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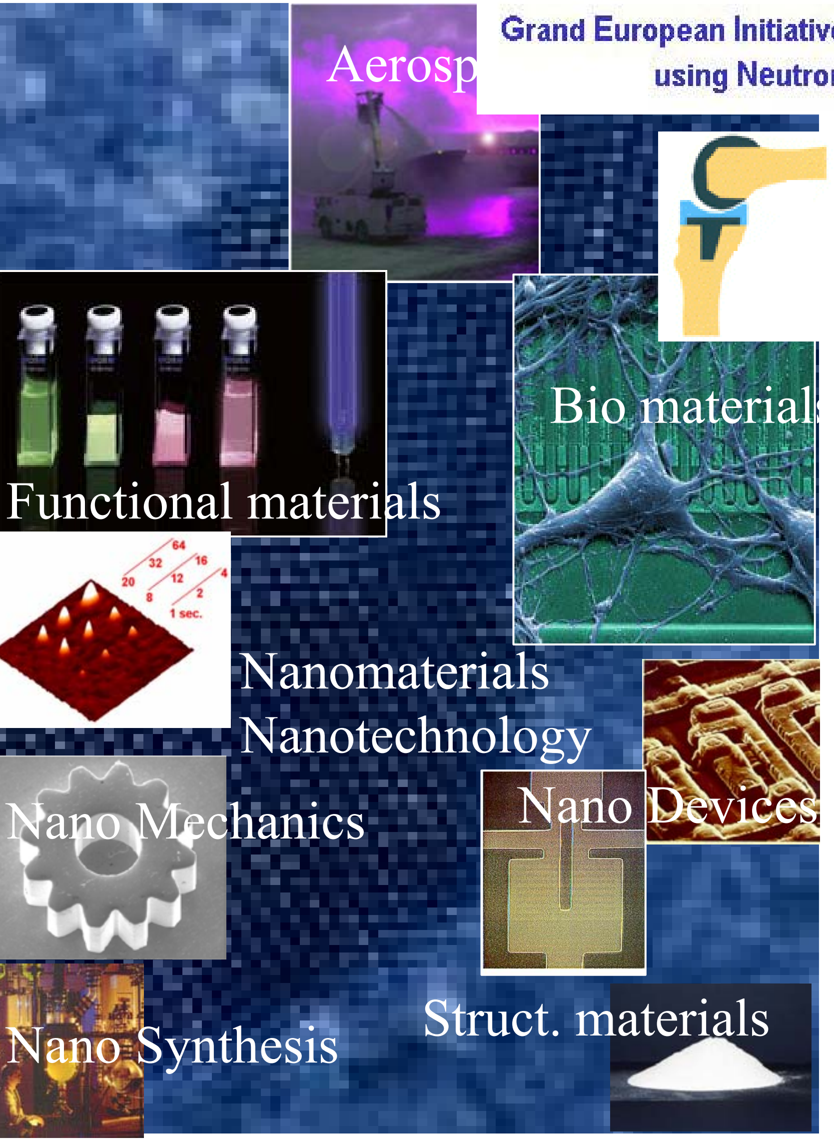
I Nanoscience and neutron fluxes
  a) What neutrons cannot do
  b) What neutrons can do

