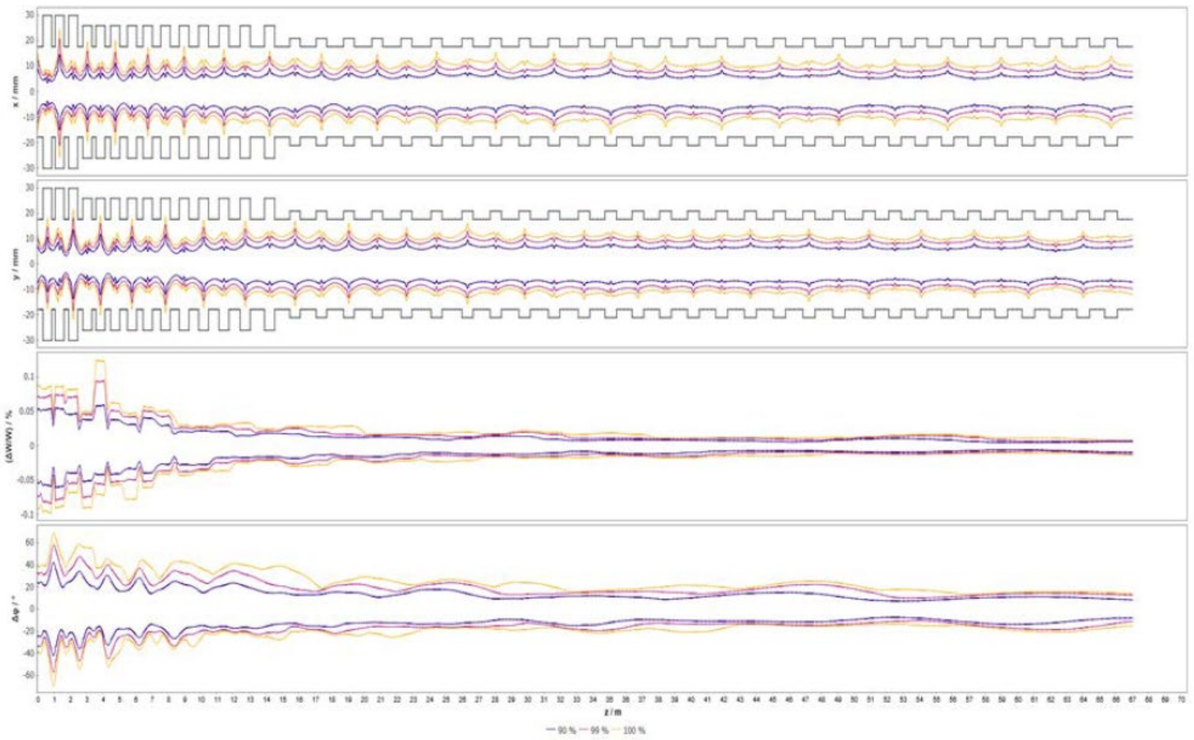
HBS Accelerator

Room Temperature Solution

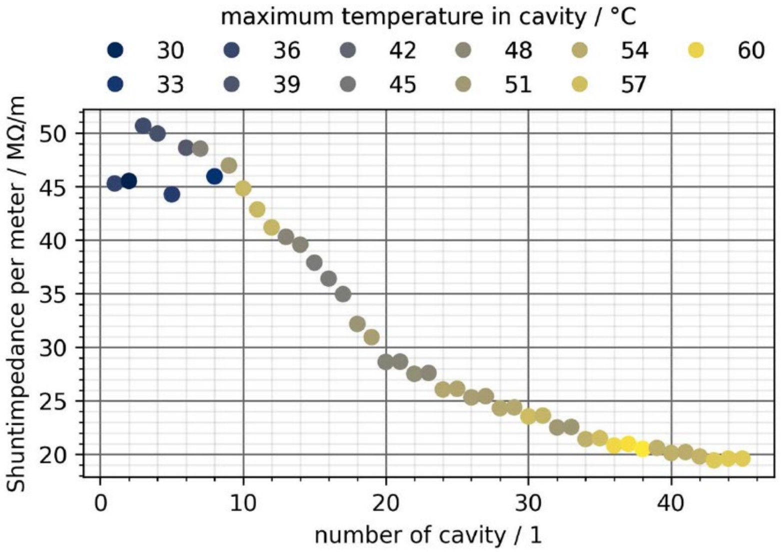
The design of the HBS Linac provides maximum flexibility:

- (Almost) every pulse scheme
- Variable beam energy
- Duty factor 0-25%

DTL Beam Dynamics

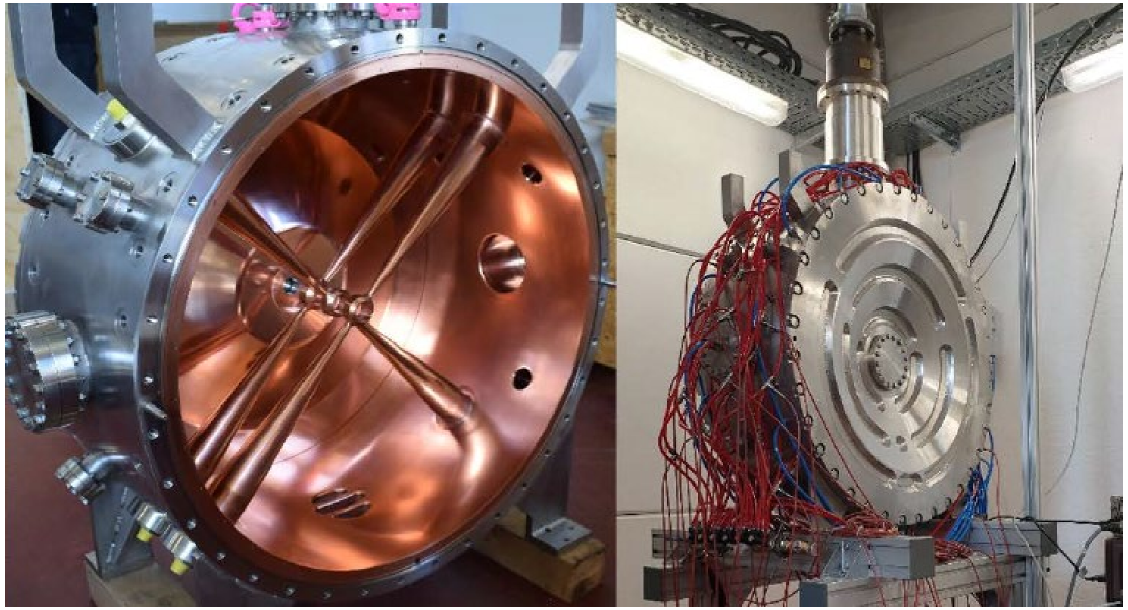


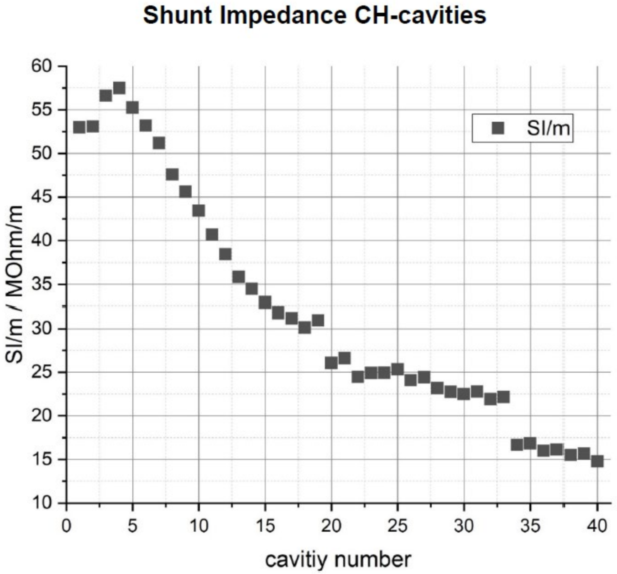
CH-DTL



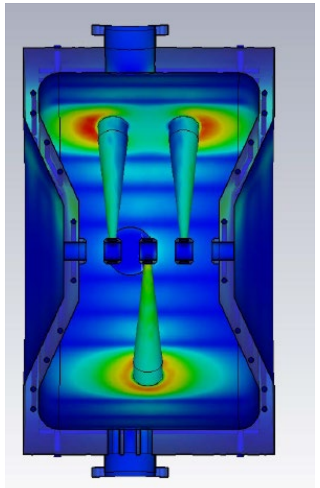
HBS Accelerator

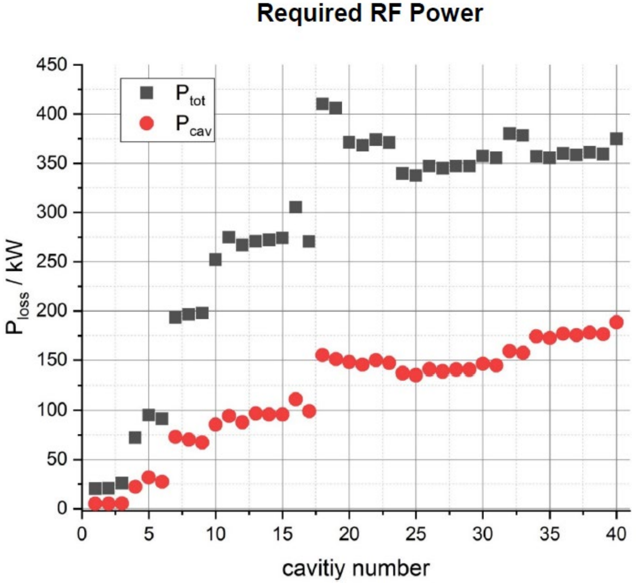
CH-Cavities





- CH-1 MYRRHA design
- Tests with up to 40 kW/m cw were successfully performed
- First thermal simulations

