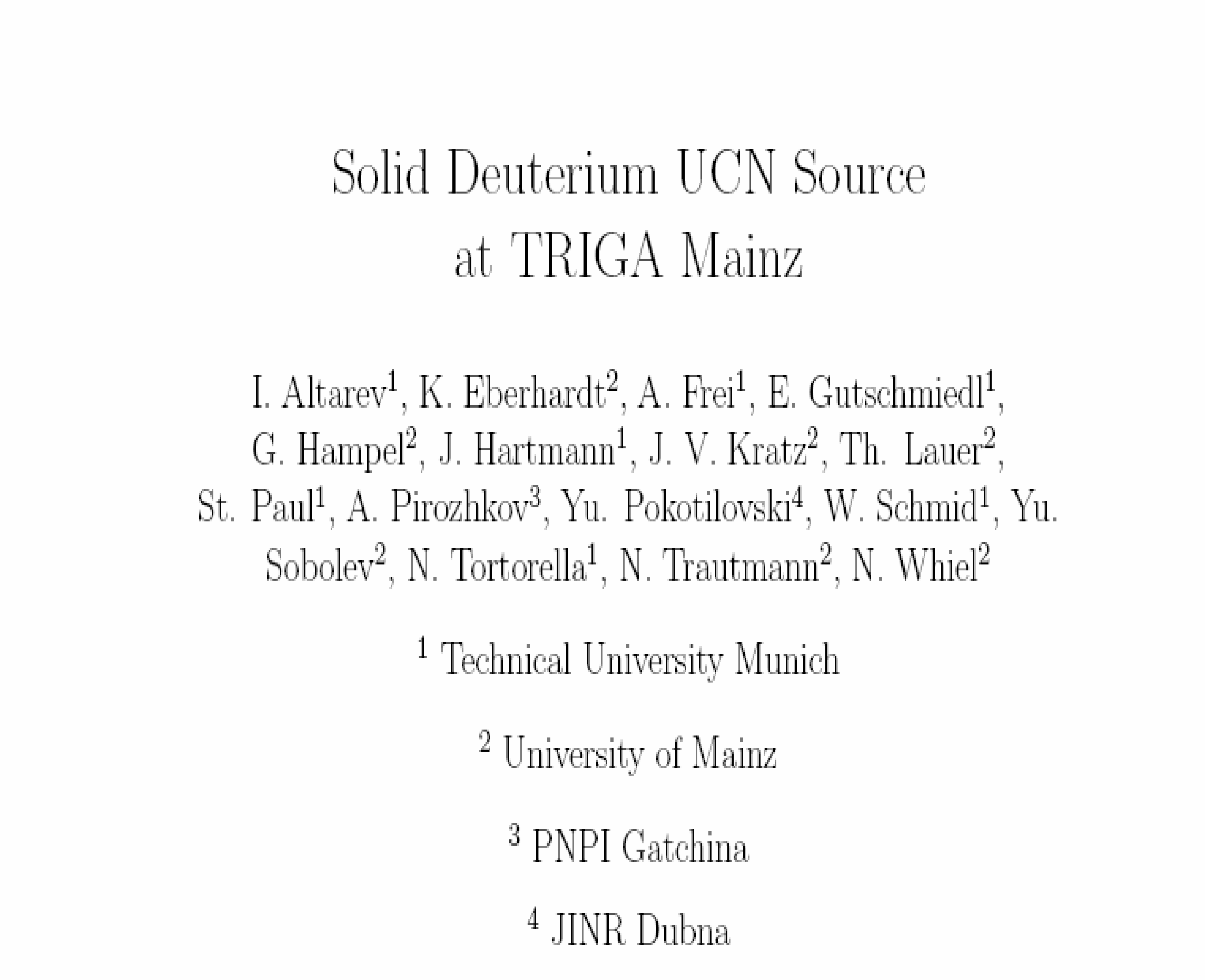


# Solid Deuterium UCN Source at TRIGA Mainz

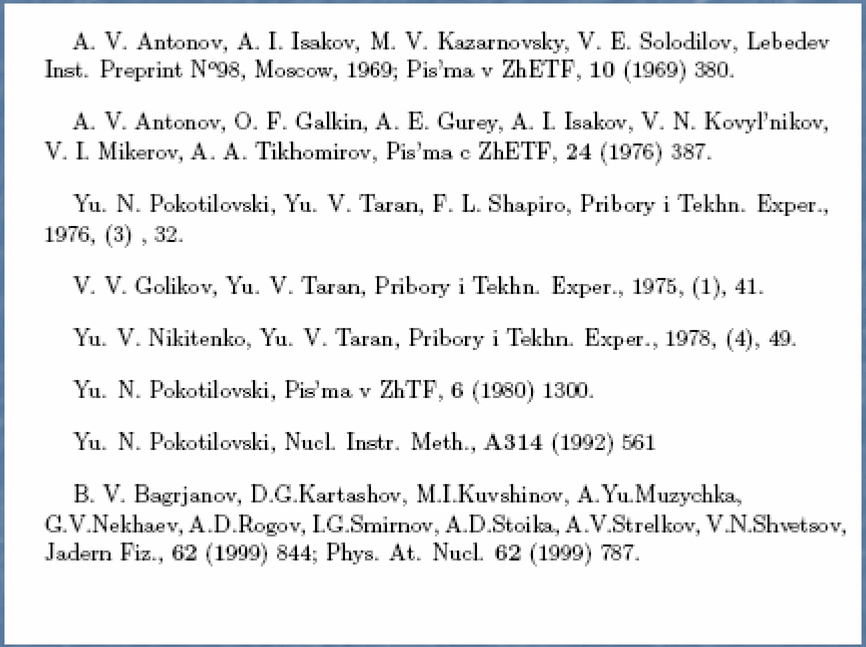
I. Altarev[1], K. Eberhardt[2], A. Frei[1], E. Gutschmiedl[1], G. Hampel[2], J. Hartmann[1], J. V. Kratz[2], Th. Lauer[2], St. Paul[1], A. Pirozhkov[3], Yu. Pokotilovski[4], W. Schmid[1], Yu. Sobolev[2], N. Tortorella[1], N. Trautmann[2], N. Whiel[2]

[1] Technical University Munich

[2] University of Mainz

[3] PNPI Gatchina

[4] JINR Dubna



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Yu. N. Pokotilovski, Pis'ma v ZhTF, 6 (1980) 1300.

Yu. N. Pokotilovski, Nucl. Instr. Meth., A314 (1992) 561

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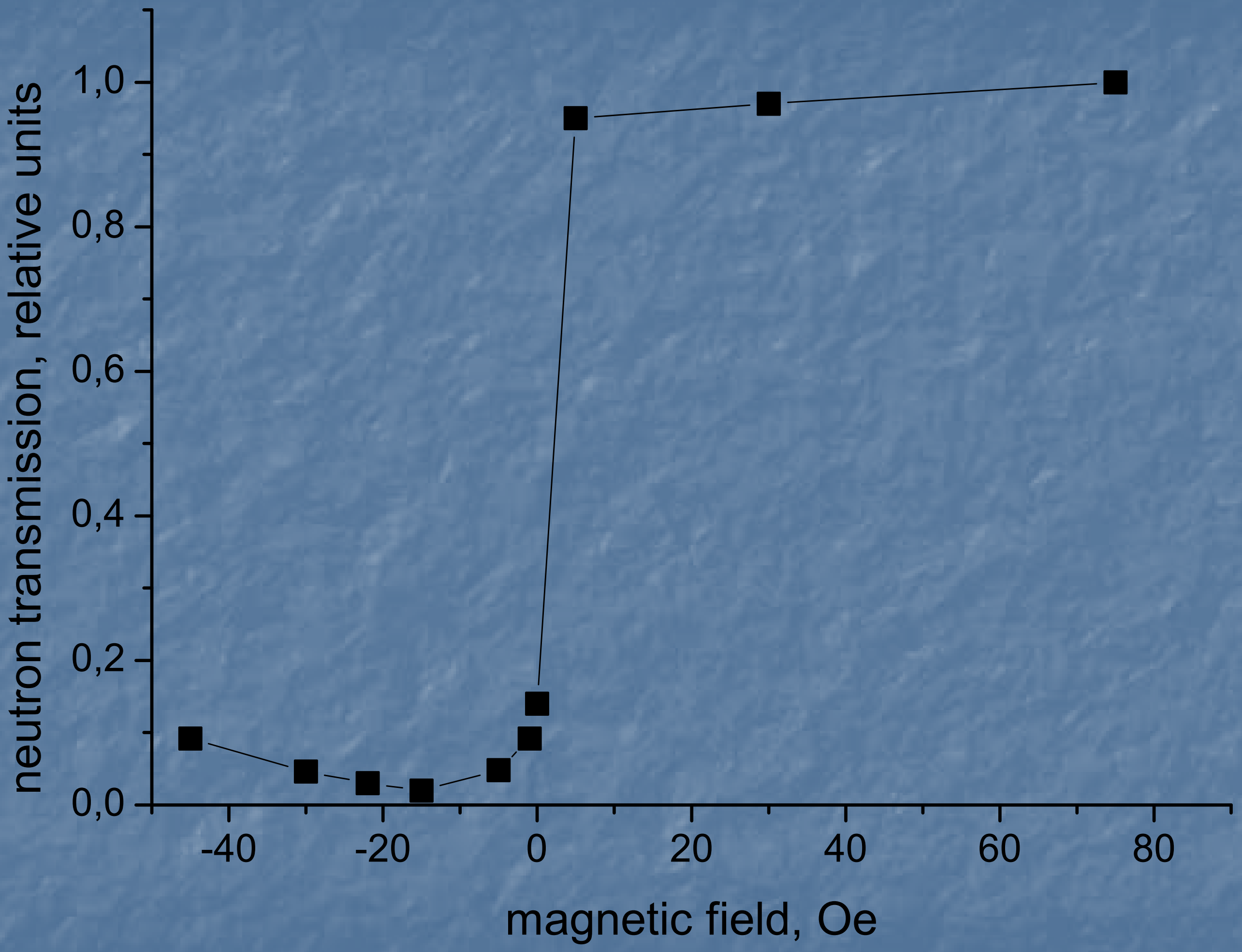
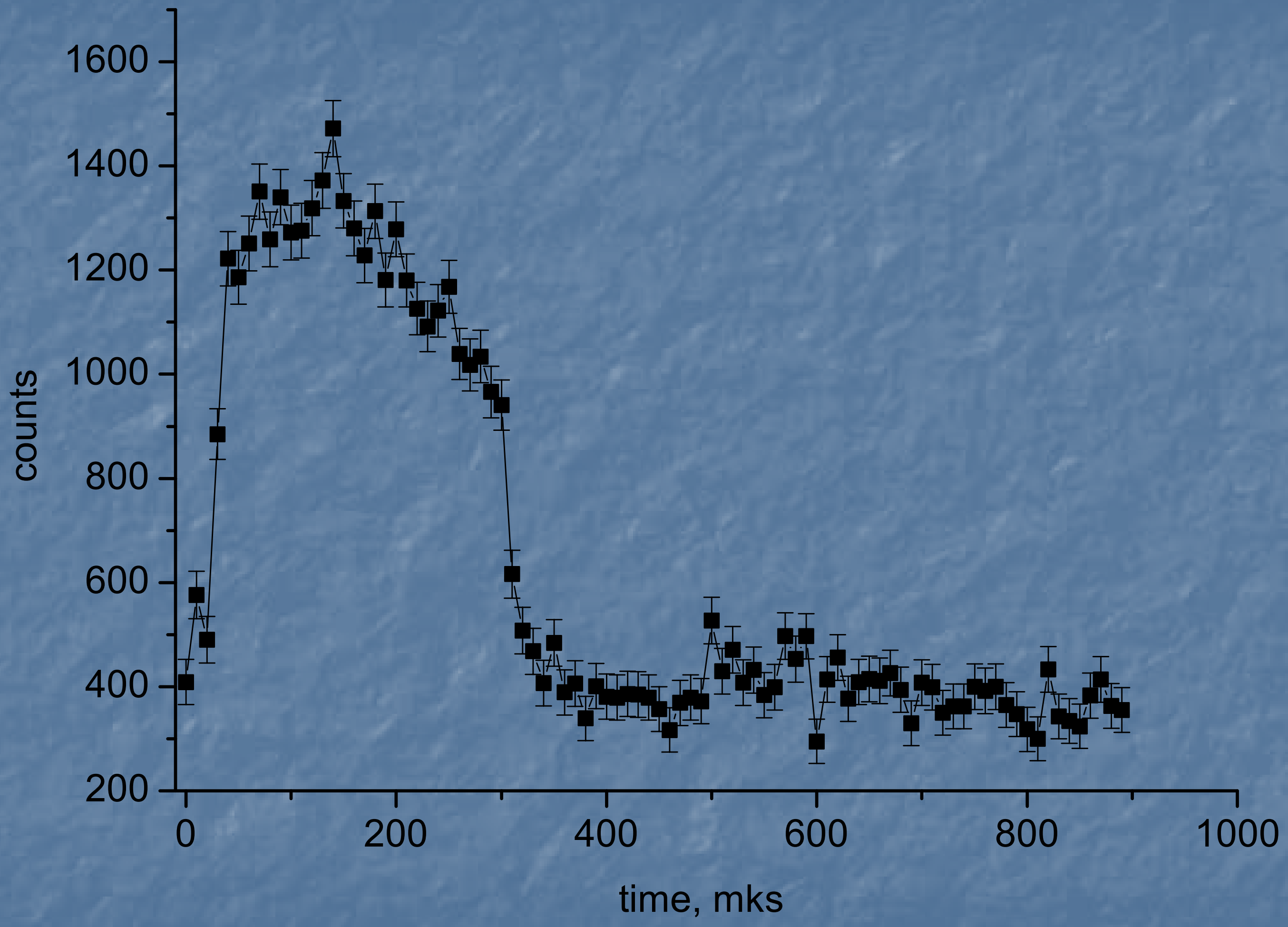
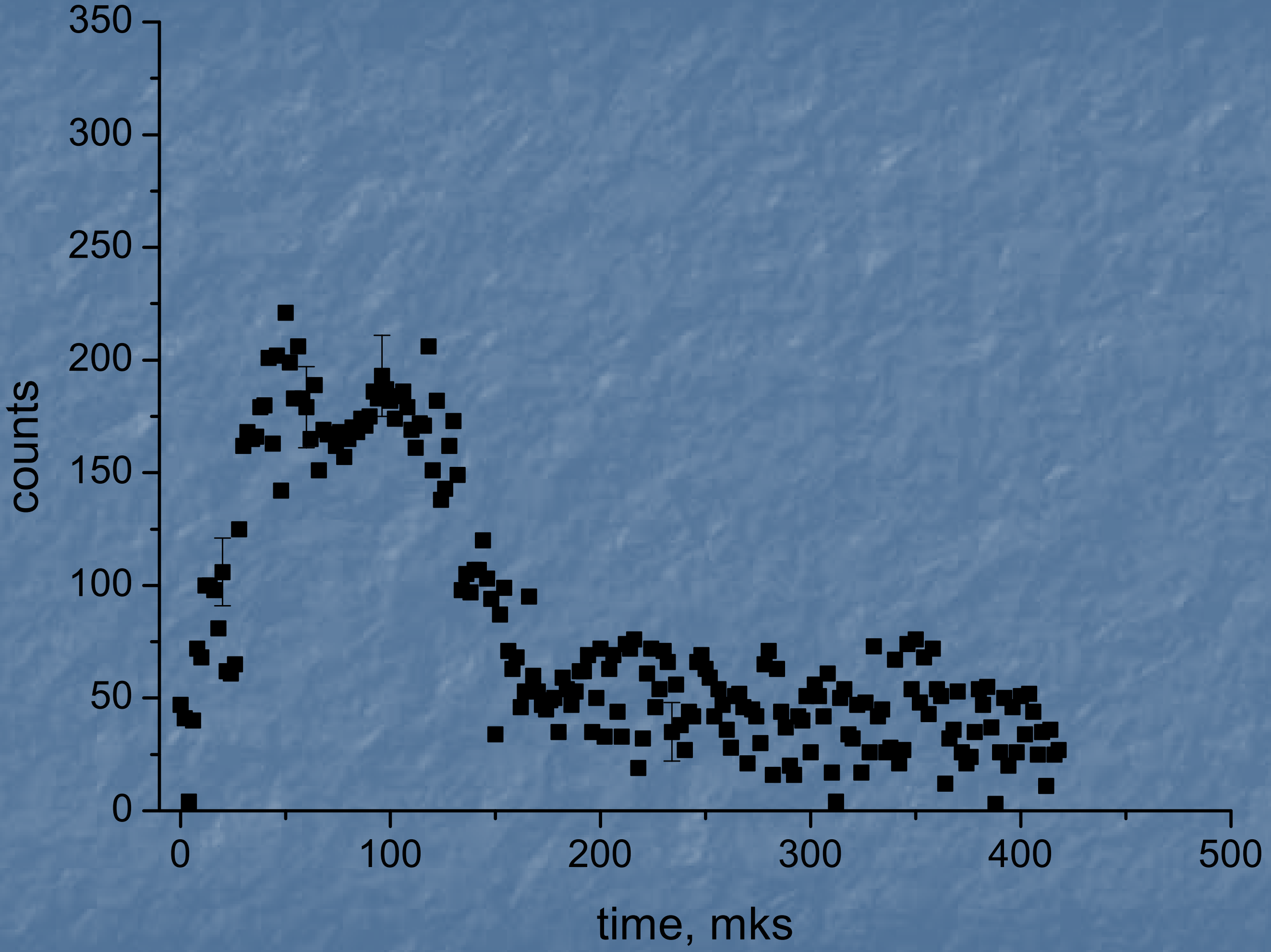
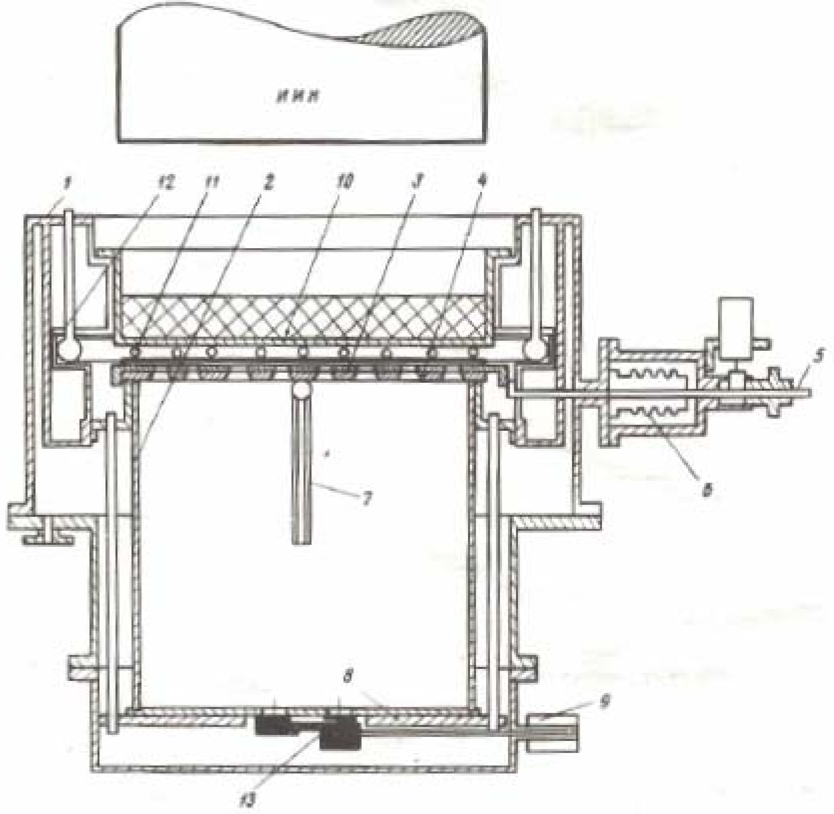
$$g = 1 + \frac{1 - \tau/T}{\tau/T + s/S + \Sigma\mu/S}$$