II Some scientific and experimental perspectives

III Some far-future perspectives

GENNESYS

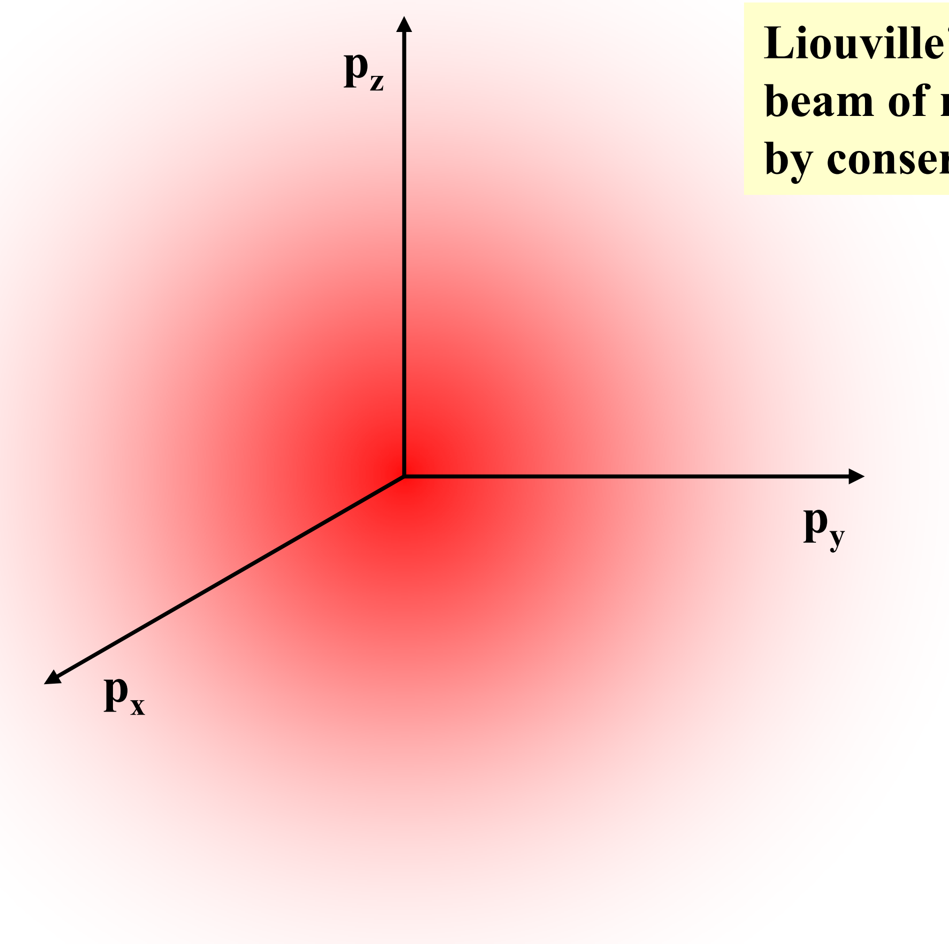
Grand European Initiative on Nanoscience and Nanotechnology using Neutron and Synchrotron Sources



GAP

Nanoscience and neutron fluxes a) What neutrons cannot do

The phase space density (in 6D) of a thermal source is constant in the centre.
It drops with exp(-E/kT); $E = p^2/2m$



a)

Liouville's theorem: The phase space density of a beam of non-interacting particles can't be increased by conservative forces acting on the ensemble.

Constant phase space density:

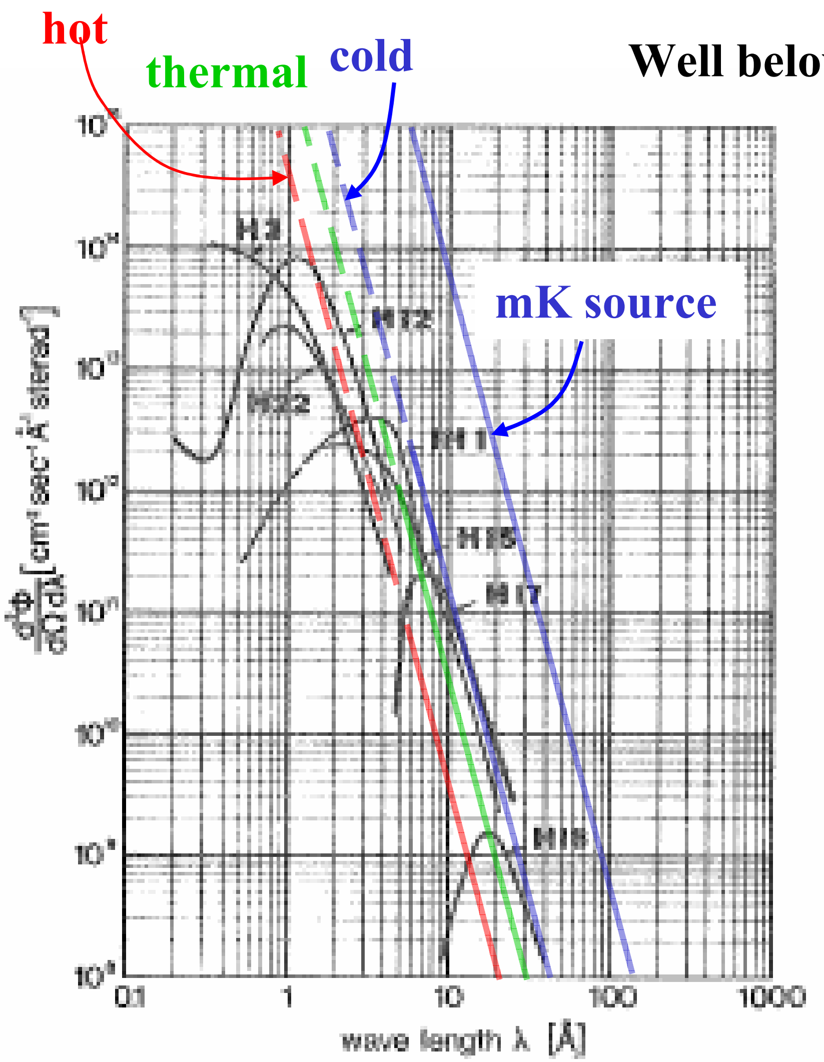
a) Imaging ($|P|$ = const.)