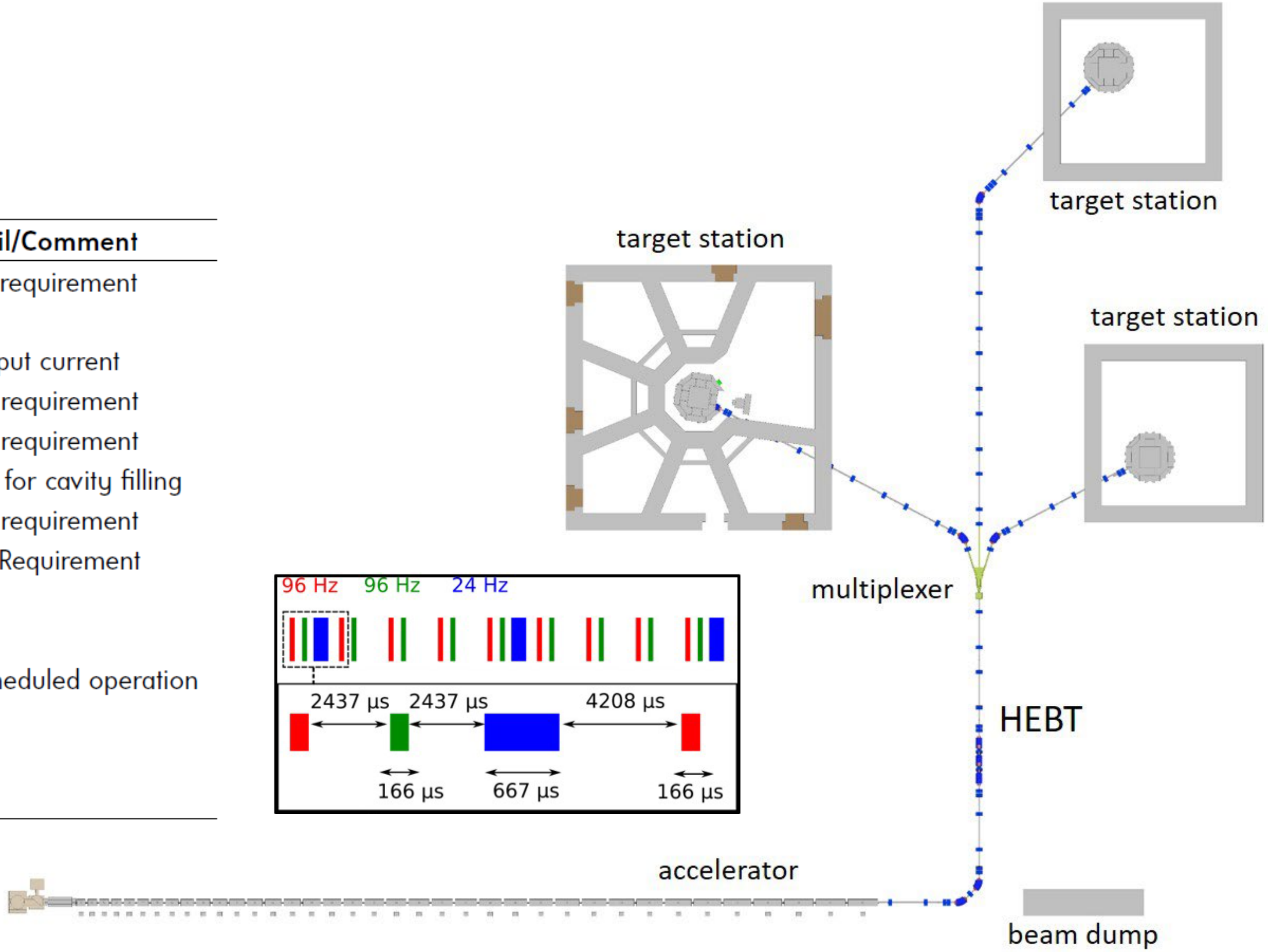




HBS Multiplexer

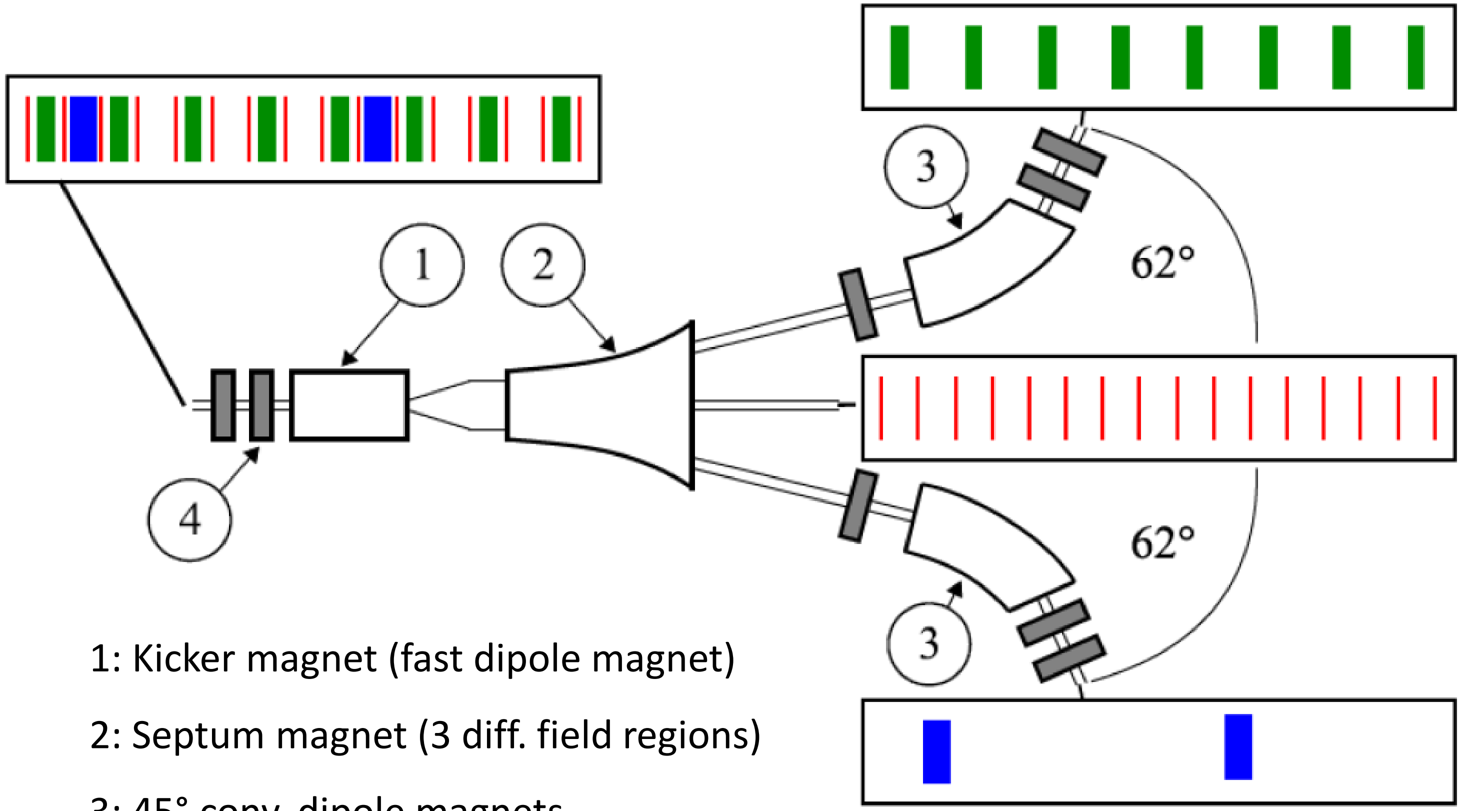
Distributing the protons

Required	Specifications	Unit	Detail/Comment
Particle type	protons	N/A	user requirement
Accelerator type	RF Linac	N/A	
Beam current	100	mA	output current
Final energy	70	MeV	User requirement
Beam duty factor	4.8	%	User requirement
RF duty factor	10	%	Required for cavity filling
Pulse length	167/667	μs	User requirement
Repetition rate	96/96/24	Hz	User Requirement
Average beam power	336	kW	
Peak beam power	7	MW	
Availability	>95	%	During scheduled operation
Maintainability	hands-on	N/A	
Life time	>25	years	
Total Linac length	<100	m	



HBS Multiplexer

Concept



1: Kicker magnet (fast dipole magnet)

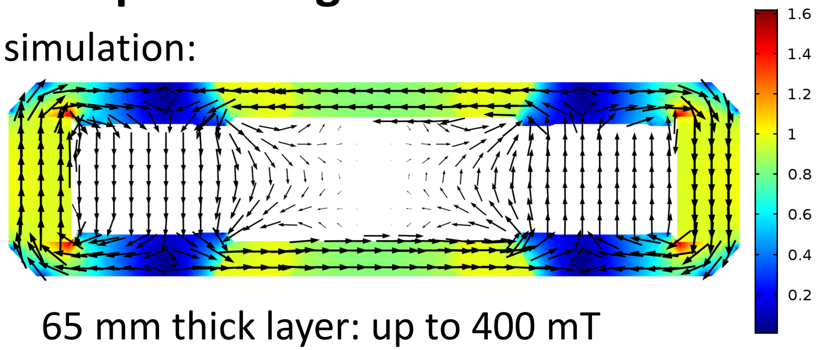
2: Septum magnet (3 diff. field regions)

3: 45° conv. dipole magnets

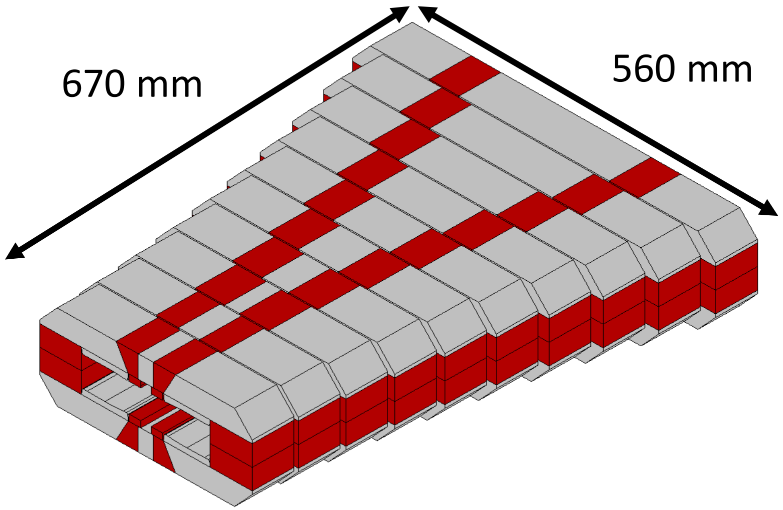
4: conv. Quadrupole magnets (in grey)

Septum magnet

simulation:



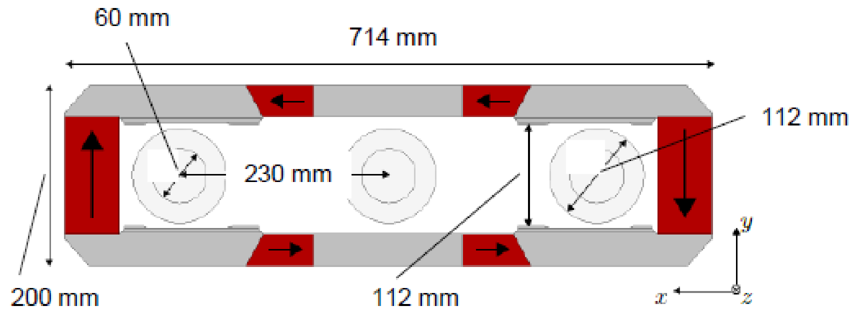
65 mm thick layer: up to 400 mT

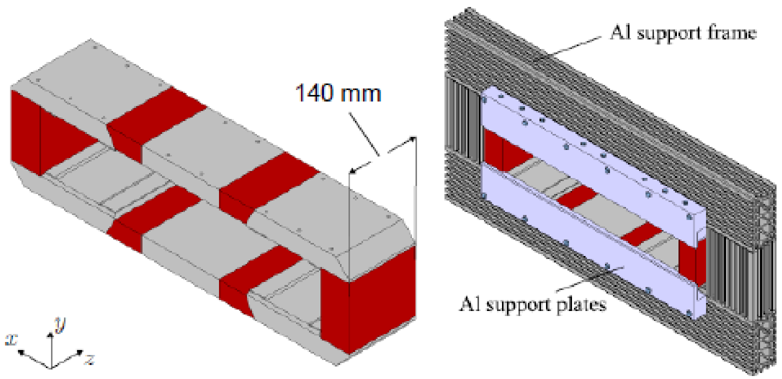


Rimmler et al., EPJ Web of Conf. 231, 02002 (2020)

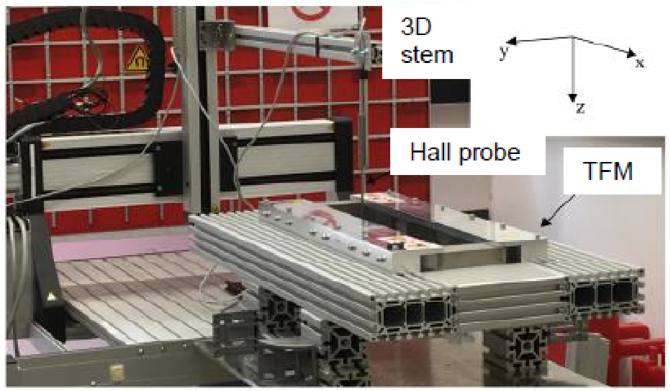
HBS Multiplexer

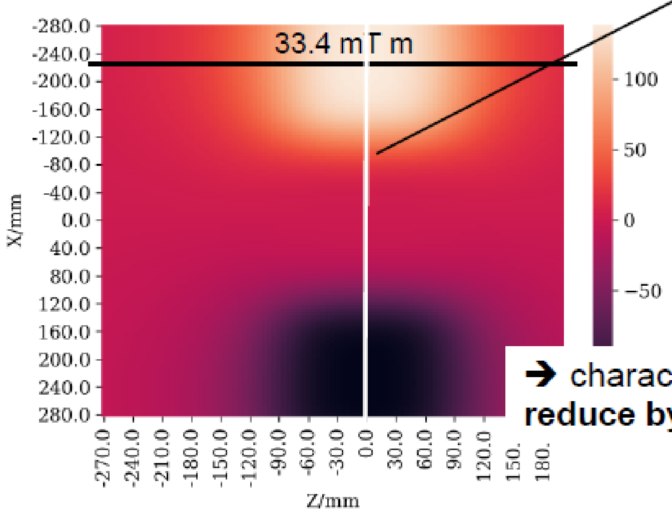
Proof of concept – Three-Field Magnet (TFM)

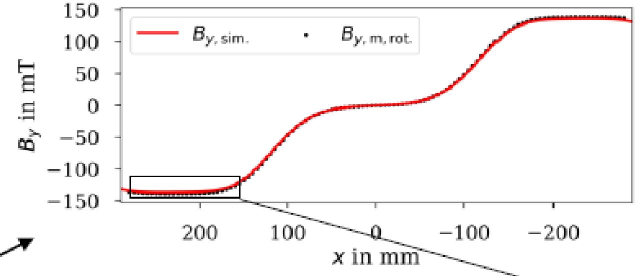


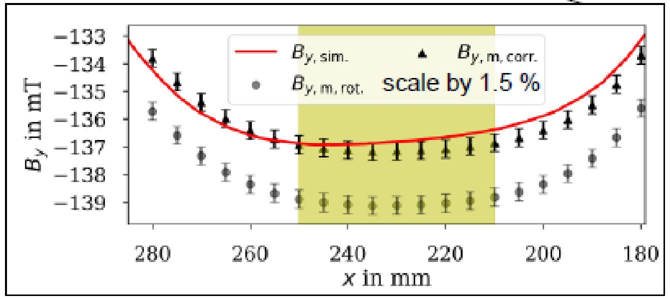


- designed to supply 32.9 mT m
- 26.3 mT m required geometrically
- account for varying remanent field in SmCo
  ➔ 25 % safety margin





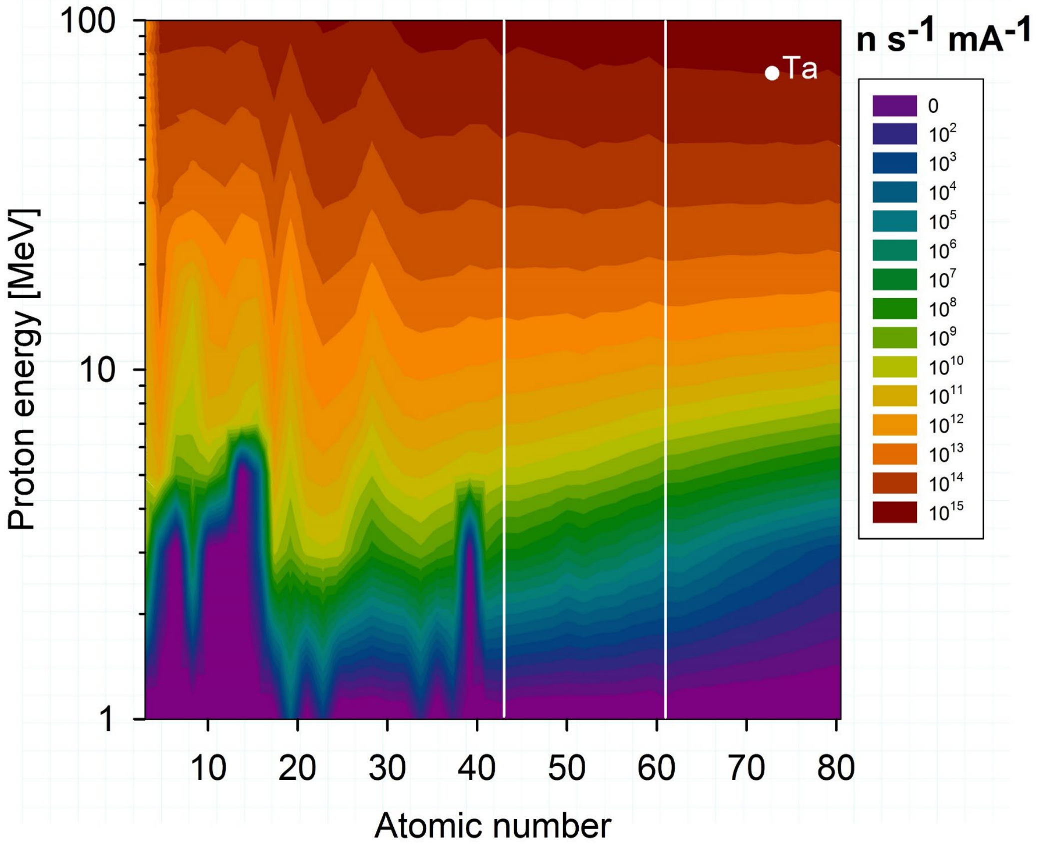


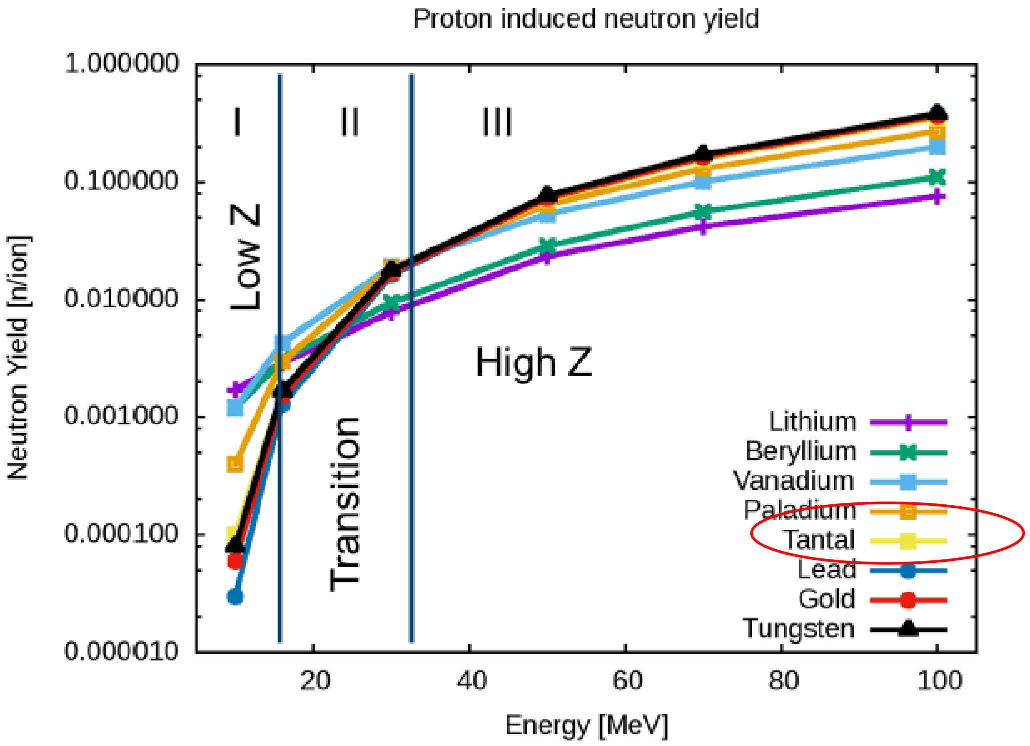


➔ characteristics reproducable, measure 33.4 mT m **reduce by 7.1 mT m**

HBS Target

Target material





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

HBS Target

Target for 100 kW HBS pulsed proton beam

High Z materials

- High neutron yield at increased ion energies
- Low range of neutrons

Refractory Metals

- Good general thermo-mechanical properties at high temperatures
- Good corrosion resistance
- Nb, Mo, Ta, W, Re