neutron transmission, relative units
1,0
0,8
0,6
0,4
0,2
0,0
-40
-20
0
20
40
60
80
magnetic field, Oe

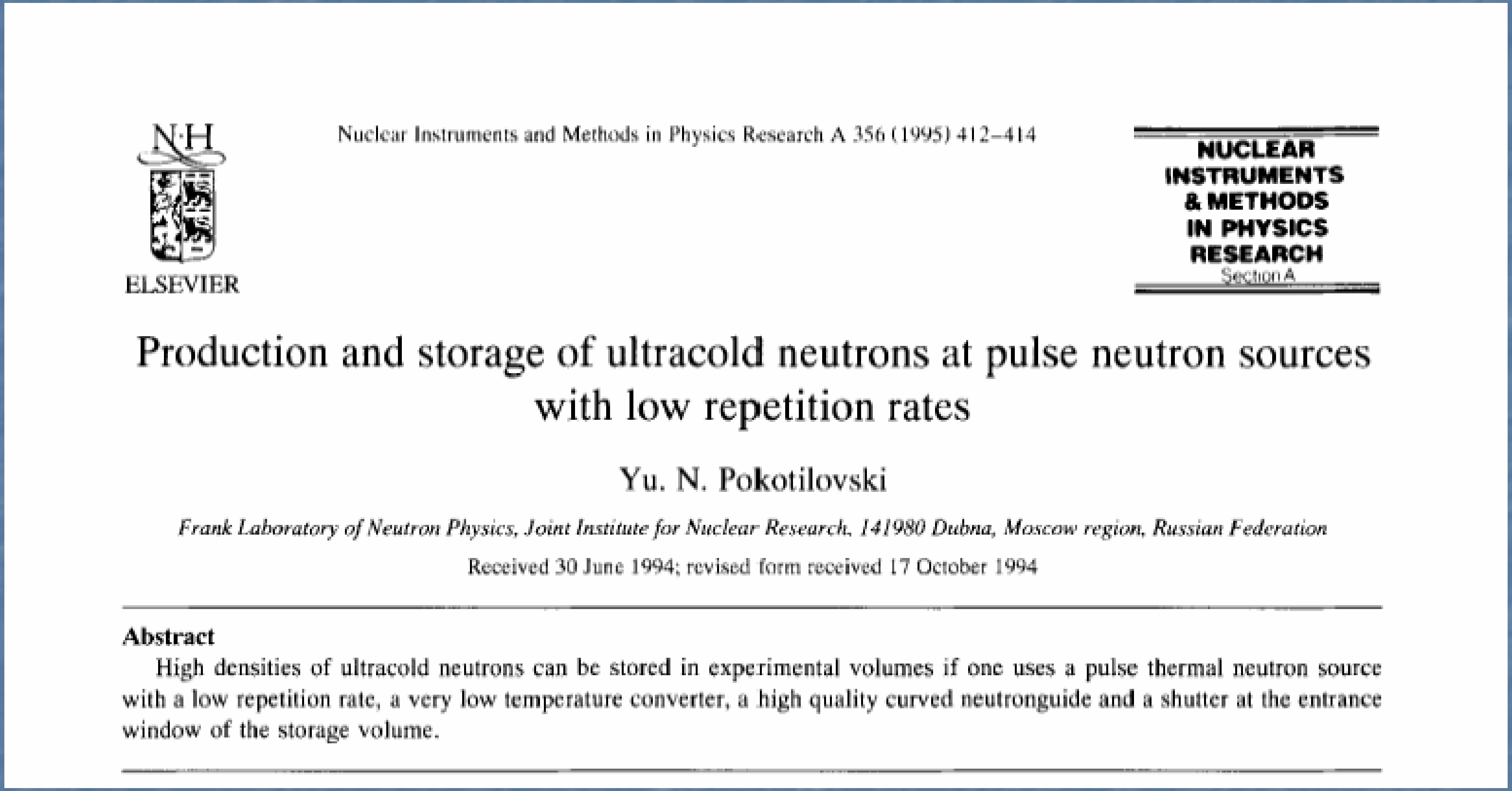

counts
1600
1400
1200
1000
800
600
400
200
0
200
400
600
800
1000
time, mks



counts
0
50
100
150
200
250
300
350
0
100
200
300
400
500
time, mks



Экспериментальная установка для накопления УХН: *1* — корпус установки, *2* — медная ловушка, *3*, *4* — быстродействующий затвор, *5* — шток, *6* — сильфонный узел, *7* — медленный затвор, *8* — устройство перемещения фильтров, *9* — соленоид, *10* — блок замедлителя, *11* — конвертор, *12* — система охлаждения конвертора, *13* — детекторы



N·H
ELSEVIER

Nuclear Instruments and Methods in Physics Research A 356 (1995) 412–414

NUCLEAR
INSTRUMENTS
& METHODS
IN PHYSICS
RESEARCH
Section A

# Production and storage of ultracold neutrons at pulse neutron sources with low repetition rates

Yu. N. Pokotilovski

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Received 30 June 1994; revised form received 17 October 1994

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**Abstract**

High densities of ultracold neutrons can be stored in experimental volumes if one uses a pulse thermal neutron source with a low repetition rate, a very low temperature converter, a high quality curved neutronguide and a shutter at the entrance window of the storage volume.

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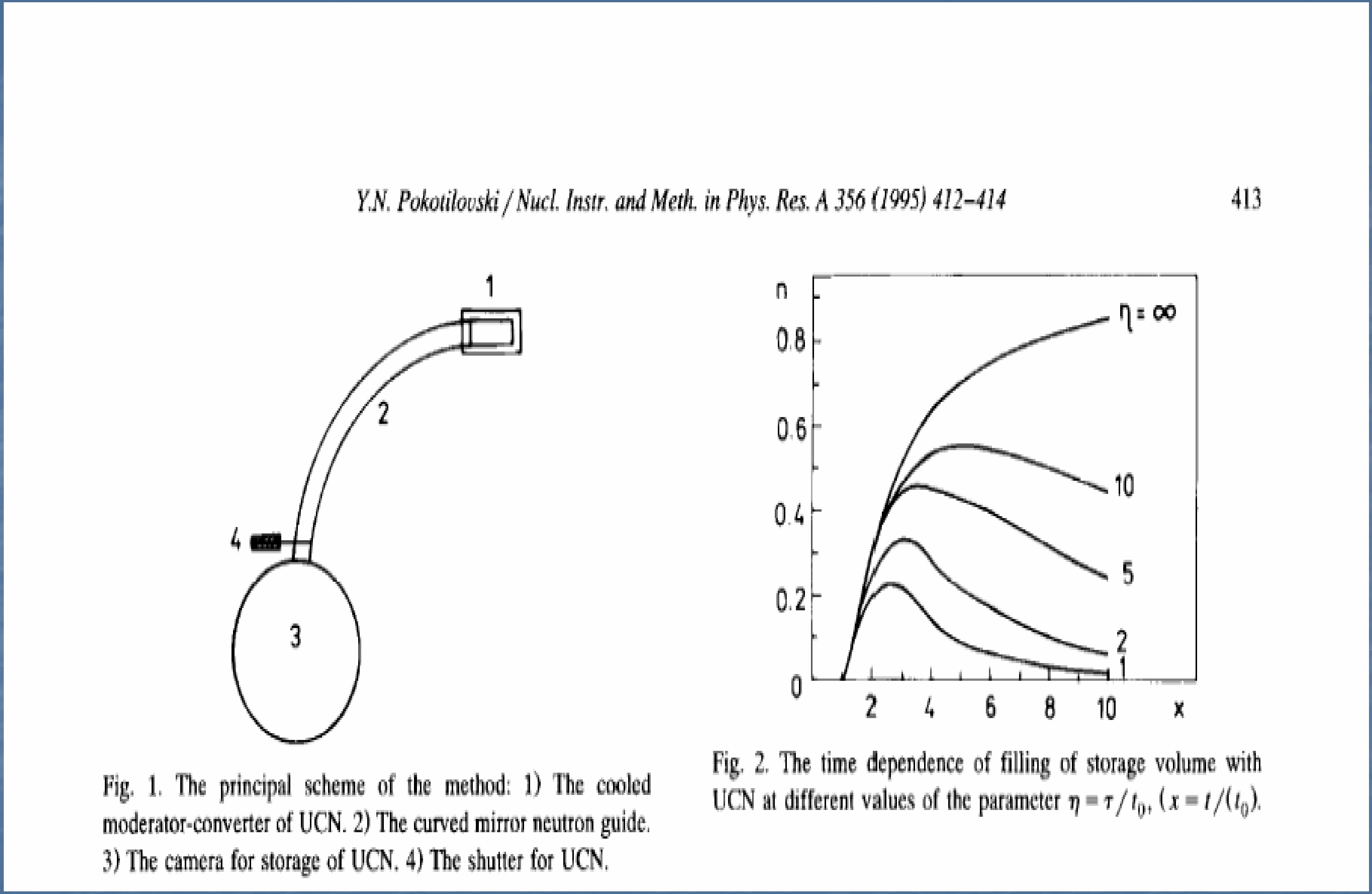
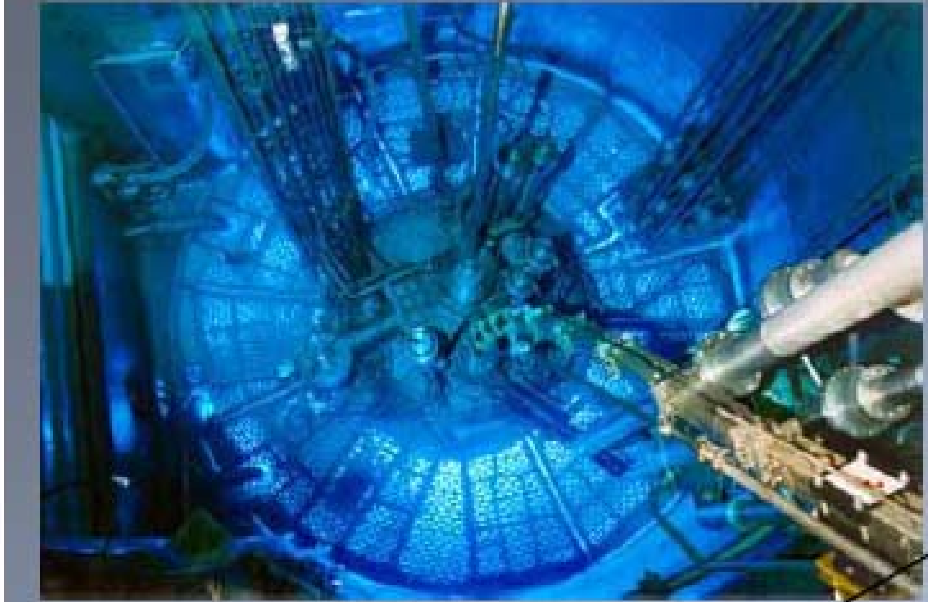


*Y.N. Pokotilovski / Nucl. Instr. and Meth. in Phys. Res. A 356 (1995) 412–414* 413

Fig. 1. The principal scheme of the method: 1) The cooled moderator-converter of UCN. 2) The curved mirror neutron guide. 3) The camera for storage of UCN. 4) The shutter for UCN.