b) Acceleration ($P_2^2 = P_1^2 + 2mE$)

Increase of phase space density

c) Cooling !

d) Non-equilibrium production



The brilliance of ILL Grenoble

Well below kT: $B = \dfrac{d^2\Phi}{d\lambda\, d\Omega} \approx \left(\dfrac{\lambda_0}{\lambda}\right)^5 \times N \left[\dfrac{\text{neutrons}}{\text{cm}^2\ \text{s Å sterad}}\right]$

$\lambda_0 = 1$Å;

≈ $8 \cdot 10^{15}$ for cold source λ ⏲ 5Å;

≈ $2 \cdot 10^{15}$ for thermal source λ ⏲ 3Å;

Implications of Liouville's theorem:

a) Imaging (| P | = const.):
Stay at the point of B where you are;

b) Acceleration ($P_2^2 = P_1^2 + E \cdot 2m$):
Move along $1/\lambda^5$ line; N = constant;

c) Cooling !
Move the $1/\lambda^5$ line to the right; increase N;

* Gain brightness by starting with a colder source and accelerating the beam;

Nanoscience and n-beam brilliance: What neutrons can't do

The mean brilliance of SNS will be less by a factor of ≈ 3
the peak brilliance of SNS will be higher by a factor ≤ 100;

Can we examine single nanoparticles with neutrons?

The brilliance of a beam of non-interacting particles can't be changed if $<\lambda>$ = const.

2 examples (for ILL brilliance):

Diffraction: **Collimated beam of 3 Å±10% and 10^{-5} sterad :**
An area of 10×10 nm^2 is passed by 0.00005 n/s.

Imaging: **Focused microbeam of 5 Å±10% and 1 sterad :**
An area of 10×10 nm^2 is passed by 2.6 n/s.

The typical interaction probability along 10 nm is in the range of ⏲10^{-5};

⇒ Direct examination of a single nano-particle is not possible at present neutron sources;

The brilliance of a synchrotron (FEL) is ≈ 14 (17) orders of magnitudes above a n-source.

Nanoscience and coherence: What neutrons can do

Neutron beams have just the right coherence volumes to observe he internal structure and the space/time correlations of ensembles of nanoparticles. But µg – mg are needed

Lateral: $x_c = \dfrac{L}{k \cdot a} = \dfrac{\lambda}{2\pi} / \alpha$; α = 'backward beam divergence';