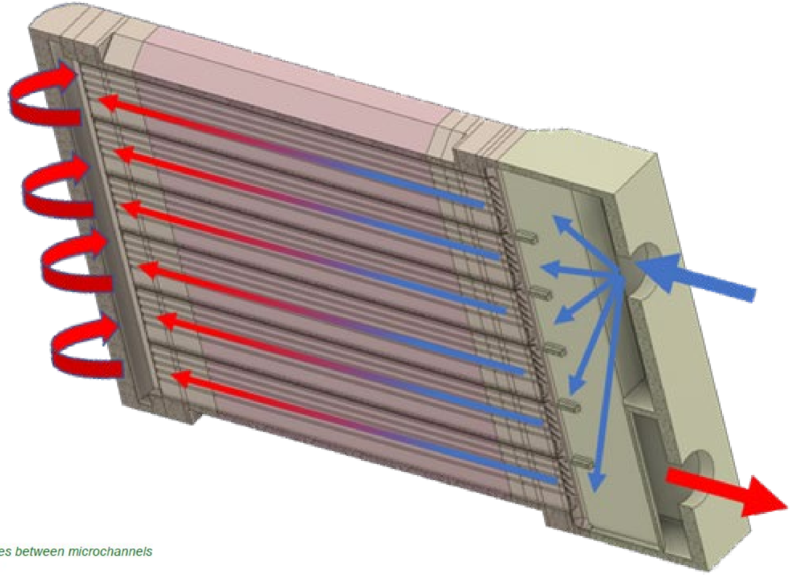
Tantalum

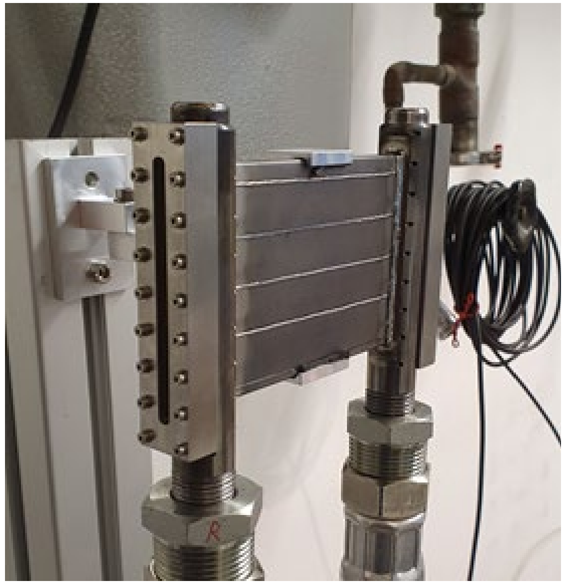
- High blistering threshold
- Ductile material
- Structural material
- Good workability

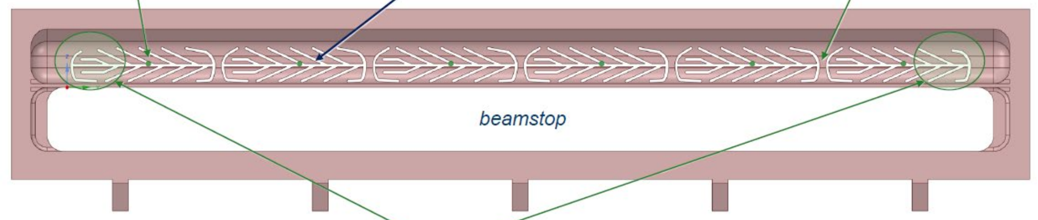
HBS Target

Design

- Material: Tantalum
- Required: high blistering threshold
- **Wanted: high power density**
- **Goal: 100 kW at 100 cm² (1kW/cm²)**
- Coolant: Water (8 m/s inside channels)
- Reliable



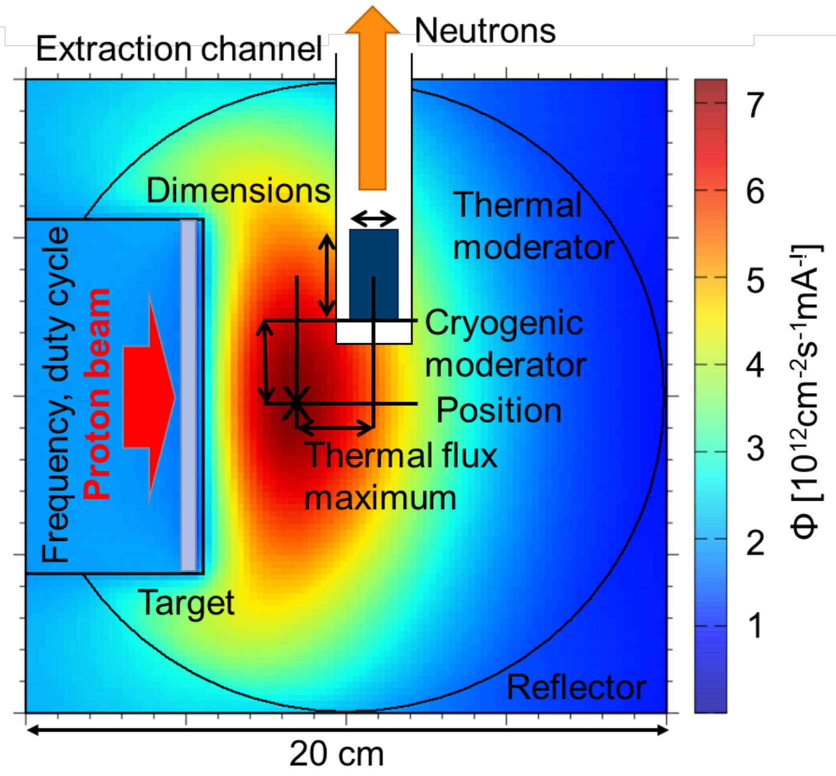




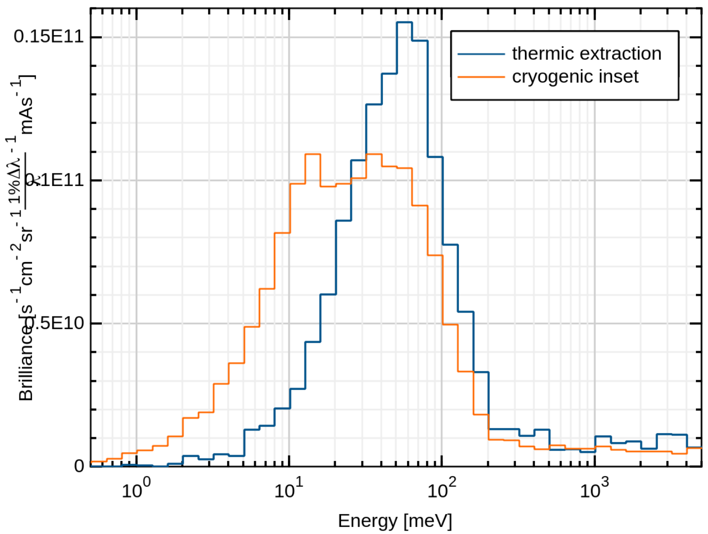
Succesful test at JUDITH-2 electron gun with up to 1 kW/cm² heat input on the surface