Fig. 2. The time dependence of filling of storage volume with UCN at different values of the parameter $\eta = \tau / t_0$, ($x = t/(t_0)$).

# The UCN/VCN facility PF2



Neutron turbine
A. Steyerl (TUM - 1985)

Vertical guide tube

Cold source

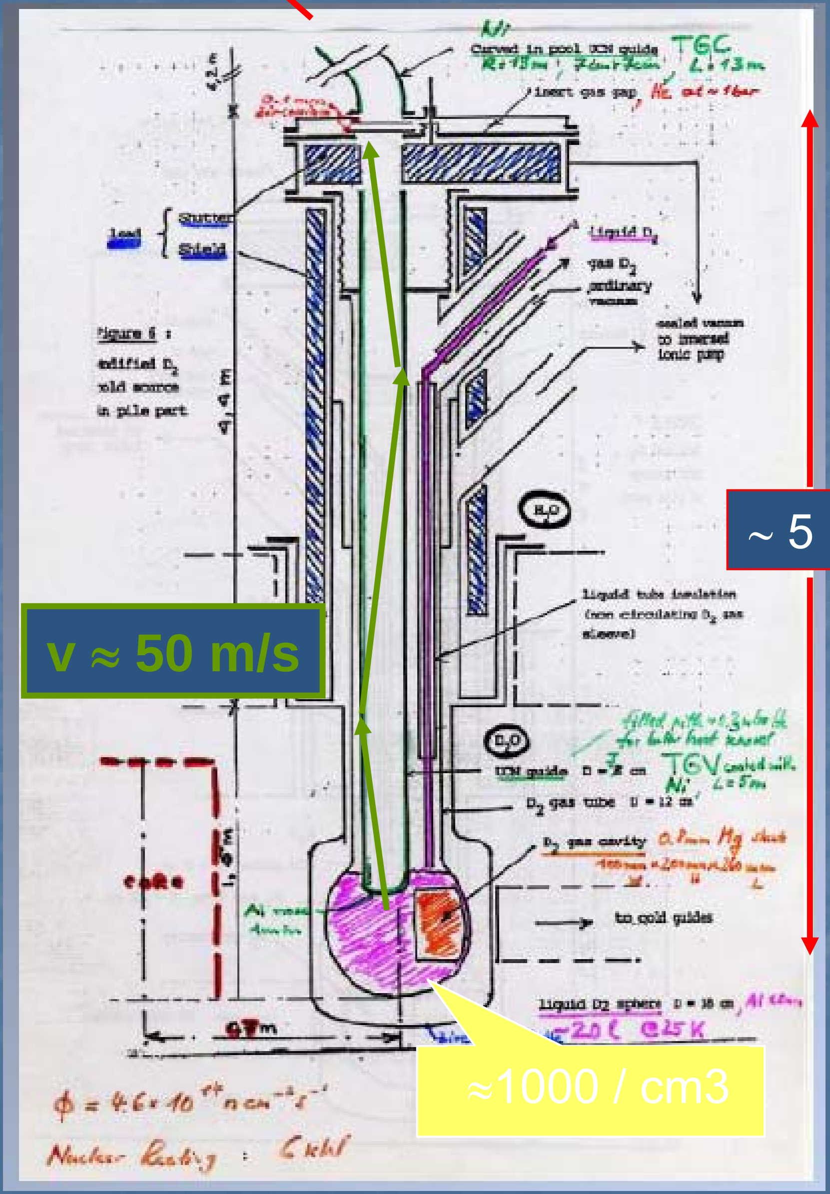
liquid $D_2$: 25 l
T = 25K

Reactor core

≈1000 / $cm^3$

to Steyerl turbine ( ~13 m )

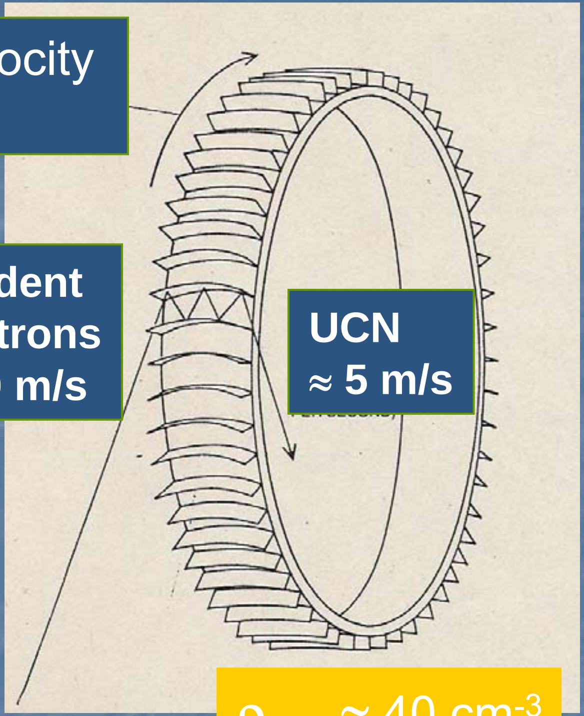
turbine



~ 5 m

v ≈ 50 m/s

≈1000 / cm3



tangential velocity ≈ 25 m/s

incident neutrons ≈ 50 m/s

UCN ≈ 5 m/s

$\rho_{UCN} \approx 40\ cm^{-3}$

## Liouville‘s theorem:

**Impossible to increase the phase-space density in a neutron beam by means of potential forces like gravity, which act collectively on the particles, or, more generally, by any mechanical magnetic, or other device.**

$$\rho = \frac{d^6N}{d^3r\,d^3p} = const.$$

## Density of neutrons with velocities between v and v+dv at thermal equilibrium

$$\rho(v)\,dv = 2\Phi_0 \cdot \frac{v^2}{\alpha^4} \cdot \exp(-v^2/\alpha^2) \cdot dv \qquad \alpha = \sqrt{2k_B T/m}$$

Density of ultra-cold neutrons: $0 \leq E \leq V_F$

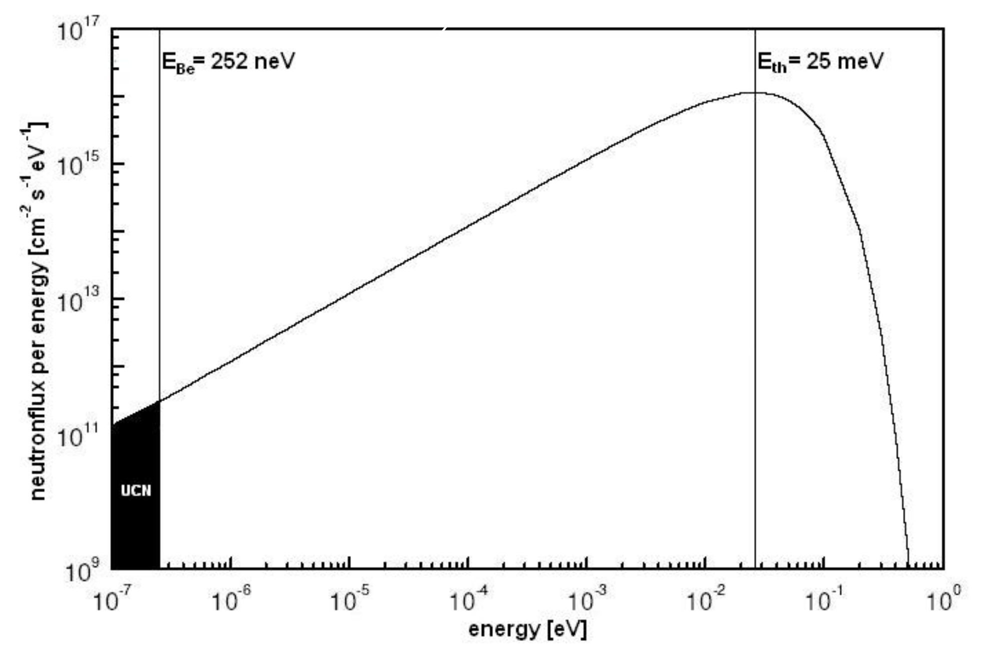
$$\rho_{UCN} = \int_0^{V_F = 1/2\,m v_{\max}^2} \rho(v)\,dv = \frac{2}{3} \cdot \frac{\Phi_0}{\alpha} \cdot \left(\frac{V_F}{k_B T}\right)^{3/2}$$

ILL-Grenoble: $T_0$ =300 K

$\alpha$ = 2.2x$10^5$ cm/s

$V_F$ = 200 neV

$\Phi_0$= $6\cdot10^{14}$ n/cm$^2$/s

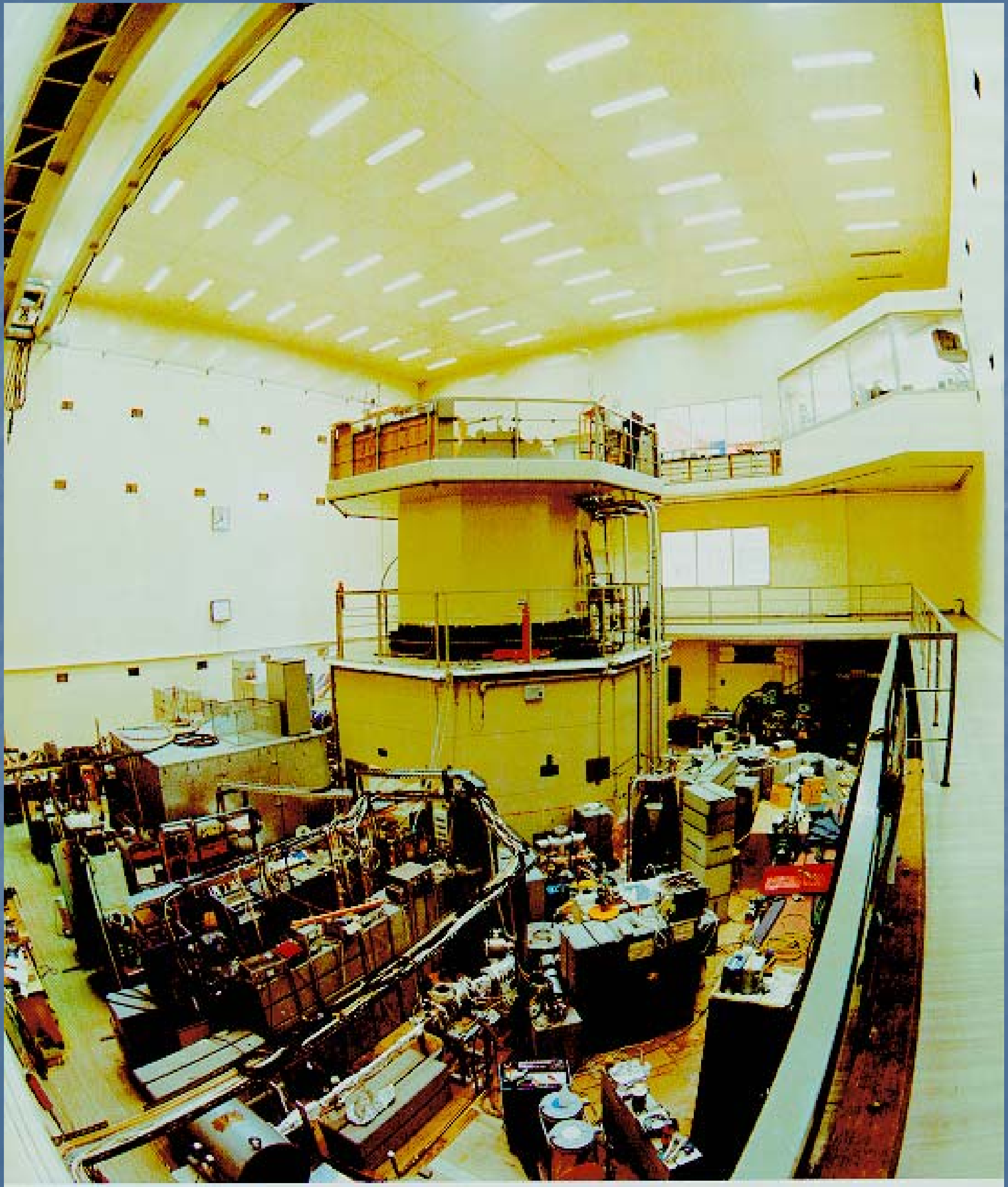


$\rho_{UCN} \approx 40$ cm$^{-3}$

**gain due to cooling**

$$\Box \left(\frac{T_0}{T}\right)^{3/2}$$

# TRIGA Mainz



**T**raining

**R**esearch

**I**sotopes

**G**eneral

**A**tomics

Mark II

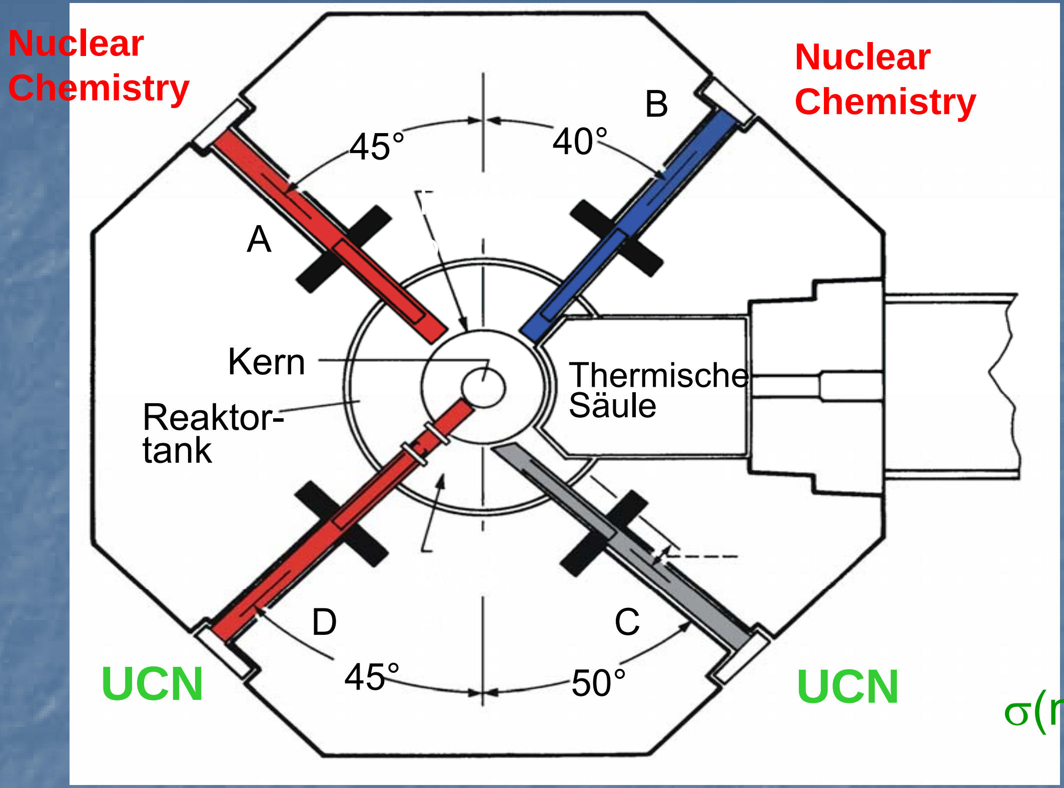
power:

DC mode
100 $kW_{th}$

pulse mode
250 $MW_{th}$
( 30-40 ms )

# TRIGA-Mainz

( K. Eberhardt, G. Hampel, J.V. Kratz, N. Trautmann, N. Wiehl )

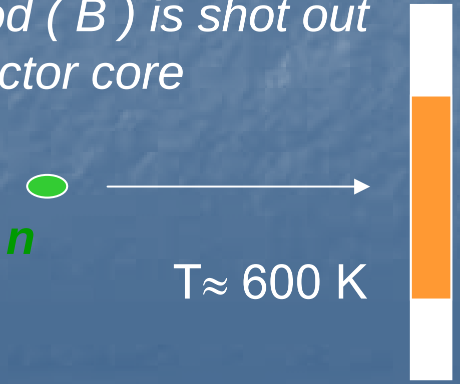


DC-operation: 100 kW

**Fuel elements:**
Zirconium hydride ( Zr / H ~ 1 )
moderator with 8% by weight U
Uranium: ( 20% $^{235}$U )

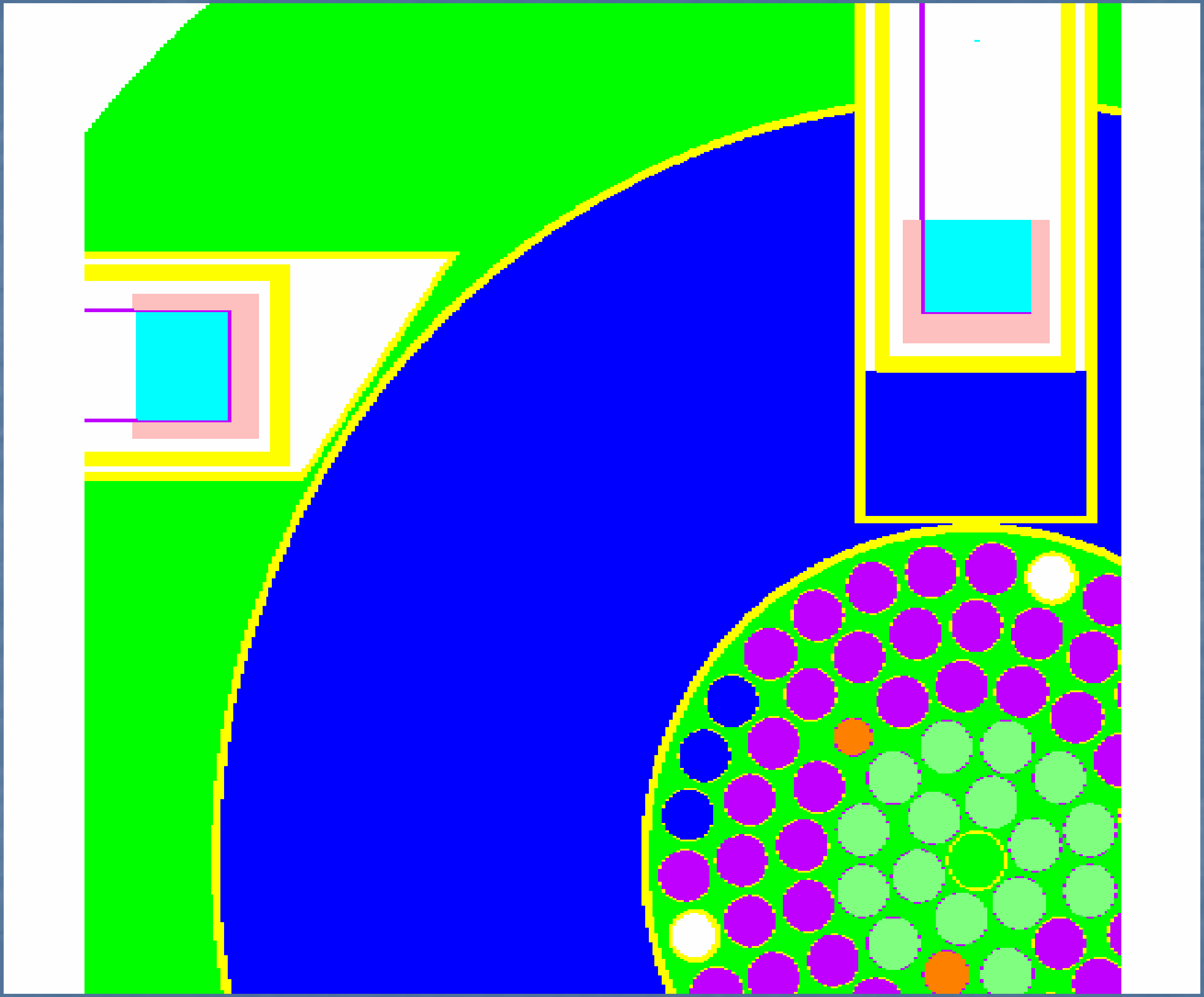
$\sigma(n,f)_{T\approx 600\ K} < \sigma(n,f)_{T\approx 300\ K} \approx 580$ barn

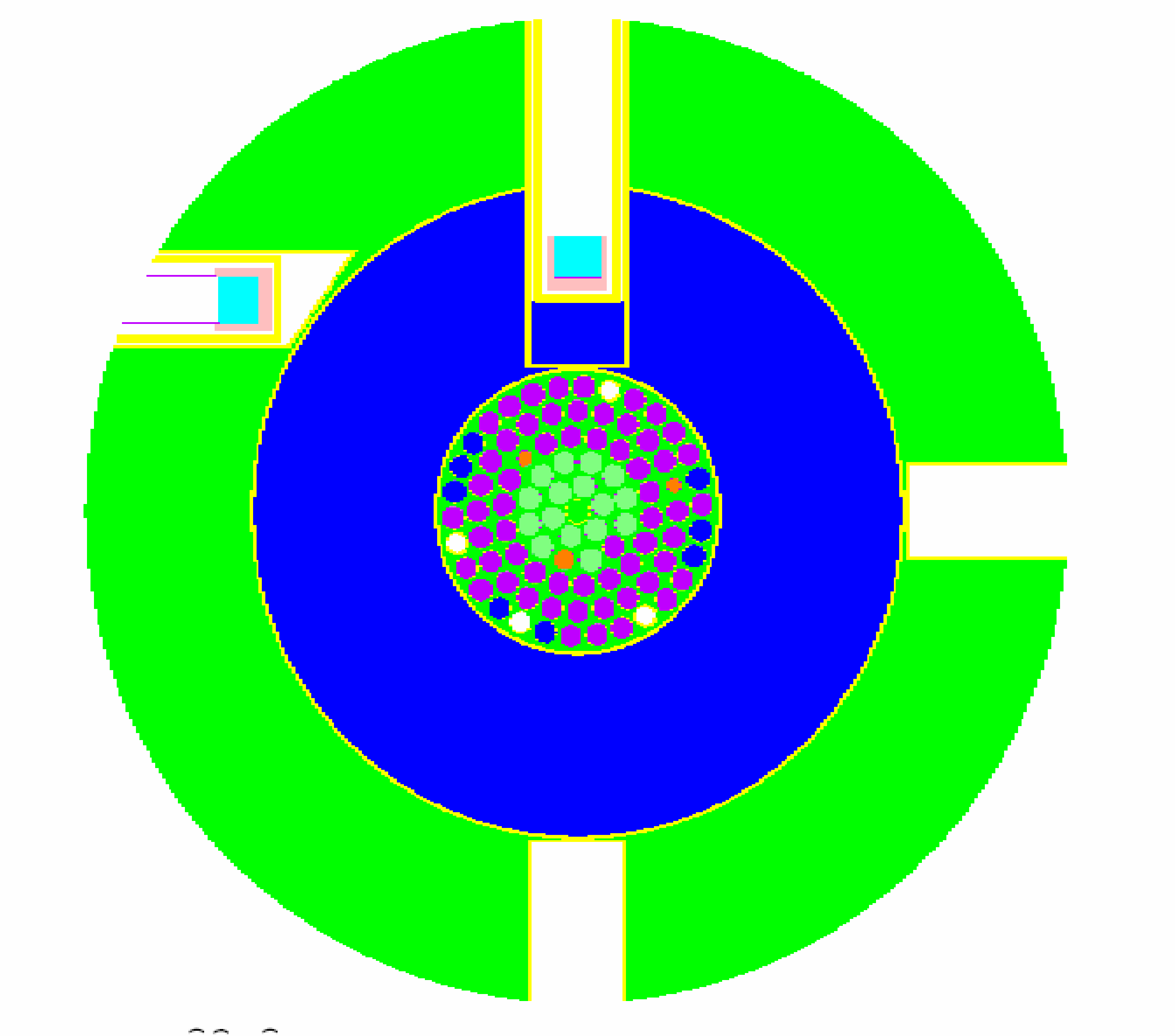
***Pulse mode:***
*Control rod ( B ) is shot out*
*of the reactor core*



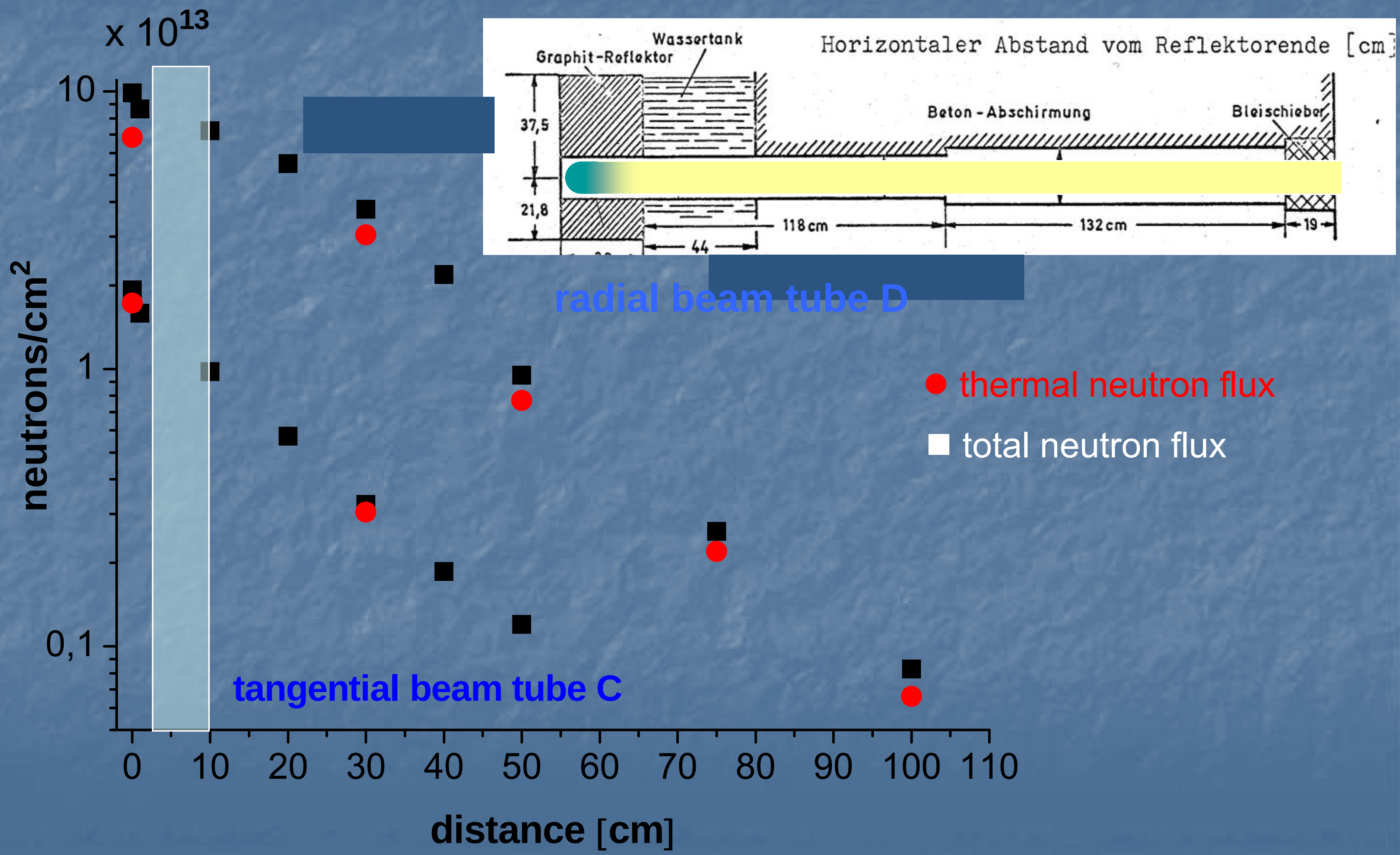
**Reactor power excursion is limited by the prompt negative temperatur coefficient of the reactivity (k)**

Pulse : 40 ms ( FWHM )
Pulse peak-power : 250 MW ( $5\times10^{15}$ n/cm$^2$/s )
Repetition rate: 1 Pulse / 5 min