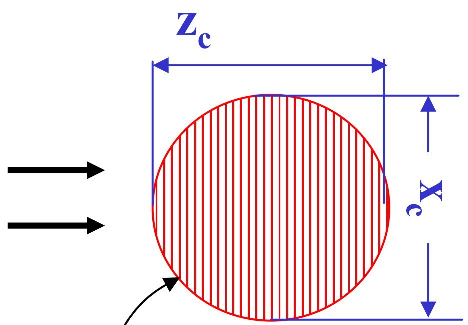
Longitudinal: $z_c = \lambda^2/(2\pi\Delta\lambda)$; steady state beam

$$V_c \cdot \Delta p^3 = ◎^3$$

Examples:

1) Diffraction: $x_c = y_c =$ 10 nm for λ = 2 Å and $\alpha \approx 4 \cdot 10^{-3}$;

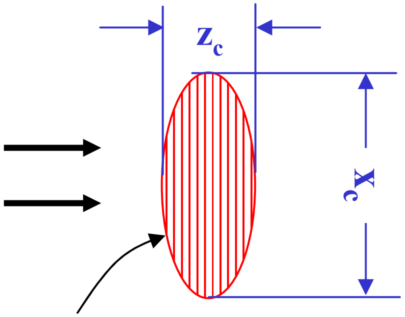
$z_c =$ 10 nm for λ = 2 Å and $\Delta\lambda/\lambda \approx 6 \cdot 10^{-3}$;



make it spherical for equal resolution in all dimensions!

2) SANS: $x_c =$ 10 (100) nm for λ = 6 Å and $\alpha = 10^{-2}$ (10^{-3});

$z_c =$ 1 nm for λ = 6 Å and $\Delta\lambda/\lambda \approx 0.1$;



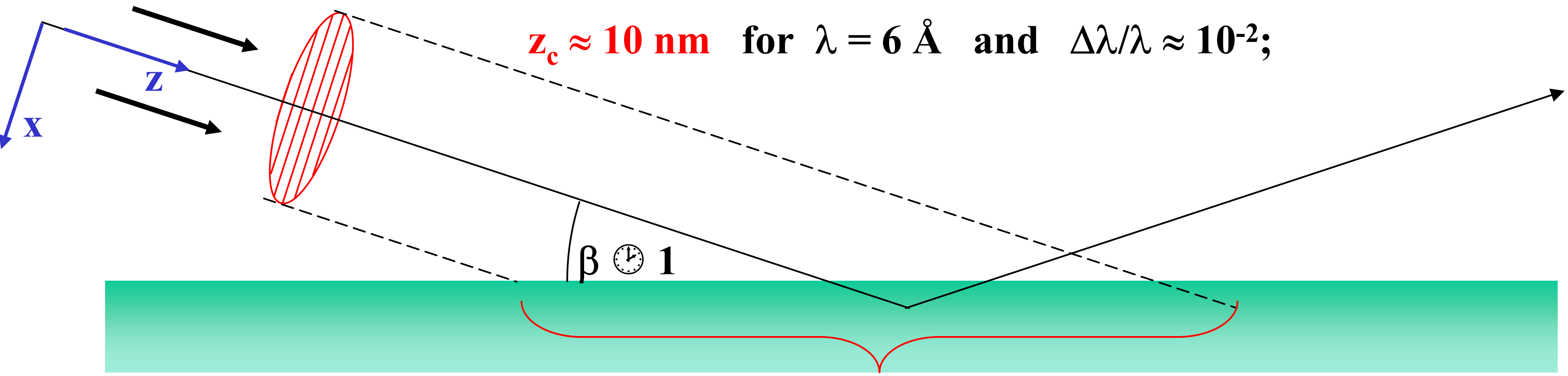
only lateral resolution counts!

3) Reflectometry:

$x_c \approx 100$ nm* for $\lambda = 6$ Å and $\alpha = 10^{-3}$; high resolution geometry

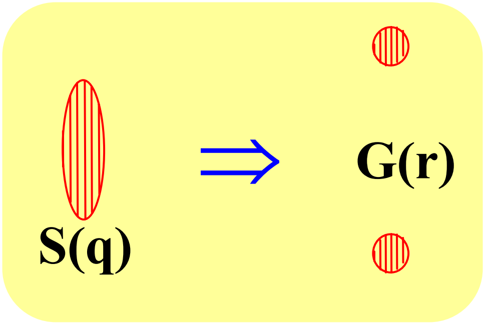
$y_c \approx 3$ nm for $\lambda = 6$ Å and $\alpha = 3 \cdot 10^{-2}$;

$z_c \approx 10$ nm for $\lambda = 6$ Å and $\Delta\lambda/\lambda \approx 10^{-2}$;



Along the beam direction, a length $l_c \approx \beta \cdot x_c \approx 10000$ nm is probed! Time difference!
Normal to the surface, a length of $\approx x_c$ is probed.