HBS Moderator

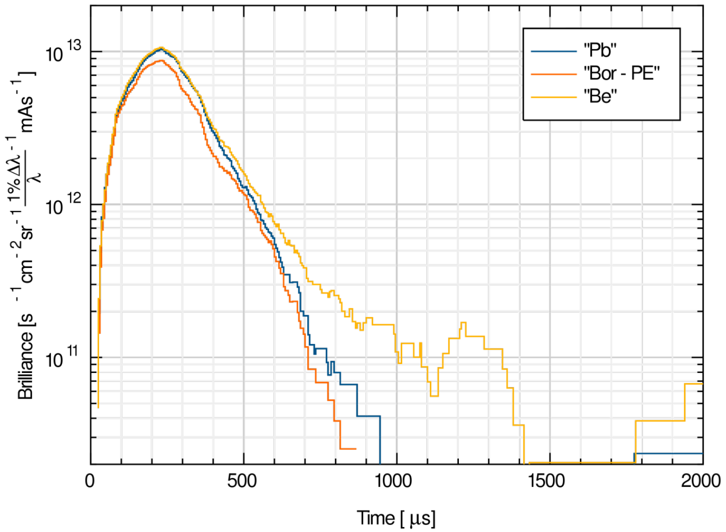
Neutron moderation

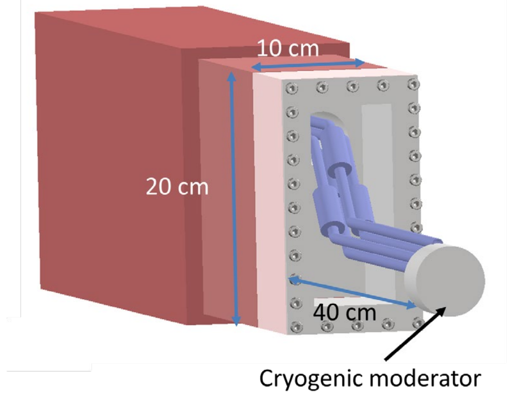


Thermal/cold neutron spectrum

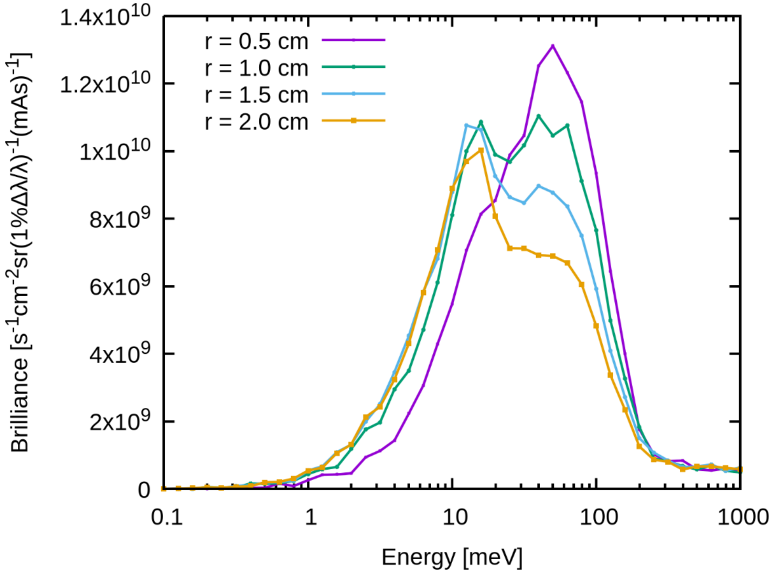


Neutron emission of PE/reflector materials





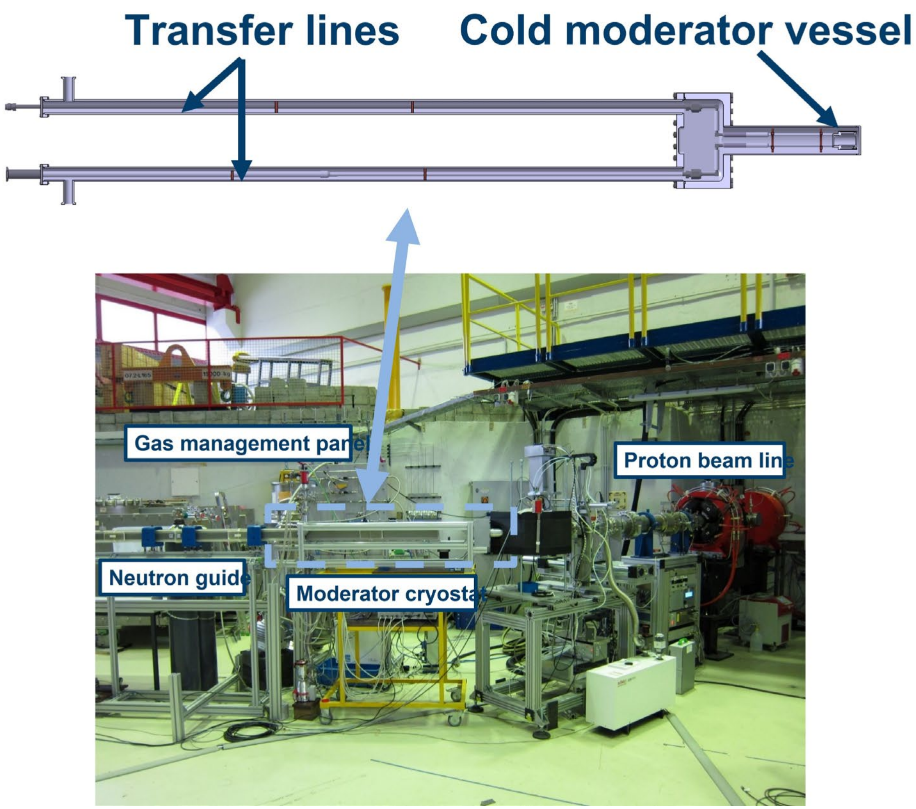
Cold moderator dimensions

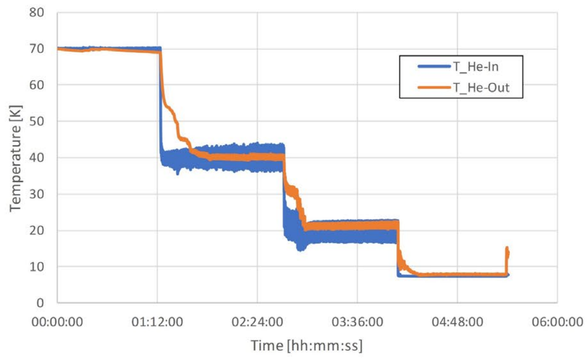


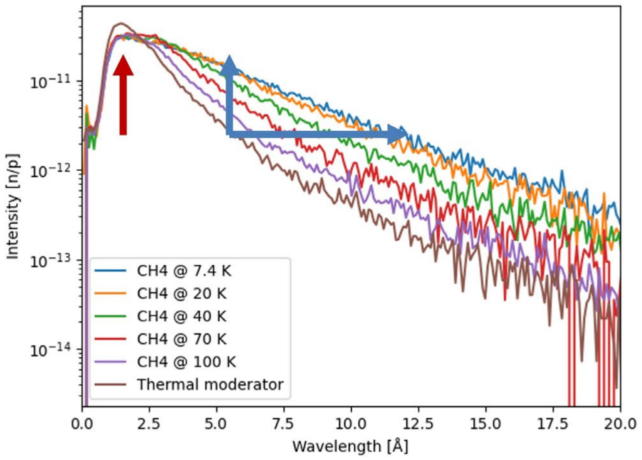
HBS Moderator

Solid methane system

- Liquefaction and freezing of methane (CH_4) by LHe cooling
- Measurements with **liquid CH_4** @ 100 K and **solid CH_4** @ 70 K, 40 K, 20 K and 7.4 K
- Clear shift to longer wavelengths and higher intensities for $T_{Mod}\downarrow$
- Thermal peak still visible for lower temperatures (bispectral) → moderator too small



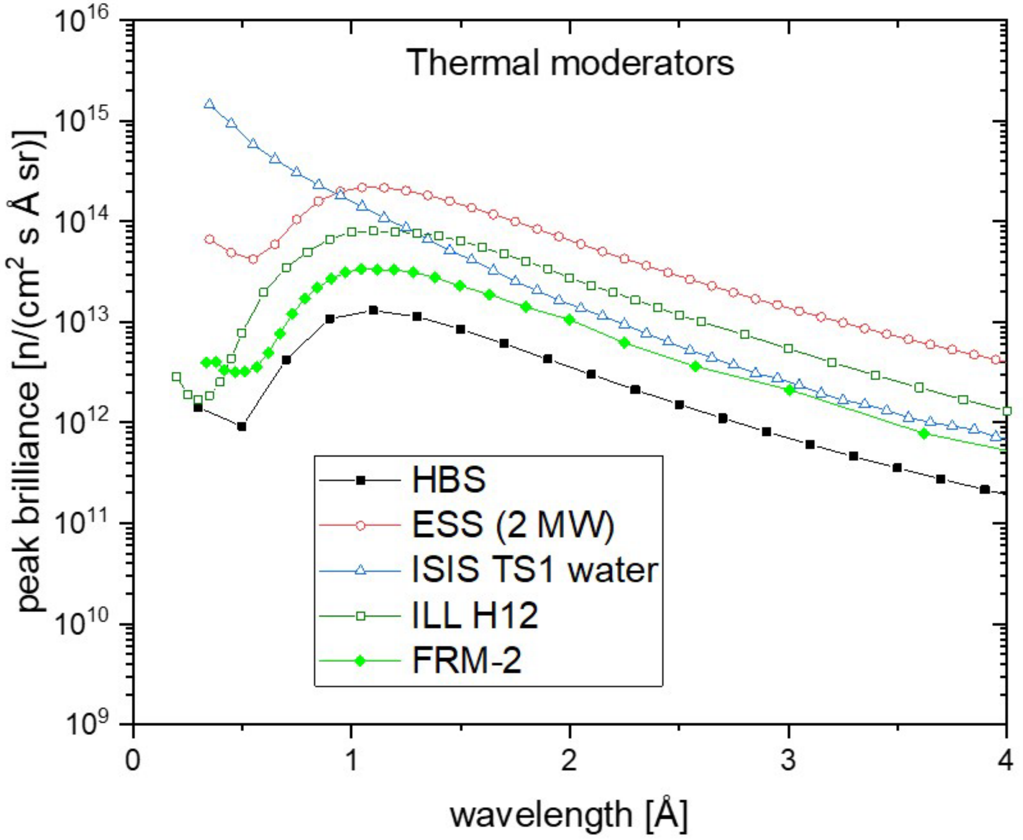


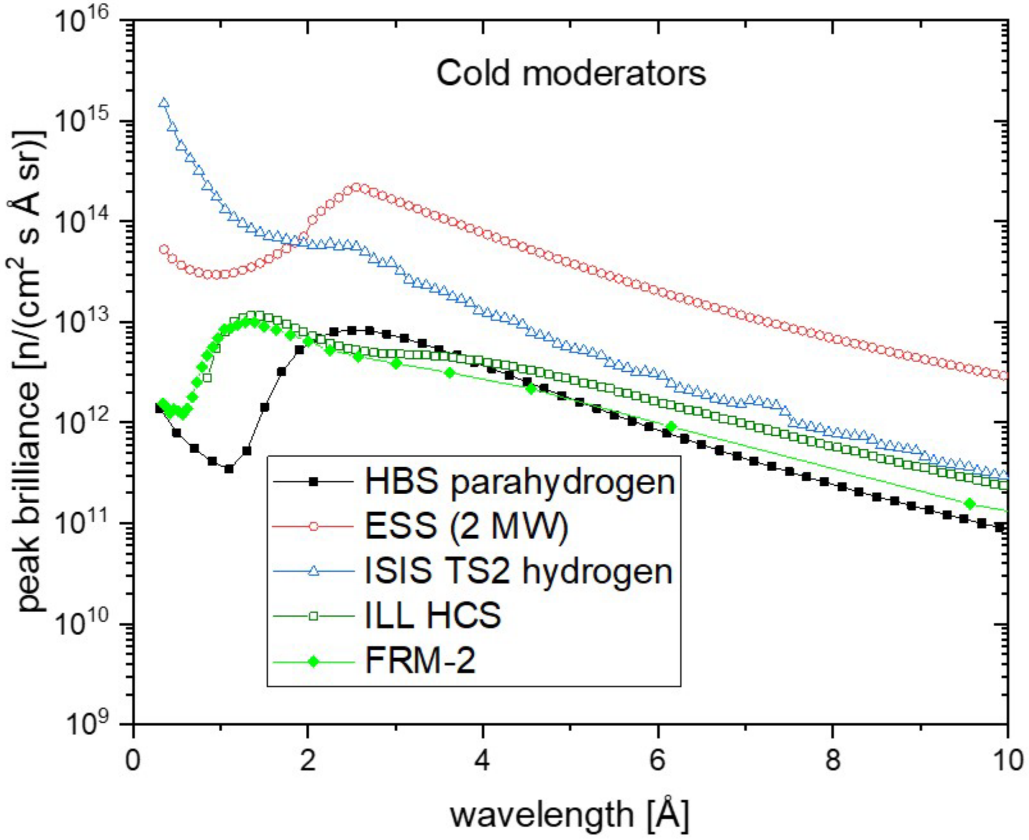


JCNS Jülich Centre for Neutron Science
HIGH BRILLIANCE SOURCE
JÜLICH Forschungszentrum