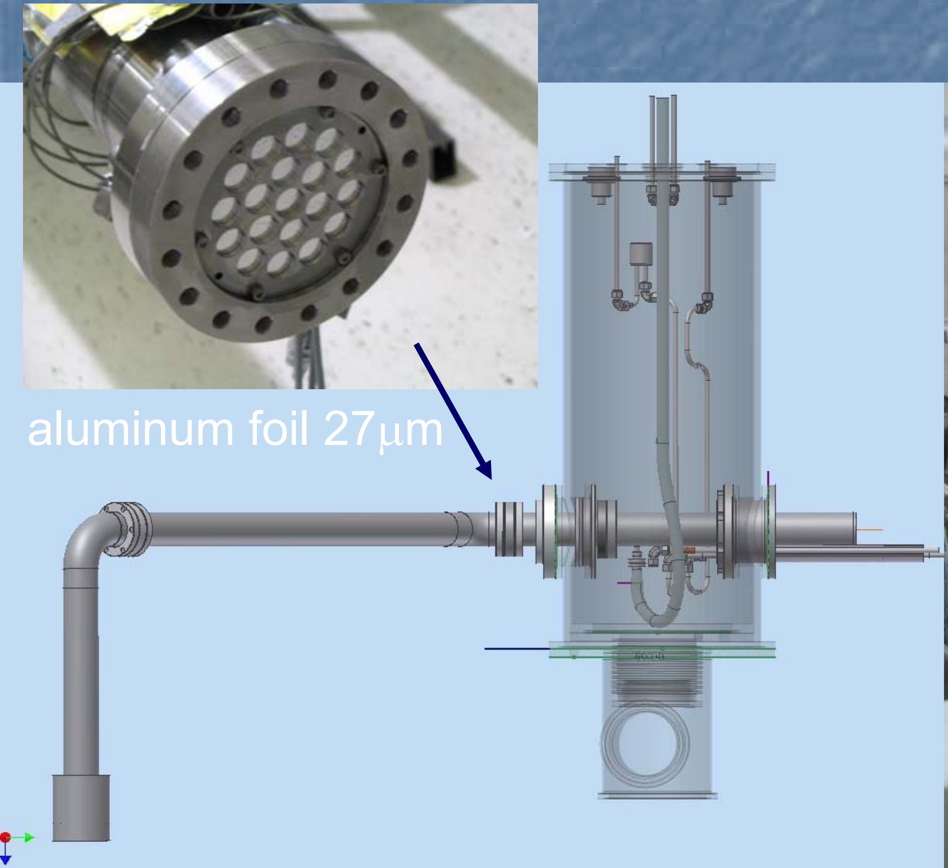


# Measured neutron flux in channel C and D ( 2$ pulse: 10 MJ)

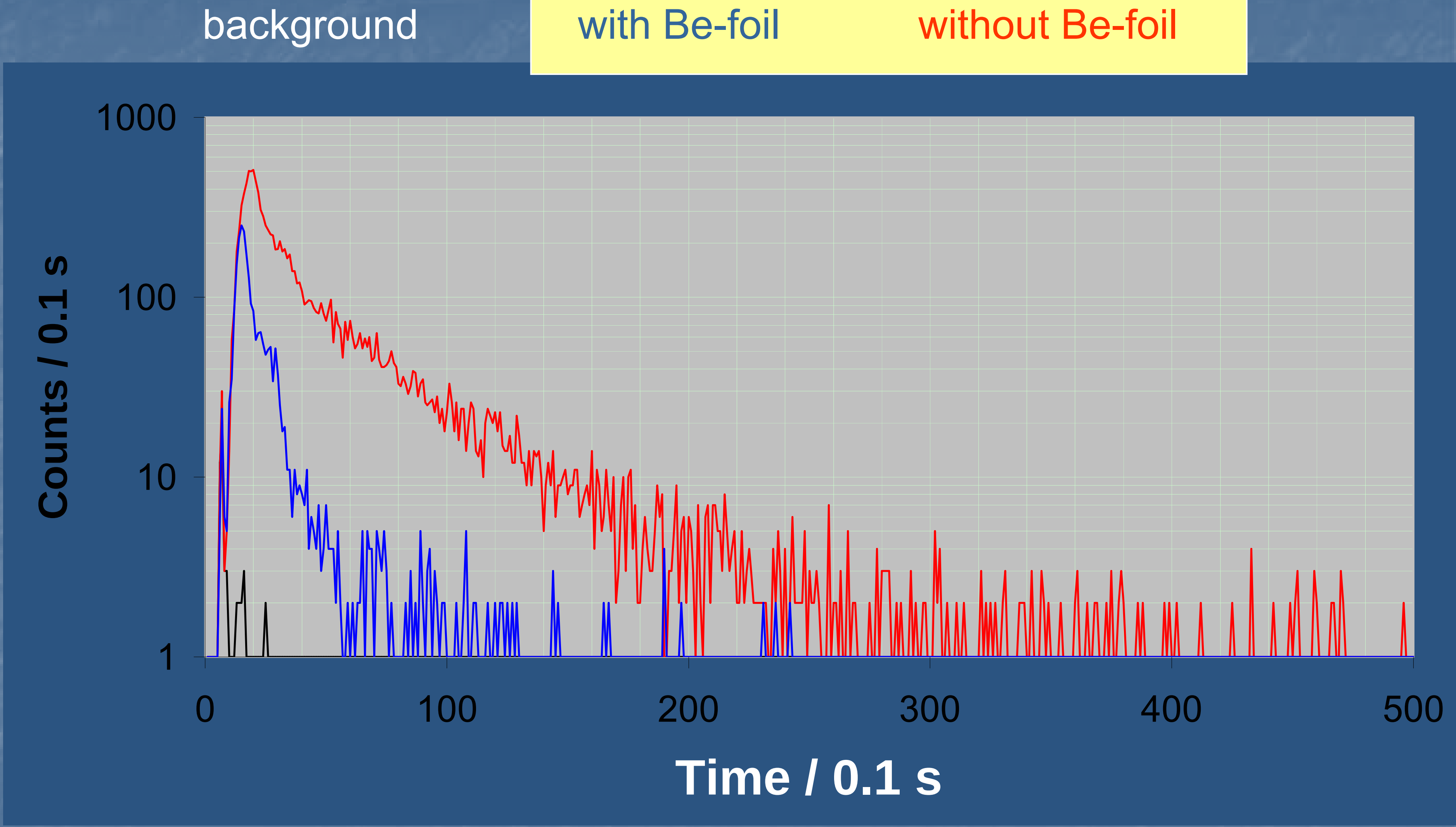


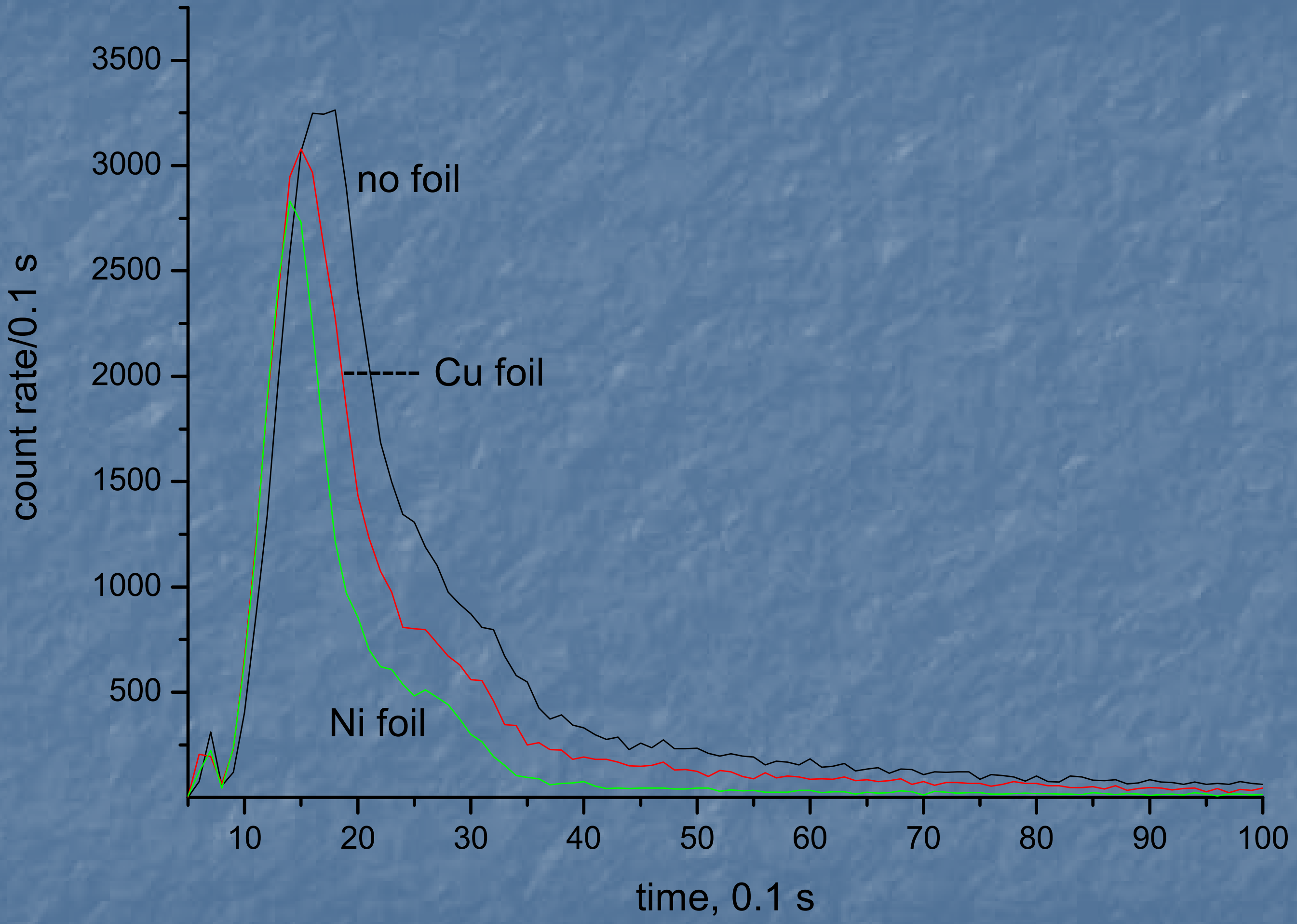
# Detector part

- Detector and cryostat two independent systems
- Changes on tube and detector (geometry/material/coating/…) easily possible
- Possible to change position and to insert objects (e.g. valves, windows,…)