***For more, split laterally the coherence volume!**
⇒ Sergis, NRSE, R. Pynn’s magn. foils;



$I \sim 1/V_c$

Time Scales Accessed by Neutron Scattering

from Paul Butler, NIS

Coherence times:

$\tau = 1/(v\cdot\Delta k)$ Crystal Spectrometers ($\Delta E = E_i - E_f = \hbar\omega$)

$\Delta E \geq 0.1$ meV $\tau \leq 6 \times 10^{-12}$ s

$\tau = t_0/(2\omega_0 T)$ Time-Of-Flight Spectrometers

$\Delta E \geq 10$ µeV $\tau \leq 6 \times 10^{-11}$ s

$\tau = 1/(v\cdot\Delta k)$ Backscattering Spectrometers

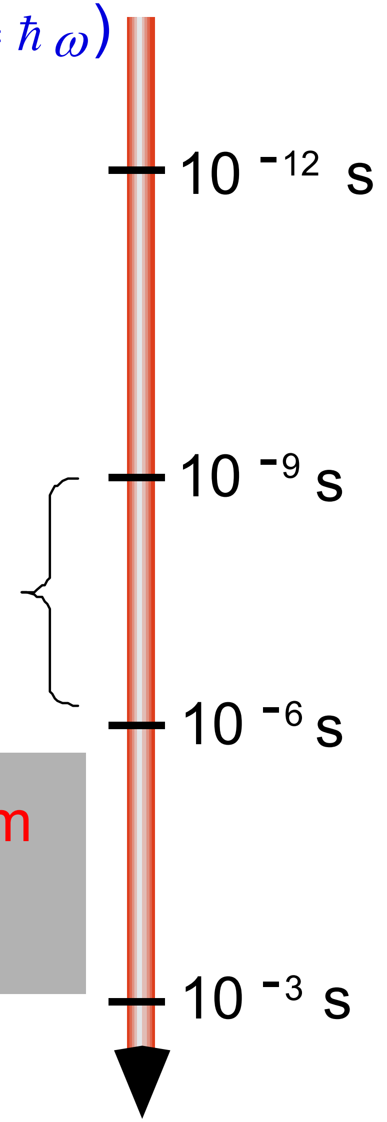
$\Delta E \geq 1$ µeV $\tau \leq 6 \times 10^{-10}$ s

$\tau = \omega_L t_0/(2\omega_0)$ Spin-Echo Spectrometers $\tau \leq 10^{-7}$ s

measuring the time modulation transfer function of a system

Time-Involved Small-Angle Neutron Experiments

Time-Slicing 'Snap Shots' $t \geq 10^{-1}$ s



Neutron contribution to nanoscience; some general remarks;

Neutrons hardly ever do anything else than examining the nanoworld.

For magnetism on an atomic base, neutrons with there magnetic moment are the major tool

Nanostructure of interfaces can be probed with high resolution; (new reflectometry method

Fundamental properties of nano-fluids (in porous media) are explored with neutrons.

'Going beyond the Bragg peak' will be a major topic in n-diffraction.

The subtle electronic structure of nanoparticles is not disturbed by neutrons.

For biological samples, the controlled H-D exchange is the major tool for labeling.

On biological samples, neutrons only cause very low radiation damage.

Realistic environments for living matter can be realized.

Neutrons allow experiments at extreme sample environments.

Requested sample volumes may be reduced (1 – 3 orders of magnitude)

by 4π analysis (this can only be done once)

by new techniques, using multi beams.

Neutron contribution to nanoscience

Using more correlation (spin echo) and modulation techniques will enhance resolution.