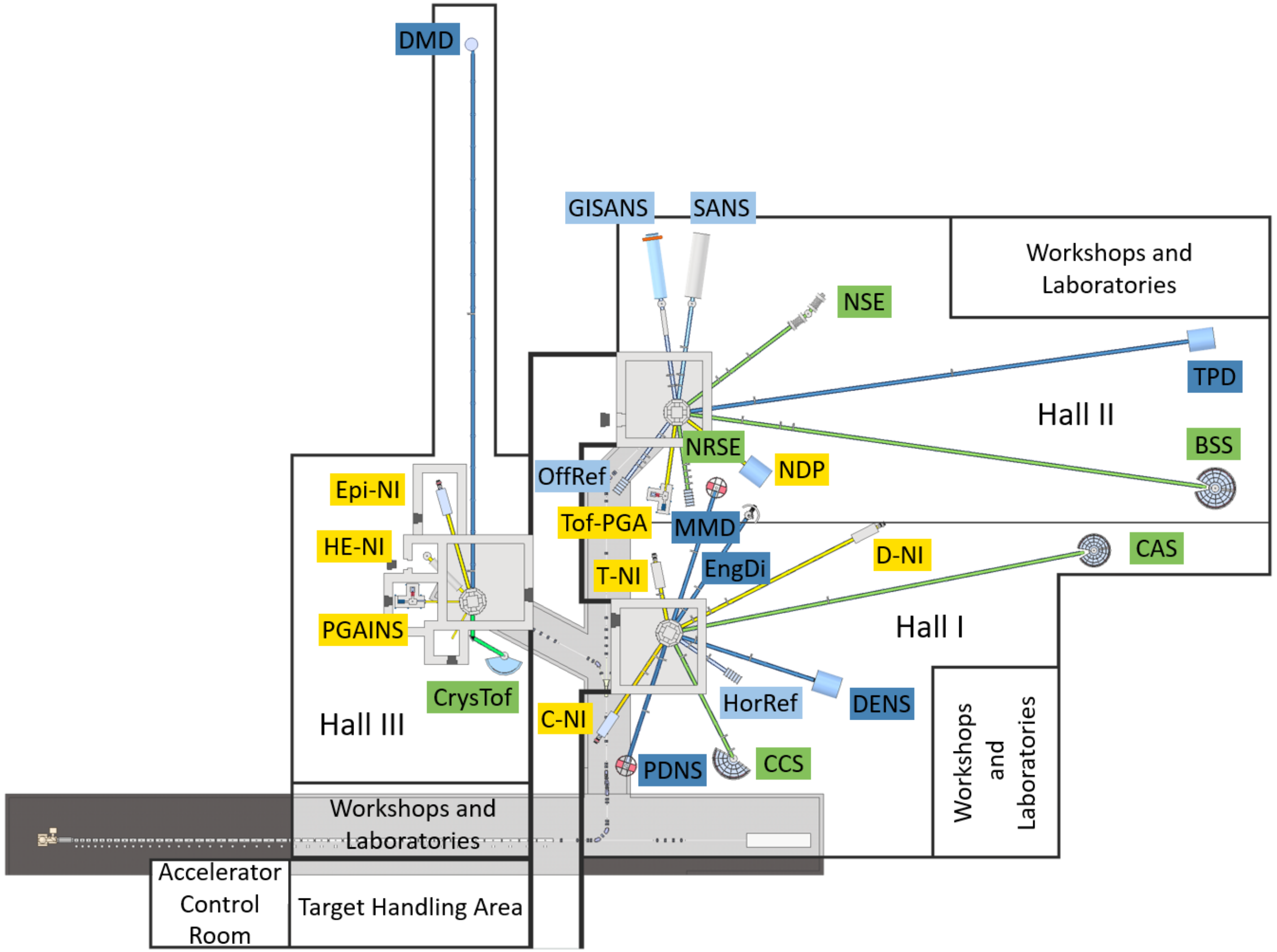
HBS Instrumentation

Peak brilliance at the 24 Hz HBS target station





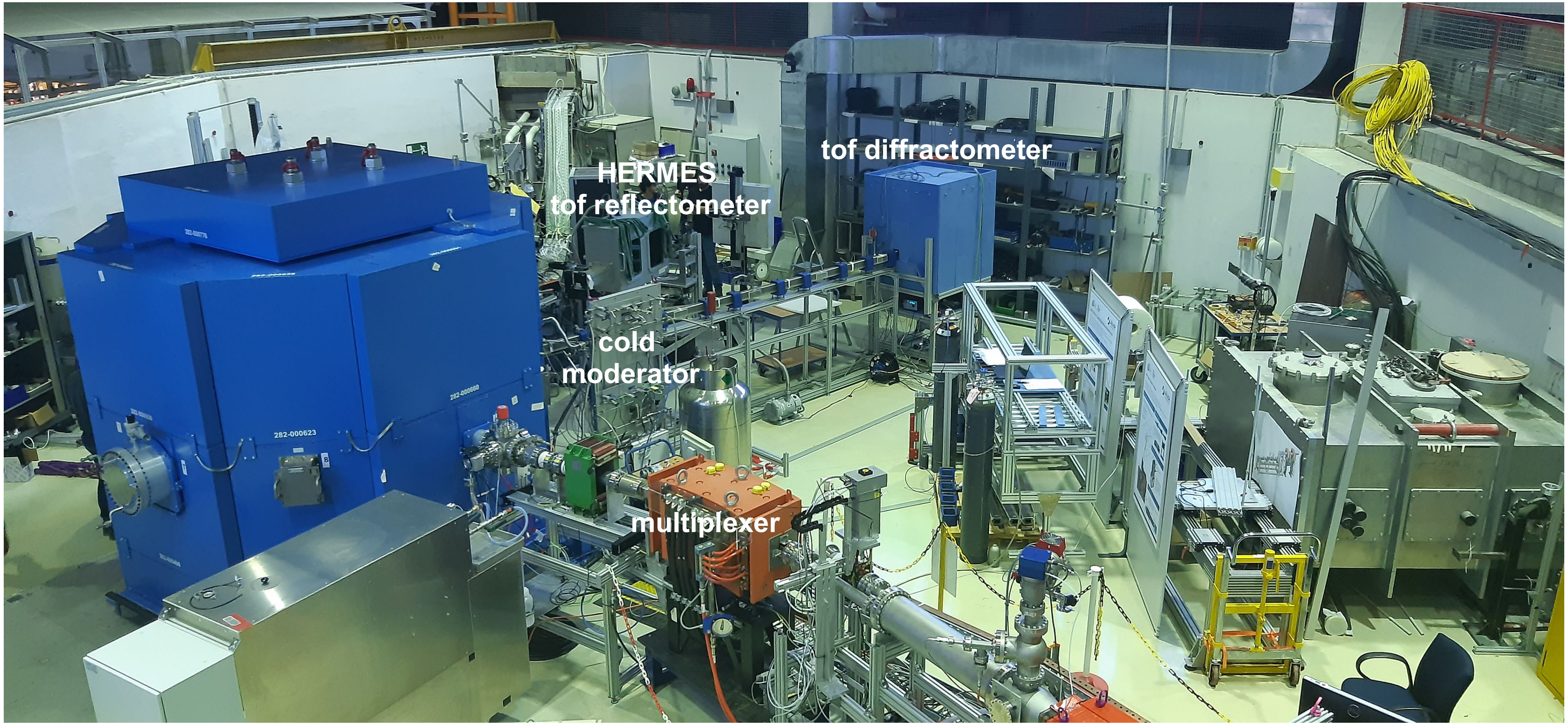
HBS Instrumentation



	Instrument	τ_{pulse} [μs]	L_{tot} [m]	Det. Cov. [Sr.]	λ_{min} [Å]	λ_{max} [Å]	$\frac{\delta\lambda_{pulse}}{\lambda_{min}}$ [%]	$\frac{\delta\lambda_{pulse}}{\lambda_{max}}$ [%]	$\phi_{average}$ 10^6[n/cm^{2}s]	Remarks
24.1	High Throughput SANS	667	24	0.01	2.0	8.7	5.5	1.3	2.2	Low angle
			15	0.7	2.0	8.7	8.8	2.0	220	Wide angle
24.2	SANS + GISANS	667	24	0.01	3.0	9.8	3.7	1.1	2.2	Low angle
			15	0.7	3.0	9.8	5.9	1.8	220	Wide angle
24.3	SANS + VSANS	667	23	0.01	2.0	9.0	5.7	1.3	2.7	Low angle
			15	0.7	2.0	9.0	8.8	2.0	220	Wide angle
24.4	Offspecular Reflectometer	667	13	0.08	2.0	12.5	10.1	1.6	1.1	
24.5	Therm. Powder Diffr.	29	80	6.25	0.6	2.7	0.2	0.1	0.7	High Res., 2 frames
		667	80	6.25	0.6	2.7	5.5	1.2	120	High Int., 2 frames
24.6	NSE	667	35	0.04	5	16	1.3	0.5		Very cold neutrons
24.7	NRSE	667	14	0.04	5	16	3.8	1.2		Very cold neutrons
24.8	Backscattering Spectrometer	70	85	2.5	5.8	7.8	0.06	0.04	8	
24.9	PGNAA-1	667	12.4		0.03	9			220	
24.10	NDP	667	15		2	15			44000	
96.1	Hor. Reflectometer	252	11	0.01	5	8.64	1.8	1.0	87	Small sample
		252	11	0.01	1.6	5.25	5.7	1.7	14	Multi Beam
96.2	Engineering Diffr.	35	21.8	3.0	0.8	2.68	0.8	0.2	0.5	
96.3	Diffuse scatt. Spectr.	252	21.5	2.39	2	3.9	2.3	1.2	96	
96.4	Pol. Diffuse Neutron Spectr.	252	21.5	2.04	2	3.9	2.3	1.2	21	
96.5	Small sample Diffr.	252	20.4	9	2	4	2.4	1.2	49	
96.6	Cold Chopper Spectr.	252	18.5	3.14	2	10	1.5	0.7	0.9	
96.7	Thermal Chopper Spectr.	252	60	3.14	0.9	3.5	2	0.5	0.1	5 frames
96.8	CRYSTOF	252	10.5	3.14	0.9	3.5	3	1.5	0.4	
96.9	Indirect Geom. Spectr.	252	60	1.7	3	3.7	0.6	0.4	120	
96.10	Cold imaging	252	15		1	15	6.6	0.4	1.6	High Res.
		252	5		1	15	19.9	1.3	12	High Int.
96.11	Thermal imaging	252	10		0.5	4.5	20	2.2	7.8	High Res.
		252	4		0.5	4.5	50	5.5	49	High Int.
96.12	Diffr. Imaging	252	35		1	15	2.8	0.2	8	
Epi.1	Dis. Mat. Diffr.	167	85	4.5	0.1	0.6	7.8	1.3		
Epi.2	PGNAA-2	167	21						4.4	
Epi.3	Epitherm. Imaging	167	35	0	1.8					