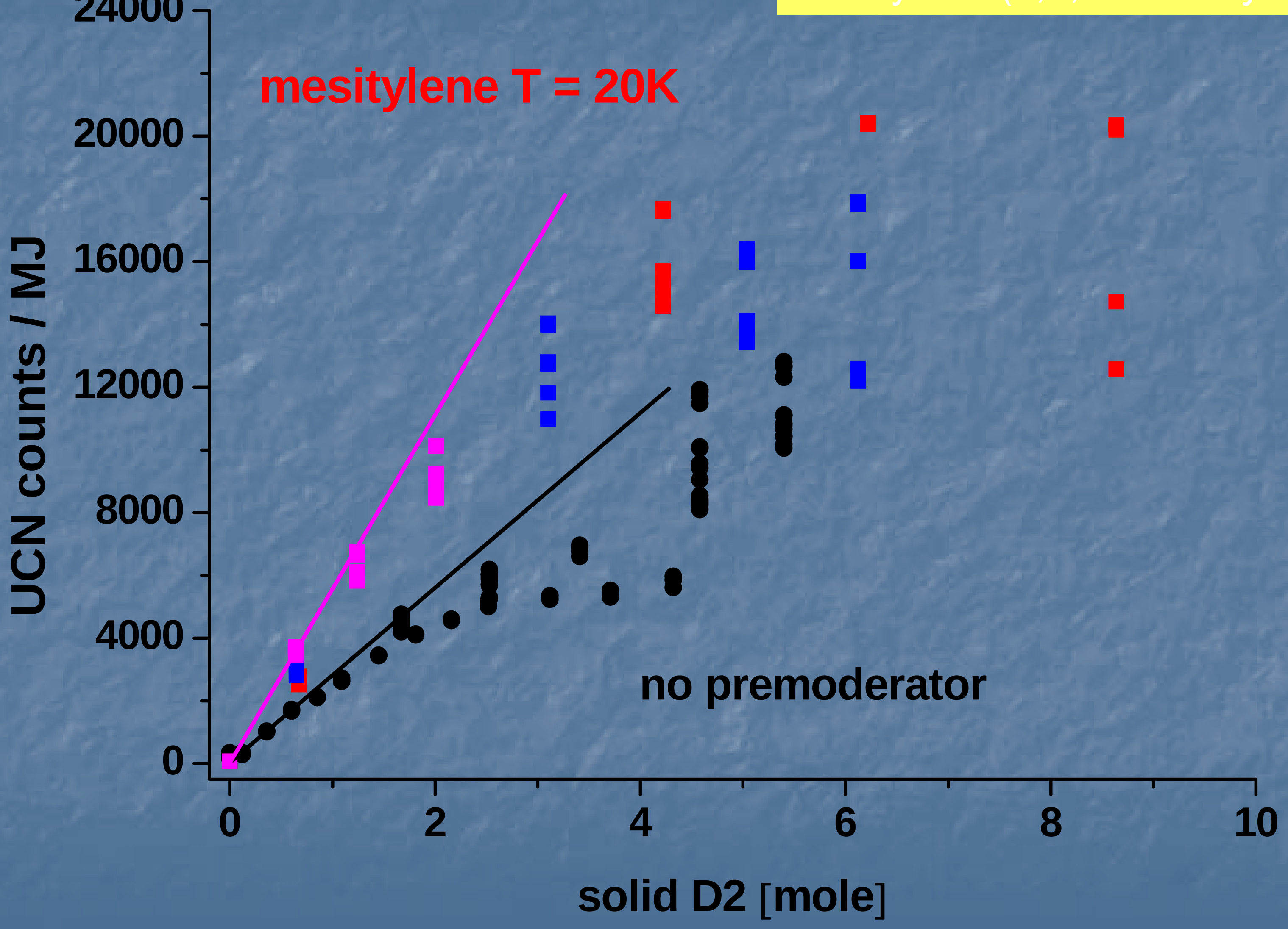
## Quantity of frozen $D_2$ : 2 mole

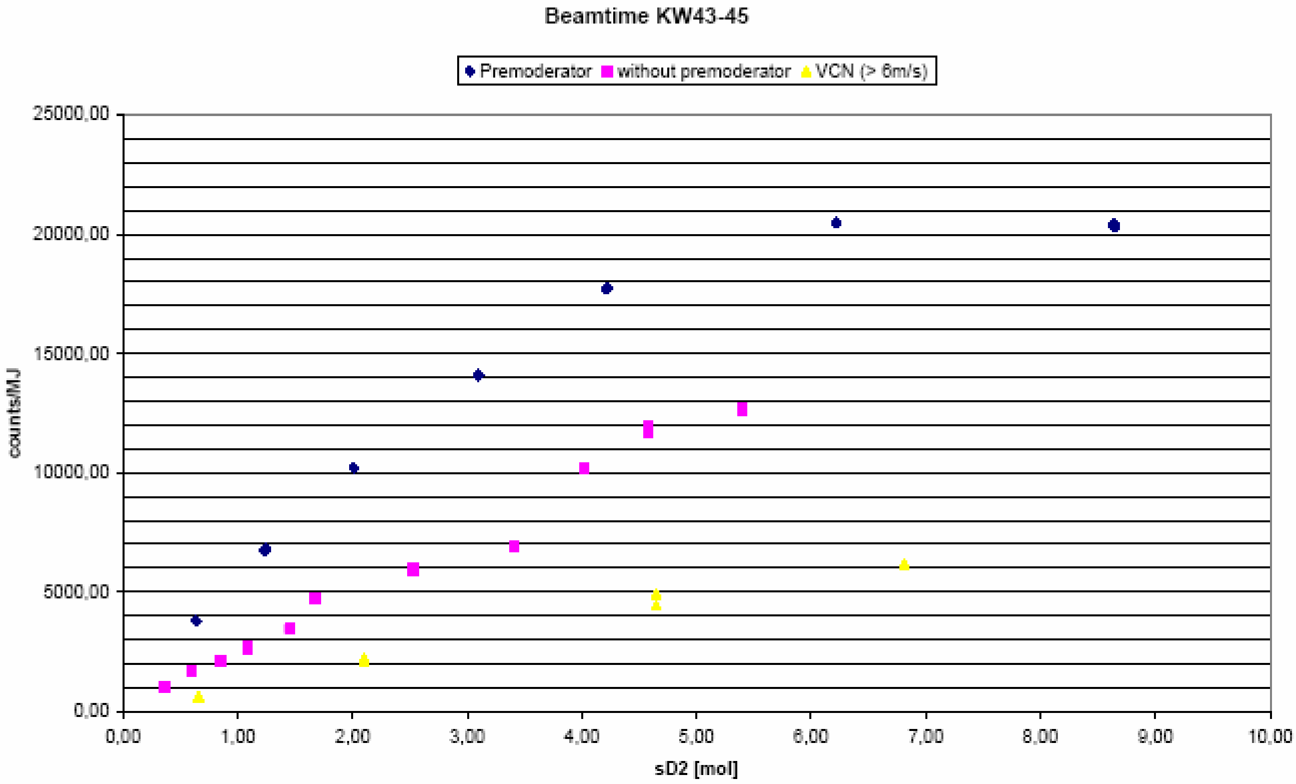




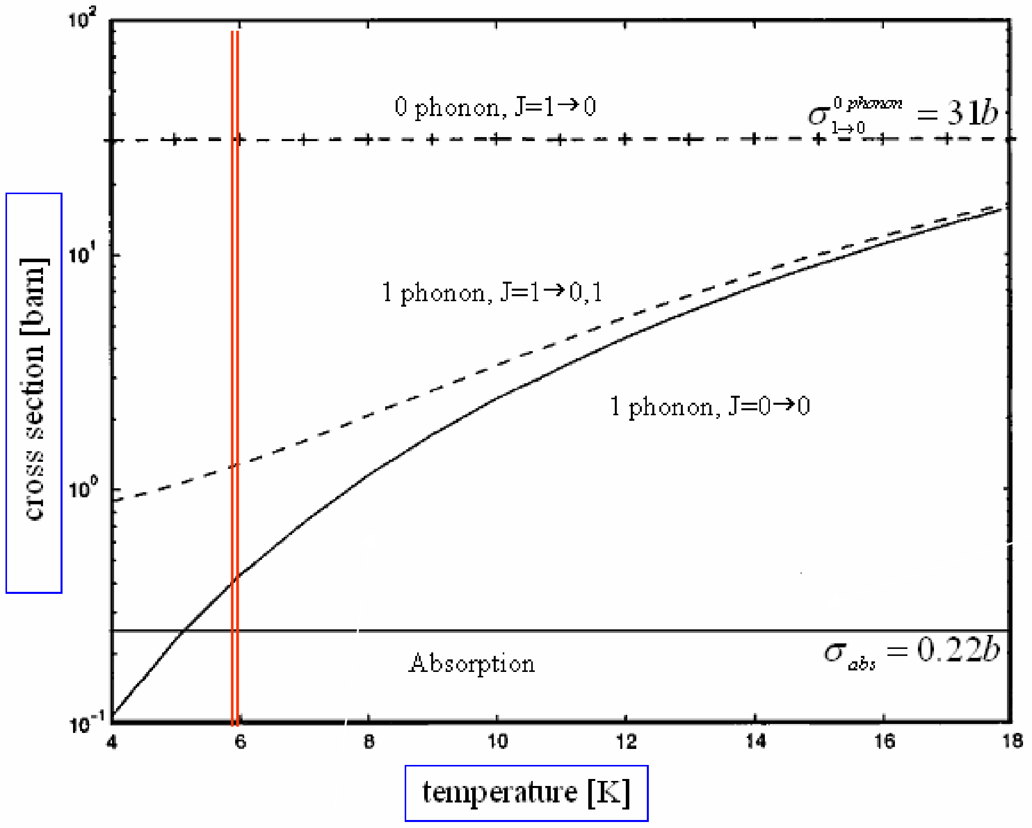
count rate/0.1 s
3500
3000
2500
2000
1500
1000
500
10
20
30
40
50
60
70
80
90
100
time, 0.1 s
no foil
Cu foil
Ni foil

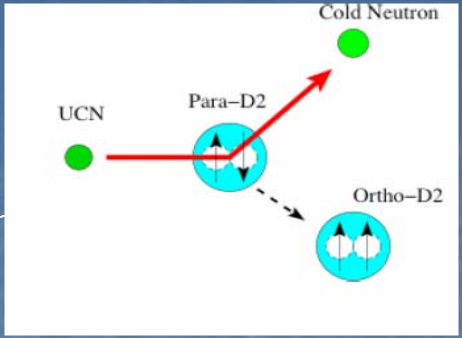
mesitylene (1,3,5-trimethylbenzene)



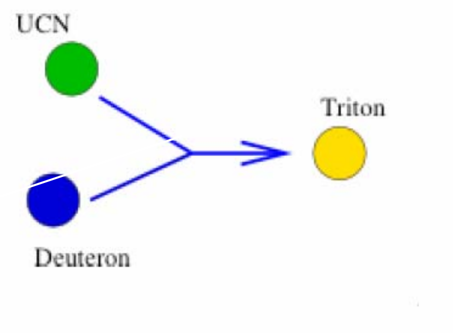

Beamtime KW43-45
♦ Premoderator ■ without premoderator ▲ VCN (> 6m/s)
counts/MJ
25000,00
20000,00
15000,00
10000,00
5000,00
0,00
0,00
1,00
2,00
3,00
4,00
5,00
6,00
7,00
8,00
9,00
10,00
sD2 [mol]

C.-Y.Liu, et al., PR B62, R3581 (2000)

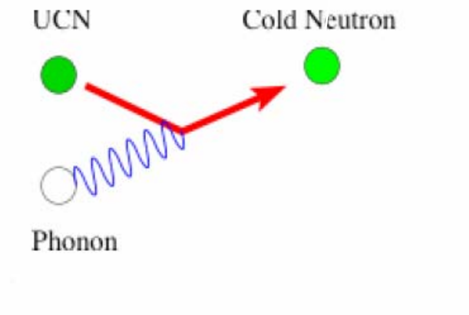




$\tau_{para} \approx$ 1.5 ms @ 100% para



$\tau_{abs} \approx$ 150 ms

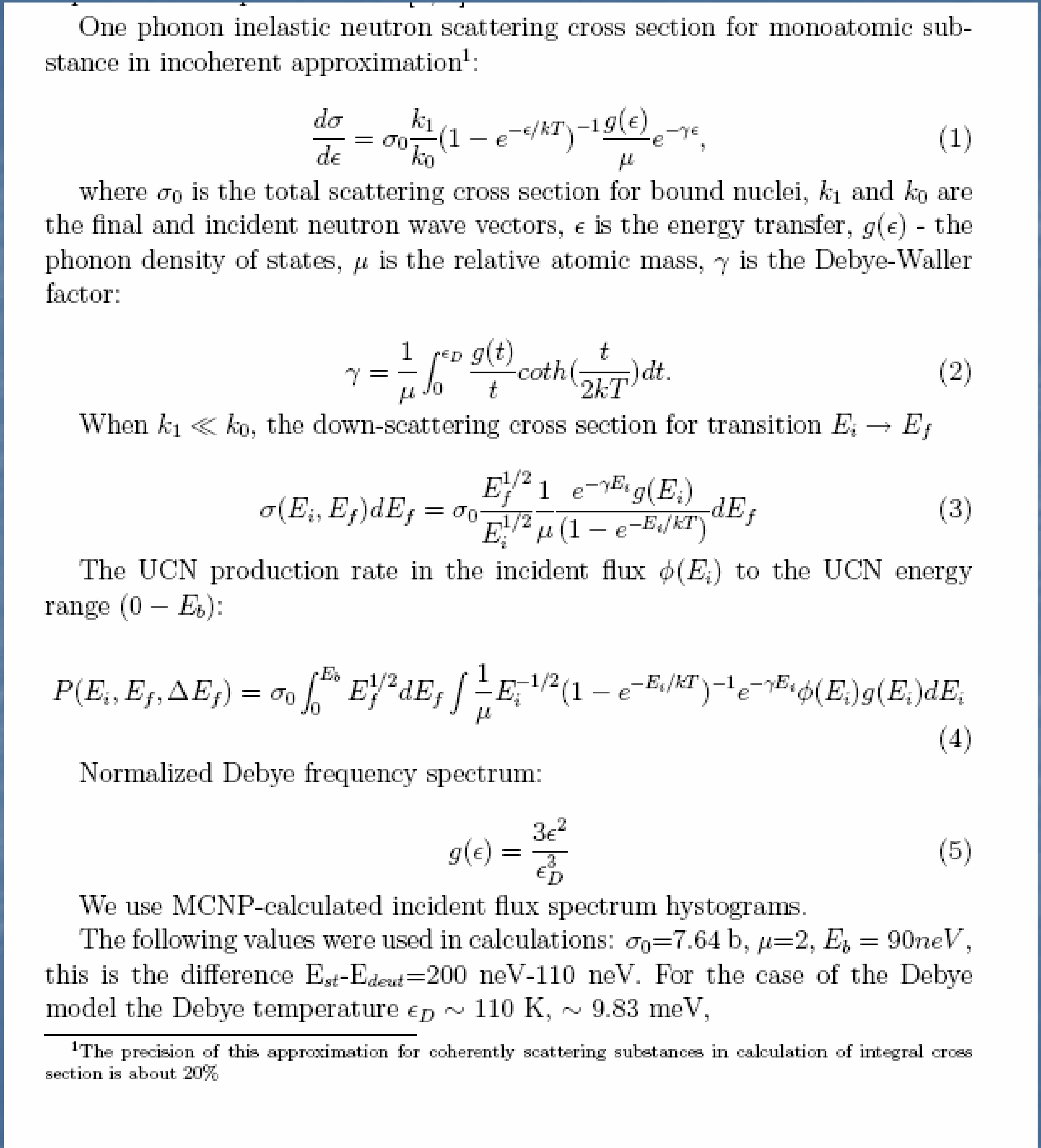


$\tau_{up} \approx$ 150 ms @ 5K

$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_{abs}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{para}} + \cancel{\frac{1}{\tau_{impurity}}}$$

Mean free path : $\langle\lambda\rangle$

$$\langle\lambda\rangle = \bar{v}_{ucn} \cdot \tau_{tot}$$



One phonon inelastic neutron scattering cross section for monoatomic substance in incoherent approximation[1]:

$$\frac{d\sigma}{d\epsilon} = \sigma_0 \frac{k_1}{k_0}(1 - e^{-\epsilon/kT})^{-1}\frac{g(\epsilon)}{\mu}e^{-\gamma\epsilon}, \qquad (1)$$

where $\sigma_0$ is the total scattering cross section for bound nuclei, $k_1$ and $k_0$ are the final and incident neutron wave vectors, $\epsilon$ is the energy transfer, $g(\epsilon)$ - the phonon density of states, $\mu$ is the relative atomic mass, $\gamma$ is the Debye-Waller factor:

$$\gamma = \frac{1}{\mu}\int_0^{\epsilon_D} \frac{g(t)}{t} coth(\frac{t}{2kT})dt. \qquad (2)$$

When $k_1 \ll k_0$, the down-scattering cross section for transition $E_i \to E_f$

$$\sigma(E_i, E_f)dE_f = \sigma_0 \frac{E_f^{1/2}}{E_i^{1/2}}\frac{1}{\mu}\frac{e^{-\gamma E_i}g(E_i)}{(1 - e^{-E_i/kT})}dE_f \qquad (3)$$

The UCN production rate in the incident flux $\phi(E_i)$ to the UCN energy range $(0 - E_b)$:

$$P(E_i, E_f, \Delta E_f) = \sigma_0 \int_0^{E_b} E_f^{1/2} dE_f \int \frac{1}{\mu} E_i^{-1/2}(1 - e^{-E_i/kT})^{-1} e^{-\gamma E_i}\phi(E_i)g(E_i)dE_i \qquad (4)$$

Normalized Debye frequency spectrum:

$$g(\epsilon) = \frac{3\epsilon^2}{\epsilon_D^3} \qquad (5)$$

We use MCNP-calculated incident flux spectrum hystograms.