Using more correlation (spin echo) and modulation techniques will enhance resolution.

The time gap between 1ms and 1 μs should be closed (for example: dynamics of mycelles).

The development of the coherence picture clearly defines the space/time range of computation.

Joint tomography with neutrons and X-rays. The software for joint evaluation is still missing.

Neutron tracer methods are very sensitive (absorption cross section Gd-157 ≈ 1Mb @ 7 Å)

Neutrons and synchrotrons may share sample environment; (ESRF + ILL: 30-40T Magnet ?)

II Some scientific and experimental perspectives for nanoscience

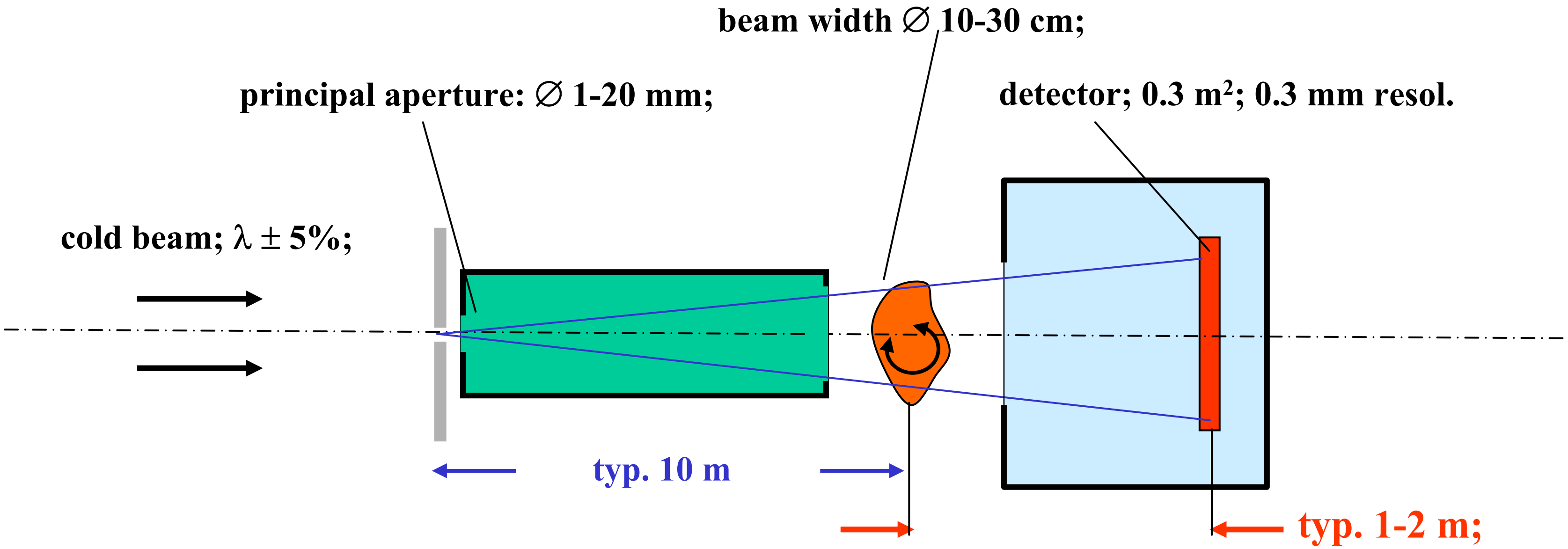
Assuming that we cannot increase brilliance, there may be only few possibilities:

- **Uniting present techniques in a new way**
- **Multiplying instruments**
- **Introducing new techniques**

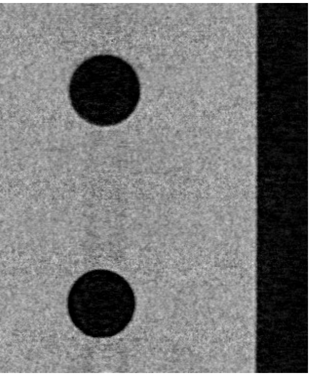
1) 3D mapping of nano-structured materials: SANS-TOMOGRAPHY;