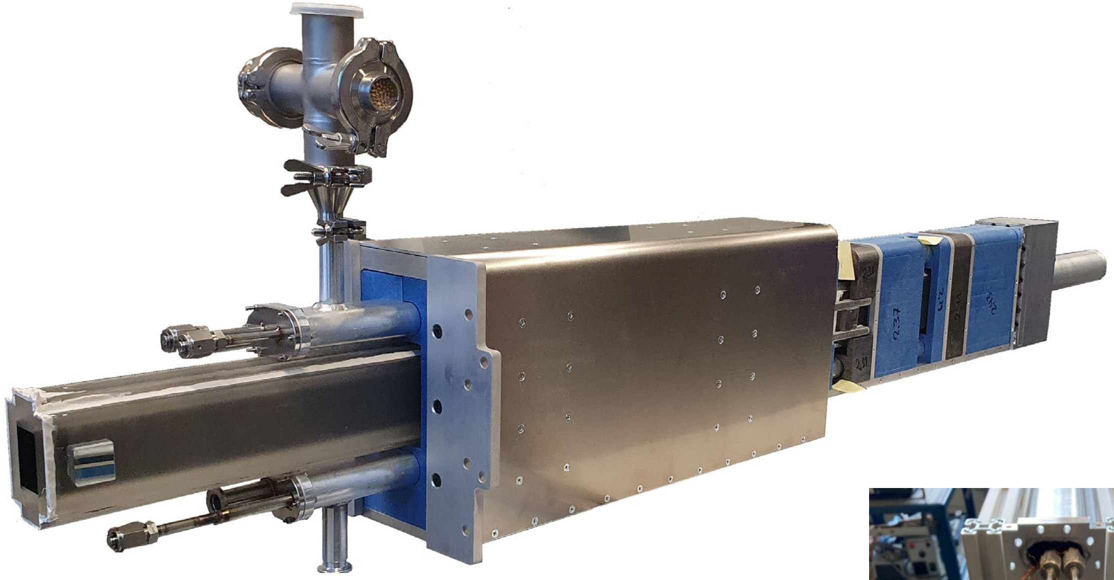
HBS Target-Moderator-Reflector Unit

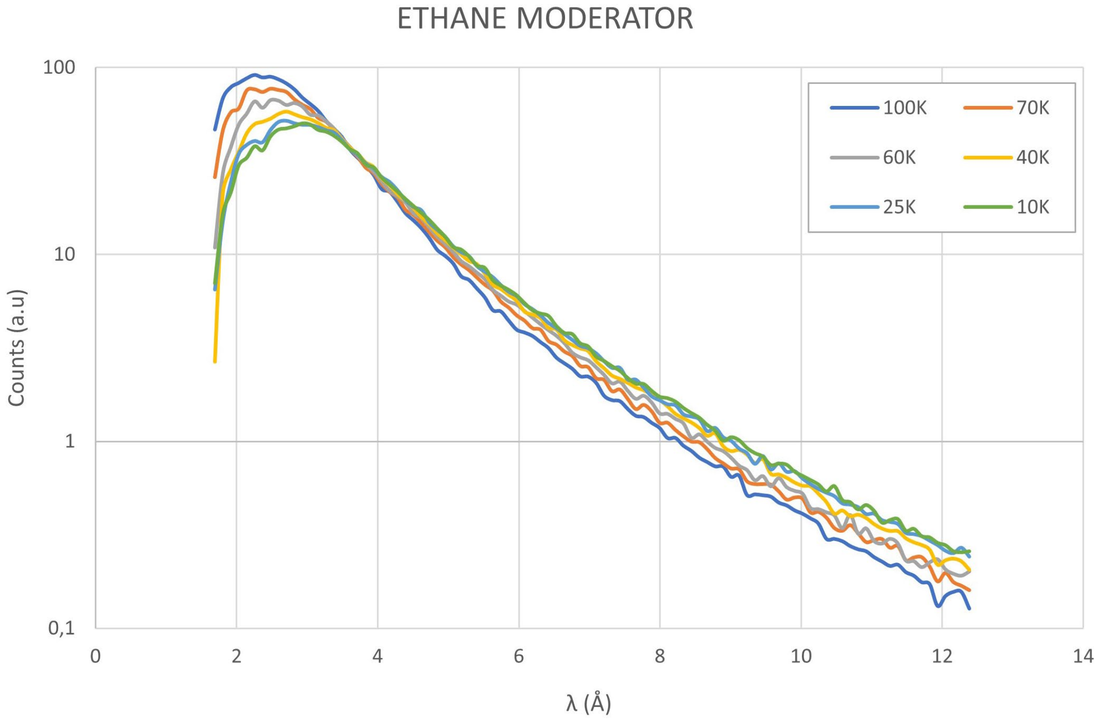
Experimental Platform at Big Karl @ COSY



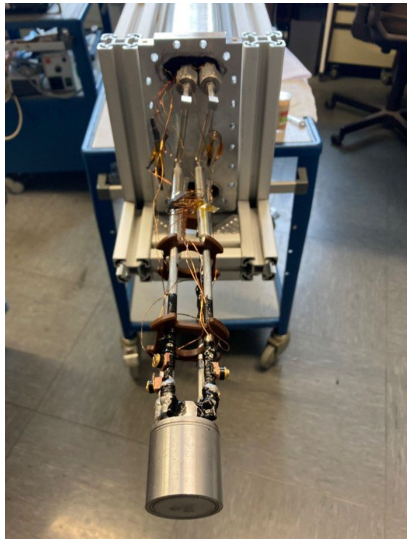
Moderator Tests

Methane, ethane, para-lH_2





- Moderator volume fillable with different gases
- Neutron guide in distance of 40 cm transporting efficiently cold neutrons

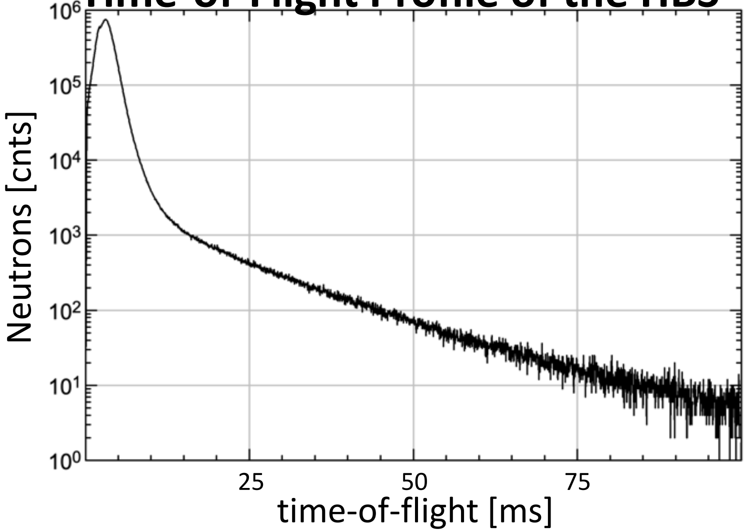


Imaging Tests

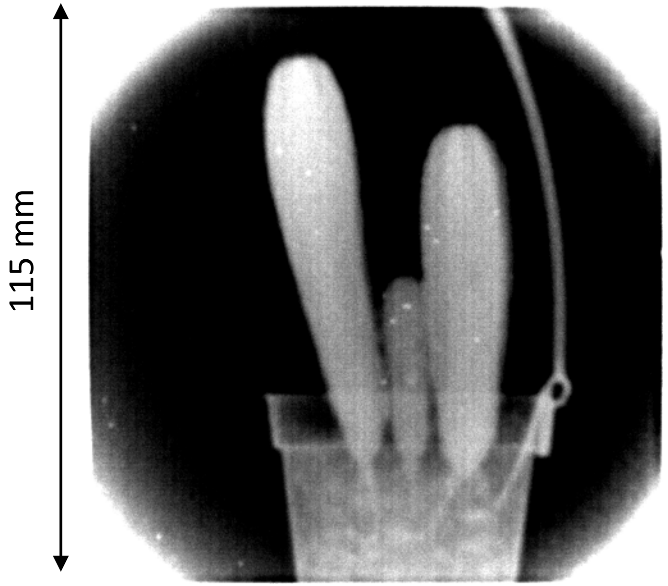
Imaging measurements with ~30 neutrons/cm$_2$/s

- Time-of-Flight (ToF) imaging proof of concept at 1m to source successful.
- High signal to noise despite proximity to target.
- Using an event counting detector, images with good counting statistics at ~250um resolution in tenth of minutes already possible.
- Due to short distance to source, energy resolution is low but sufficient for e.g. hydrogen quantification or general qualitative isotopic analysis via ToF.

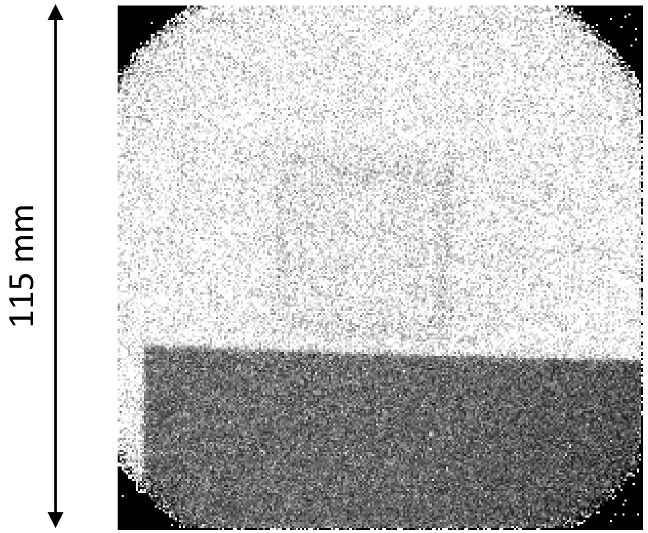
Time-of-Flight Profile of the HBS



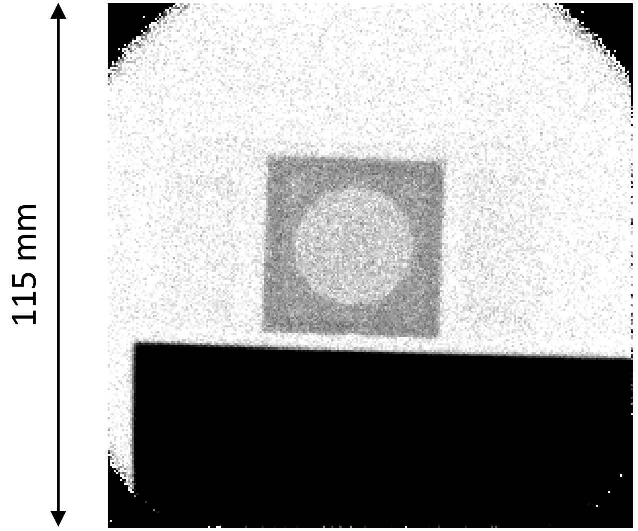
Radiograph of a Cactus
(not normalized atten.)