The following values were used in calculations: $\sigma_0$=7.64 b, $\mu$=2, $E_b = 90neV$, this is the difference $E_{st}$-$E_{deut}$=200 neV-110 neV. For the case of the Debye model the Debye temperature $\epsilon_D \sim$ 110 K, $\sim$ 9.83 meV,

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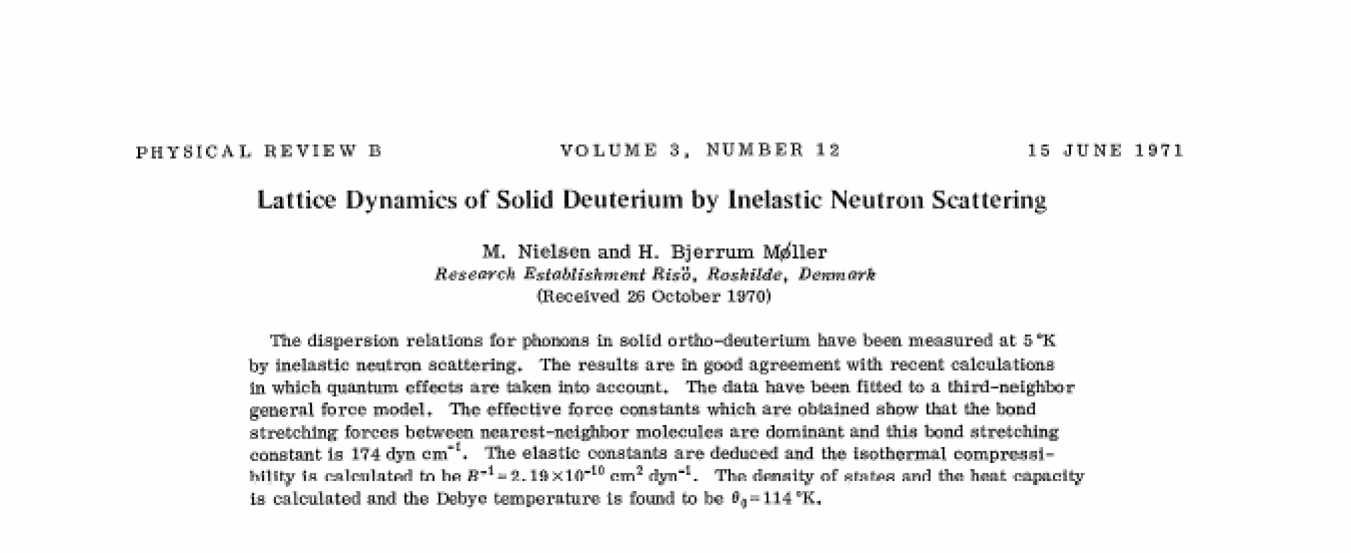
[1] The precision of this approximation for coherently scattering substances in calculation of integral cross section is about 20%



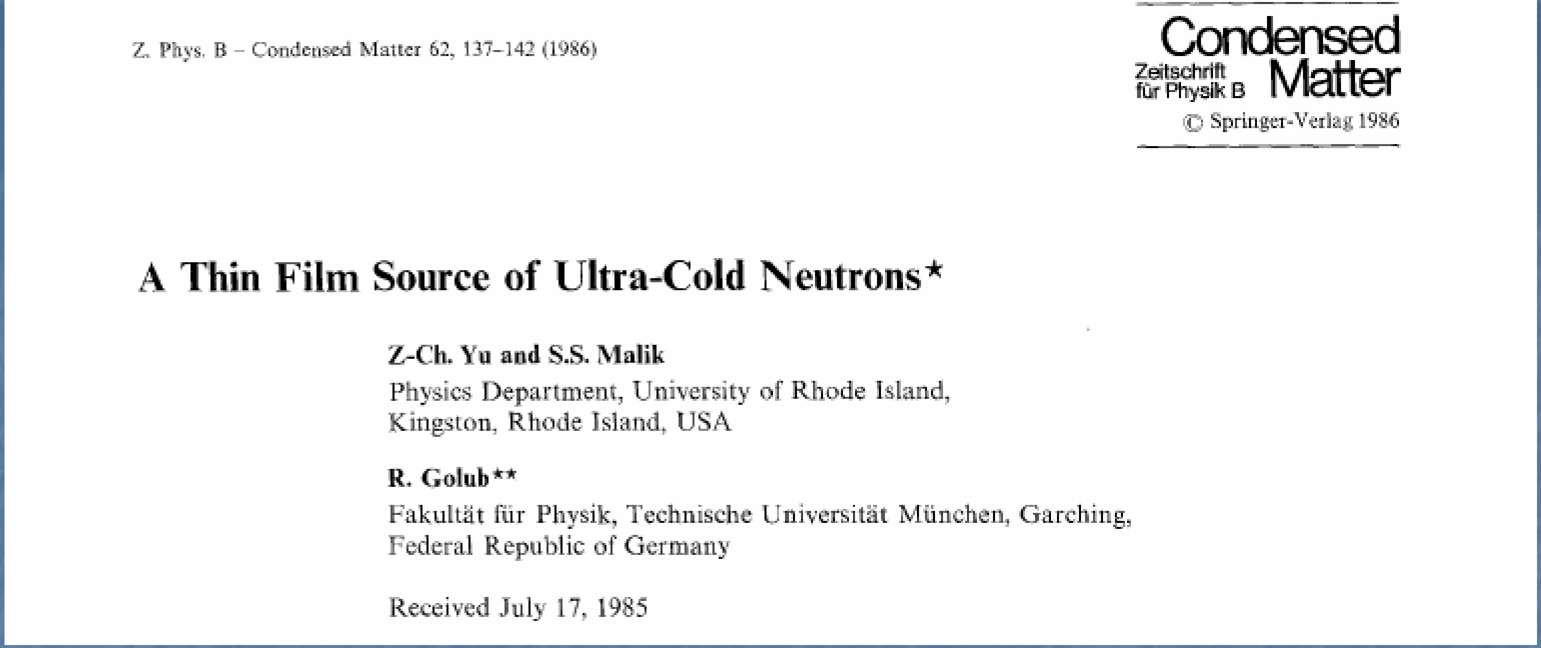
PHYSICAL REVIEW B VOLUME 3, NUMBER 12 15 JUNE 1971

# Lattice Dynamics of Solid Deuterium by Inelastic Neutron Scattering

M. Nielsen and H. Bjerrum Møller
*Research Establishment Risö, Roskilde, Denmark*

(Received 26 October 1970)

The dispersion relations for phonons in solid ortho-deuterium have been measured at 5 °K by inelastic neutron scattering. The results are in good agreement with recent calculations in which quantum effects are taken into account. The data have been fitted to a third-neighbor general force model. The effective force constants which are obtained show that the bond stretching forces between nearest-neighbor molecules are dominant and this bond stretching constant is 174 dyn $\mathrm{cm}^{-1}$. The elastic constants are deduced and the isothermal compressibility is calculated to be $B^{-1} = 2.19 \times 10^{-10}\ \mathrm{cm}^2\ \mathrm{dyn}^{-1}$. The density of states and the heat capacity is calculated and the Debye temperature is found to be $\theta_0 = 114$ °K.



Z. Phys. B – Condensed Matter 62, 137–142 (1986)

Condensed Matter
Zeitschrift für Physik B

# A Thin Film Source of Ultra-Cold Neutrons*

**Z-Ch. Yu and S.S. Malik**
Physics Department, University of Rhode Island,
Kingston, Rhode Island, USA

**R. Golub****
Fakultät für Physik, Technische Universität München, Garching,
Federal Republic of Germany

Received July 17, 1985

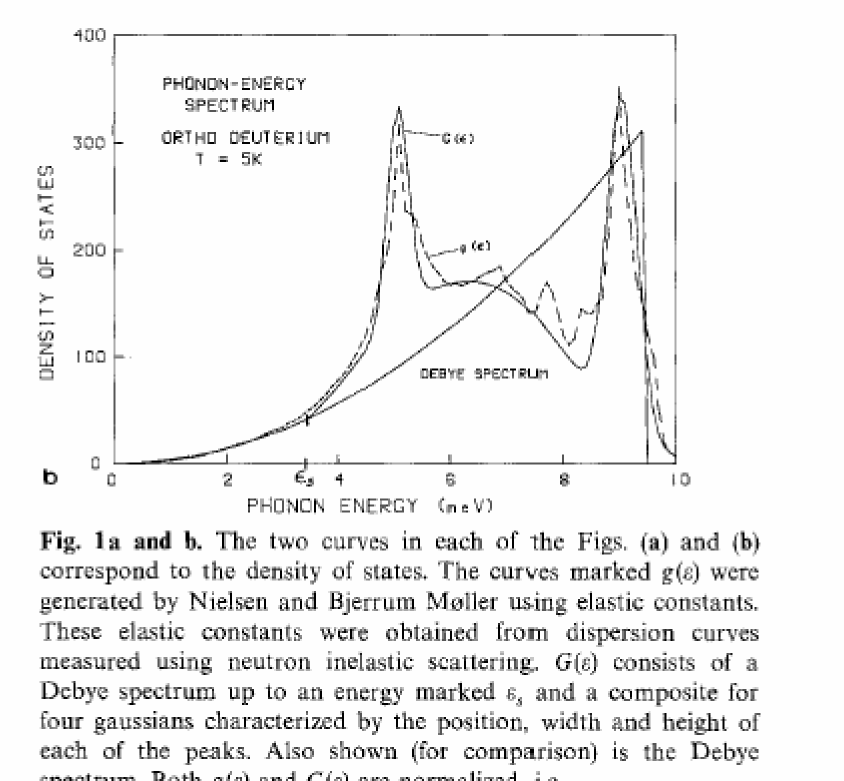
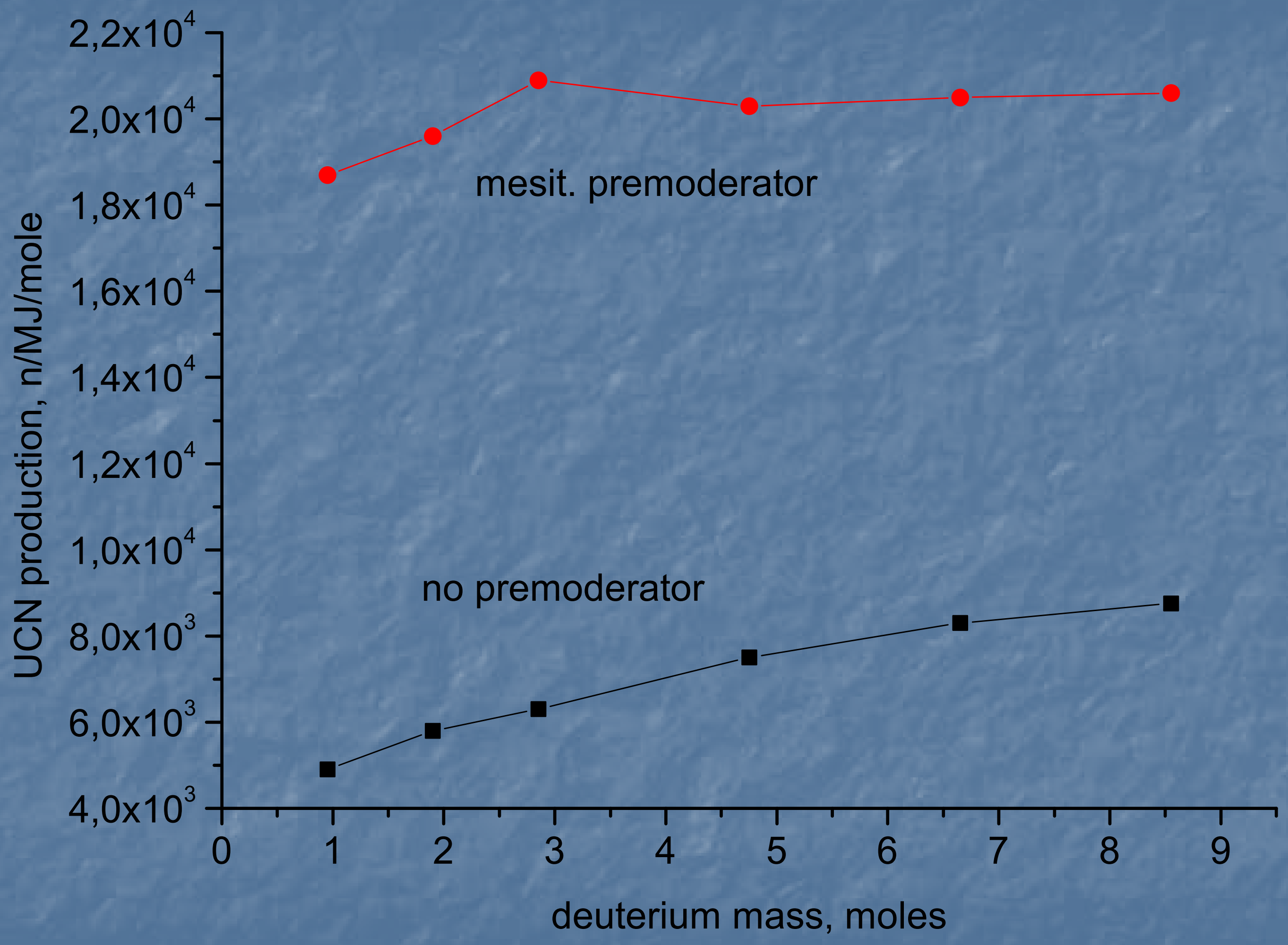
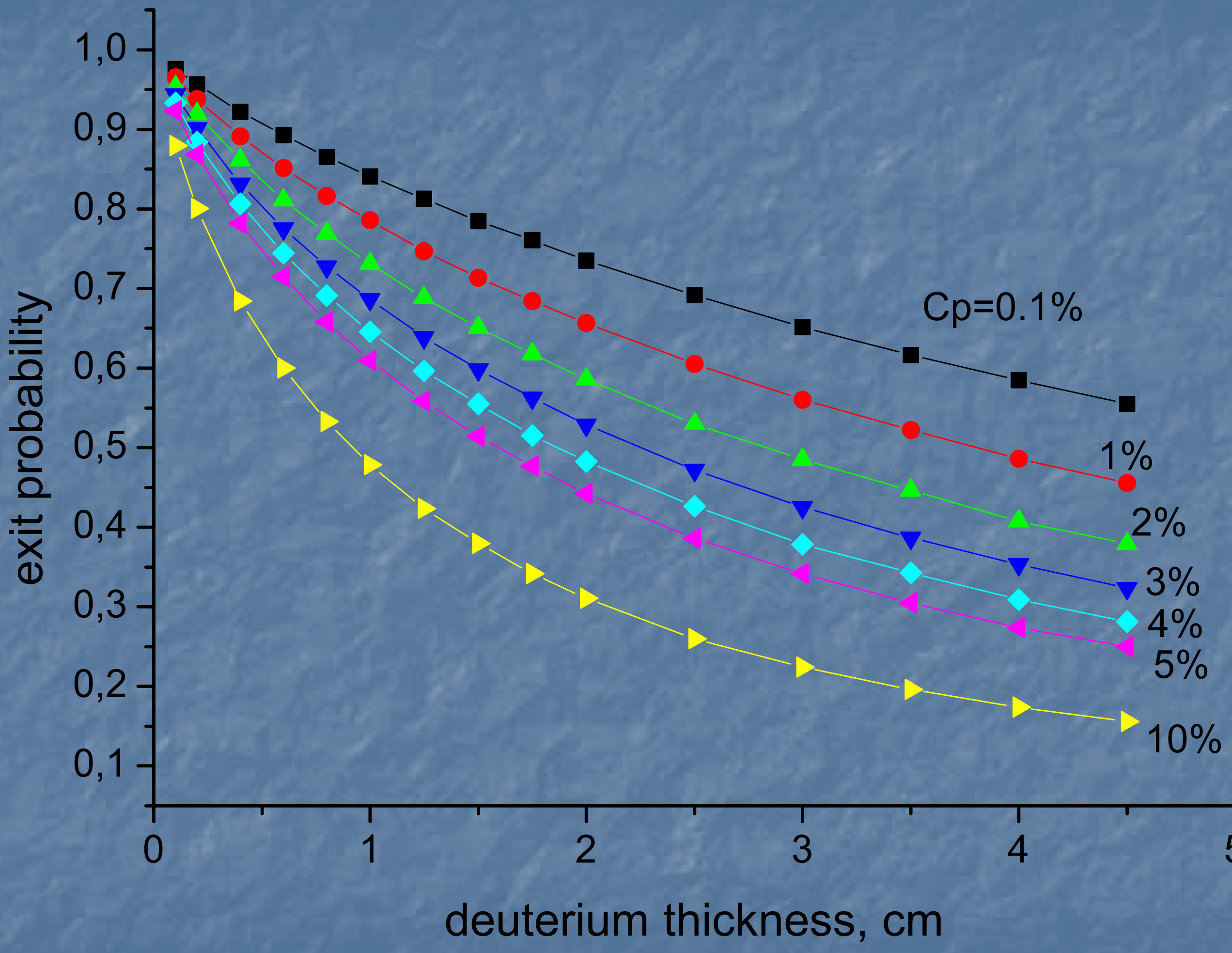
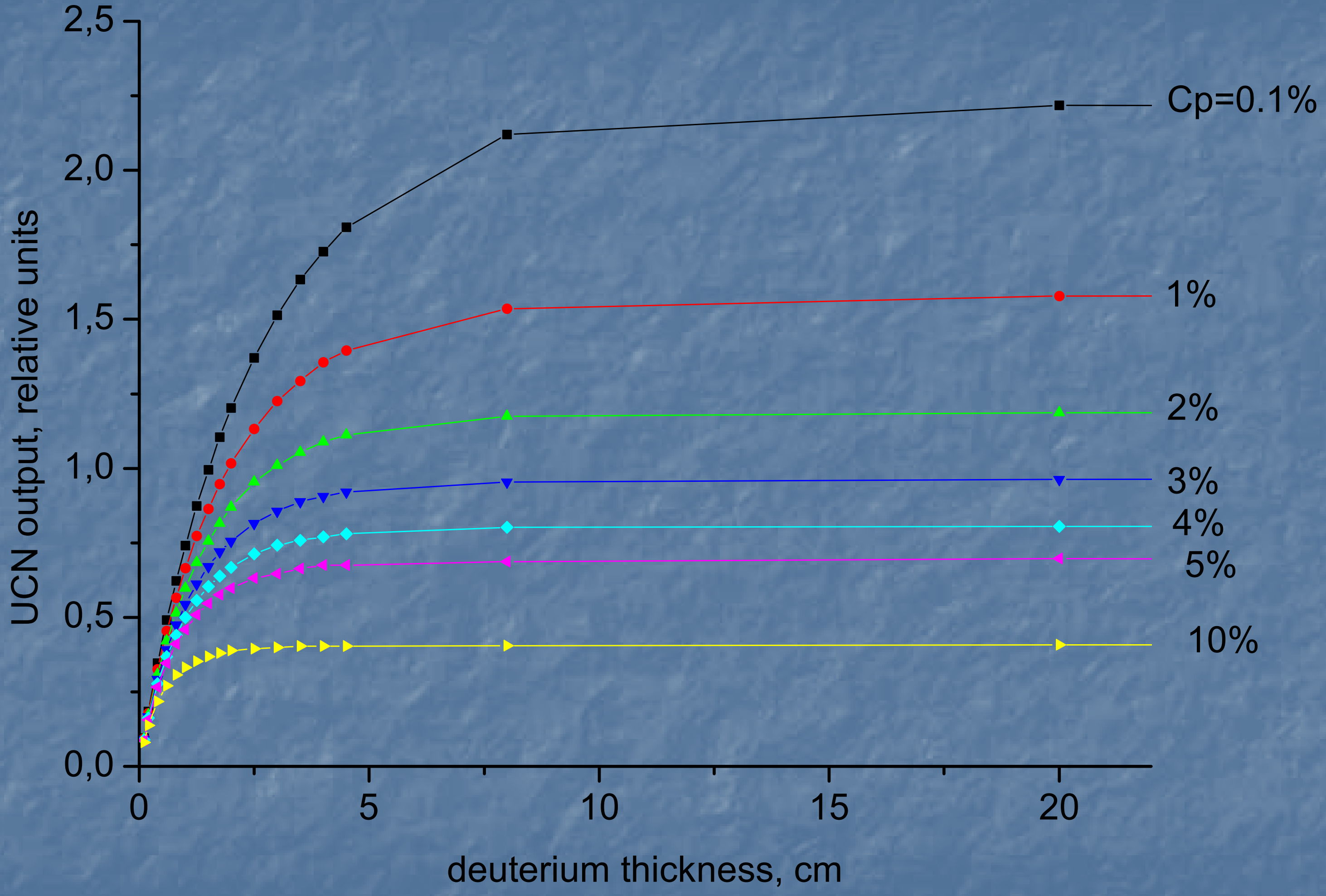


**Fig. 1a and b.** The two curves in each of the Figs. **(a)** and **(b)** correspond to the density of states. The curves marked $g(\varepsilon)$ were generated by Nielsen and Bjerrum Møller using elastic constants. These elastic constants were obtained from dispersion curves measured using neutron inelastic scattering. $G(\varepsilon)$ consists of a Debye spectrum up to an energy marked $\varepsilon_s$ and a composite for four gaussians characterized by the position, width and height of each of the peaks. Also shown (for comparison) is the Debye spectrum. Both $g(\varepsilon)$ and $G(\varepsilon)$ are normalized, i.e.

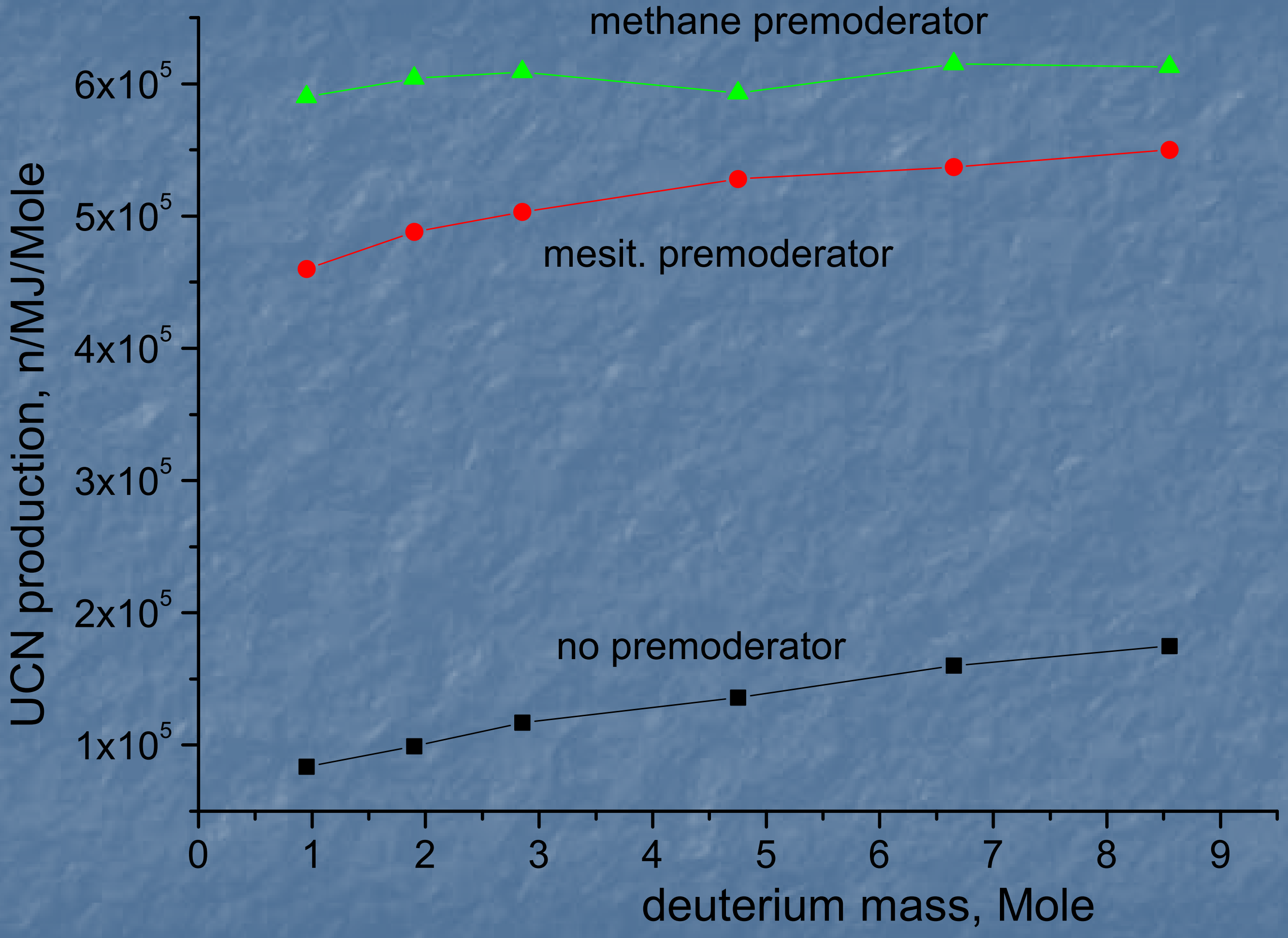


2,2x10$^4$
2,0x10$^4$
1,8x10$^4$
1,6x10$^4$
1,4x10$^4$
1,2x10$^4$
1,0x10$^4$
8,0x10$^3$
6,0x10$^3$
4,0x10$^3$
UCN production, n/MJ/mole
mesit. premoderator
no premoderator
0
1
2
3
4
5
6
7
8
9
deuterium mass, moles


exit probability
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
1
2
3
4
5
deuterium thickness, cm
Cp=0.1%
1%
2%
3%
4%
5%
10%



UCN output, relative units
2,5
2,0
1,5
1,0
0,5
0,0
0
5
10
15
20
deuterium thickness, cm
Cp=0.1%
1%
2%
3%
4%
5%
10%


methane premoderator
mesit. premoderator
no premoderator
UCN production, n/MJ/Mole
1x10^5
2x10^5
3x10^5
4x10^5
5x10^5
6x10^5
0
1
2
3
4
5
6
7
8
9
deuterium mass, Mole

# Conclusion

- First results of UCN production at the pulsed TRIGA reactor Mainz
  $\approx$ 200 000 UCN / pulse

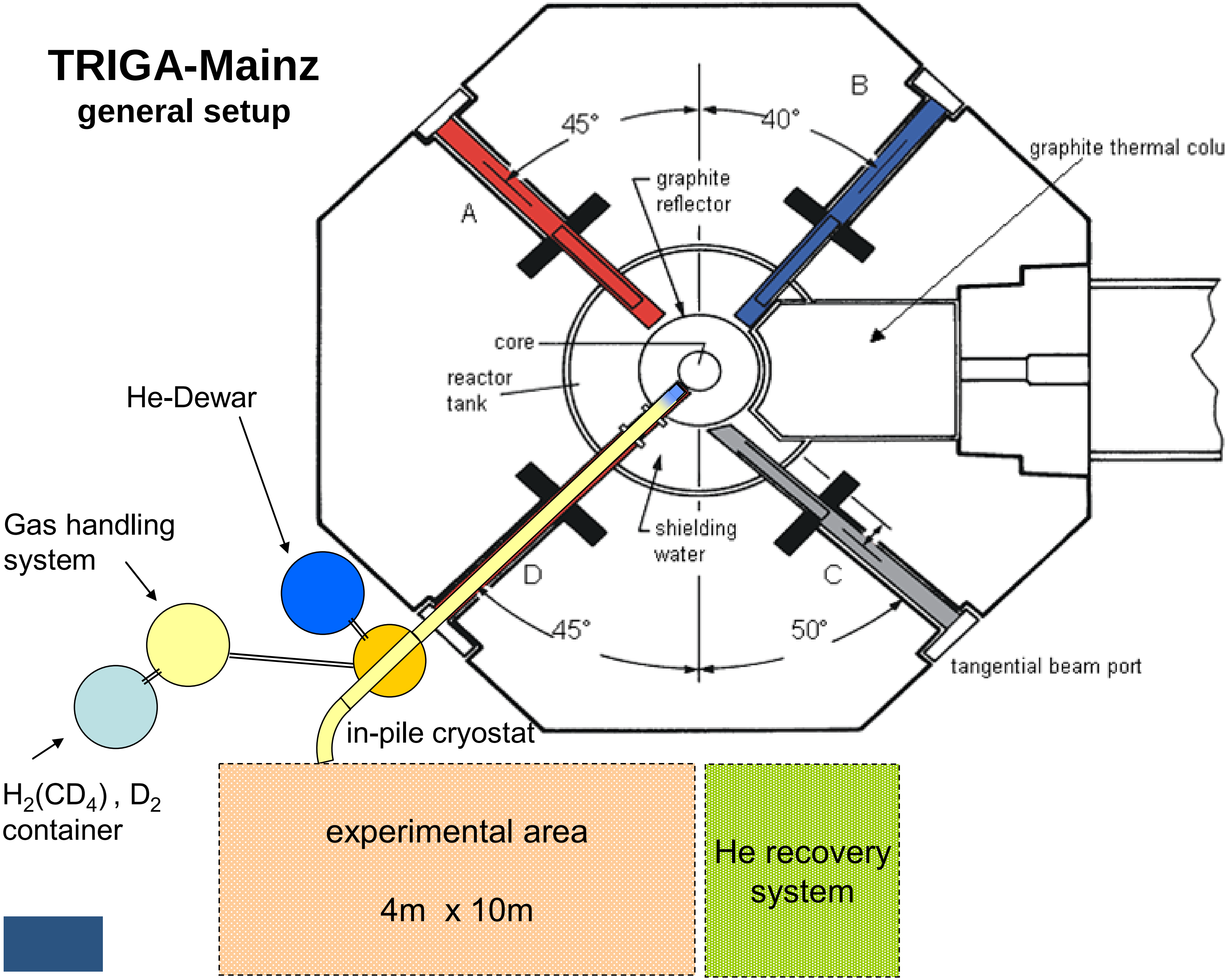
- expected gain factor: $\approx$ 50 - 100

  - beam tube D
  - premoderator $H_2$, $CH_4$
  - $^{58}$Ni coating
  - ... _

- status: UCN-source at D under construction
- time schedule: in operation from 2008 on

# TRIGA-Mainz

## general setup



He-Dewar

Gas handling system

$H_2(CD_4)$ , $D_2$ container

in-pile cryostat

experimental area

4m x 10m

He recovery system