Epithermal Neutron Radiograph



Thermal Neutron Radiograph

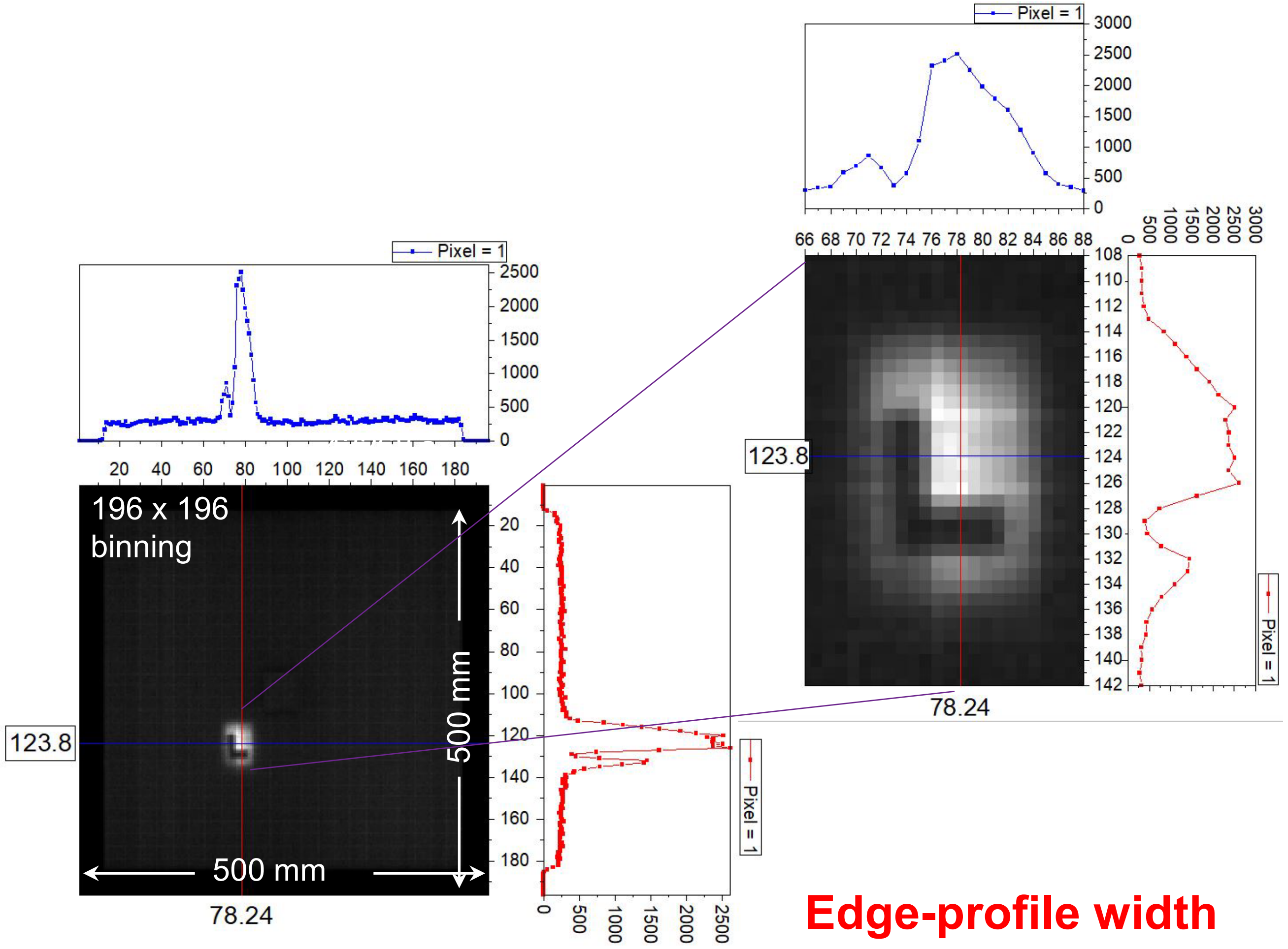


Contribution from:
Adrian Lasko (TUM)
Alexander Wolfertz (TUM)
Richi Kumar (HEREON)

Detector / Monitor Tests

- Port 2: cold methane moderator

- Spectrum from Methane cold moderator
- 7.7 m flight path in evacuated neutron guide; div. 0.1° x 0.1° (h x v)
- shielding at the sample position
- sync. T0-signal

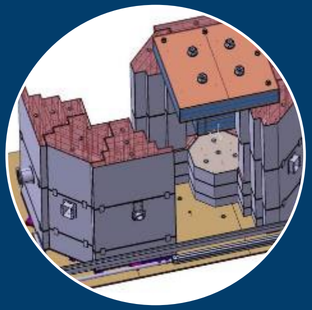


Contribution from HEREON:
Gregor Nowak
Jörn Plewka
Christian Jacobsen

Edge-profile width FWHM: 3 … 4.5 bins !

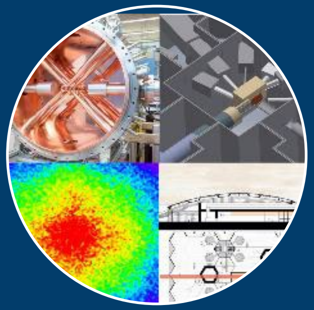
HBS project: A HiCANS facility

Road map



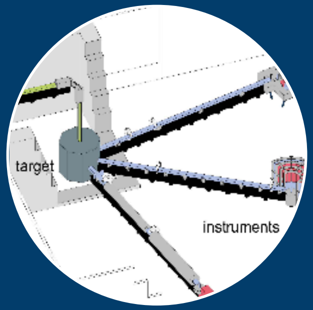
TMR
Prototype

end 2022



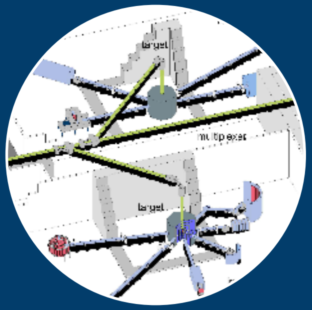
TDR
- Accelerator
- Target
- Instrumentation
- Infrastructure

2023



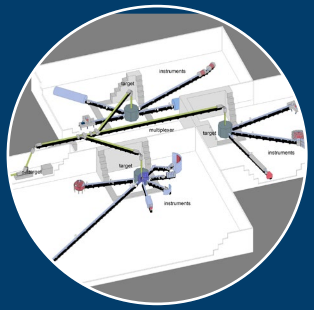
HBS Demonstrator
1 TMR
7 Instruments

3-4 years



HBS Upgrade
+2. TMR
+8 Instruments

2-3 years



HBS Upgrade
+3. TMR
+10 Instruments

2-3 years

HBS Technical Design Report

Published summer 2023

https://hbs.fz-juelich.de/?page_id=349

HBS Vision

A healthy landscape of large and small neutron sources complementing each other

Jülich Centre for Neutron Science

HIGH BRILLIANCE SOURCE

JÜLICH Forschungszentrum

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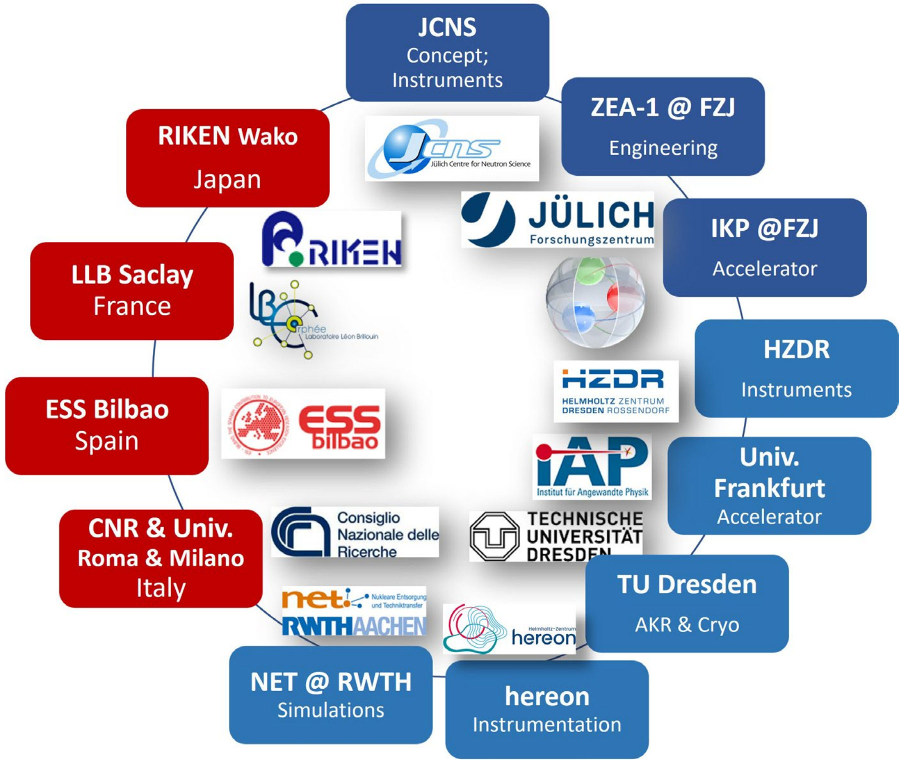
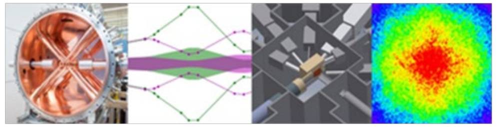


HBS Innovationpool Project



FB Matter: MML, MT GSI HIM Helmholtz-Zentrum Geesthacht HZDR JCNS

Federal Ministry of Education and Research

ELENA
European Low Energy accelerator-based Neutron facilities Association

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