Standard Tomography uses absorption for contrast;
SANTORIN uses SANS for contrast;
Application: high tech materials;

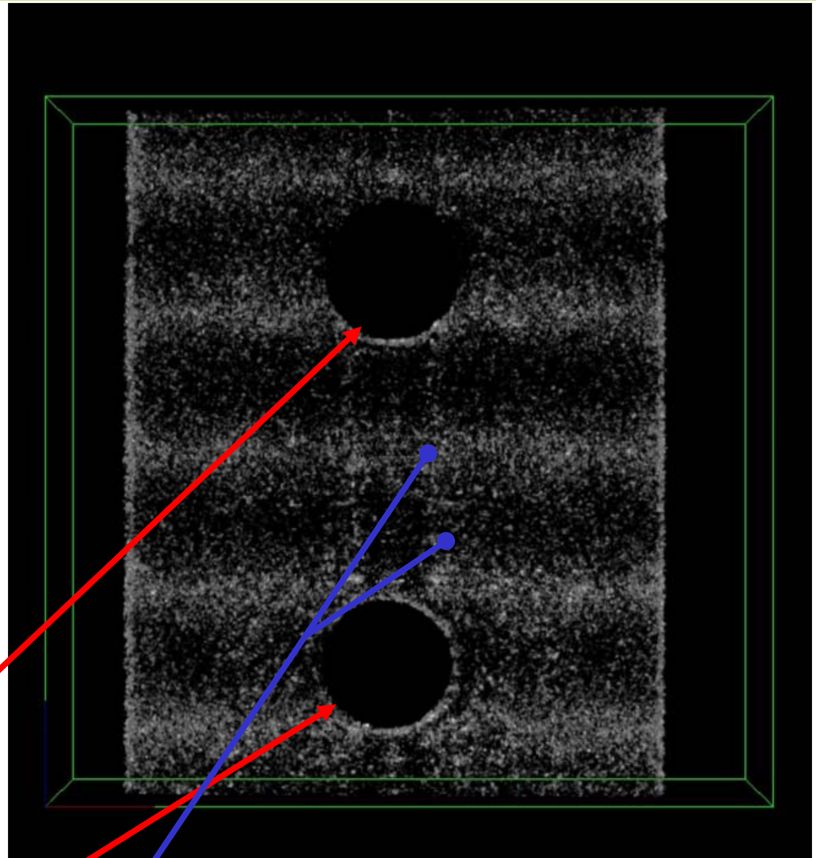
SANTORIN:
Small ANgle TOmographic and Radiographic Imaging with Neutrons



SANTORIN: Example; Strength of aircraft components



Standard radiography



SANS radiography

Ordinary hole

widened hole

Waves from rolling

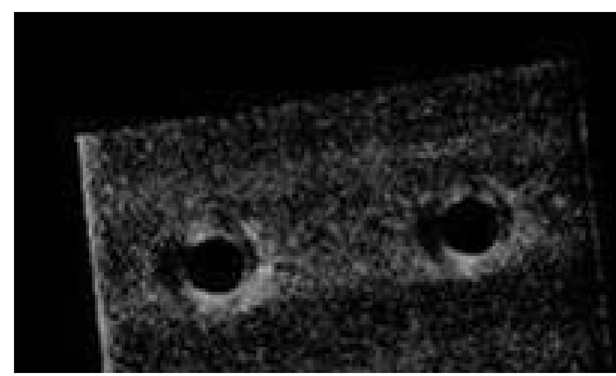
Holes (in Al) widened with a thor

⇒ high-strength rims (texture!).

⇒ Increased SANS

effect not visible at ordinary holes

This will open a new field!



SANS radiography of tapered holes

No change in composition but in texture;

2) Large scale structures, typ. size ⏲ 1 μm : USANS option; SAMBA

SAMBA: Small Angle Multi Beam Analysis

There is need to examine nano- and microstructured materials for larger correlation lengths!

Examples:

- Nanotube-clustering in glue
- Micro-structure of tires
- Bubbles in Vicor glass
- Oil in Sediments
- Hardening of concrete
- Structure of marble

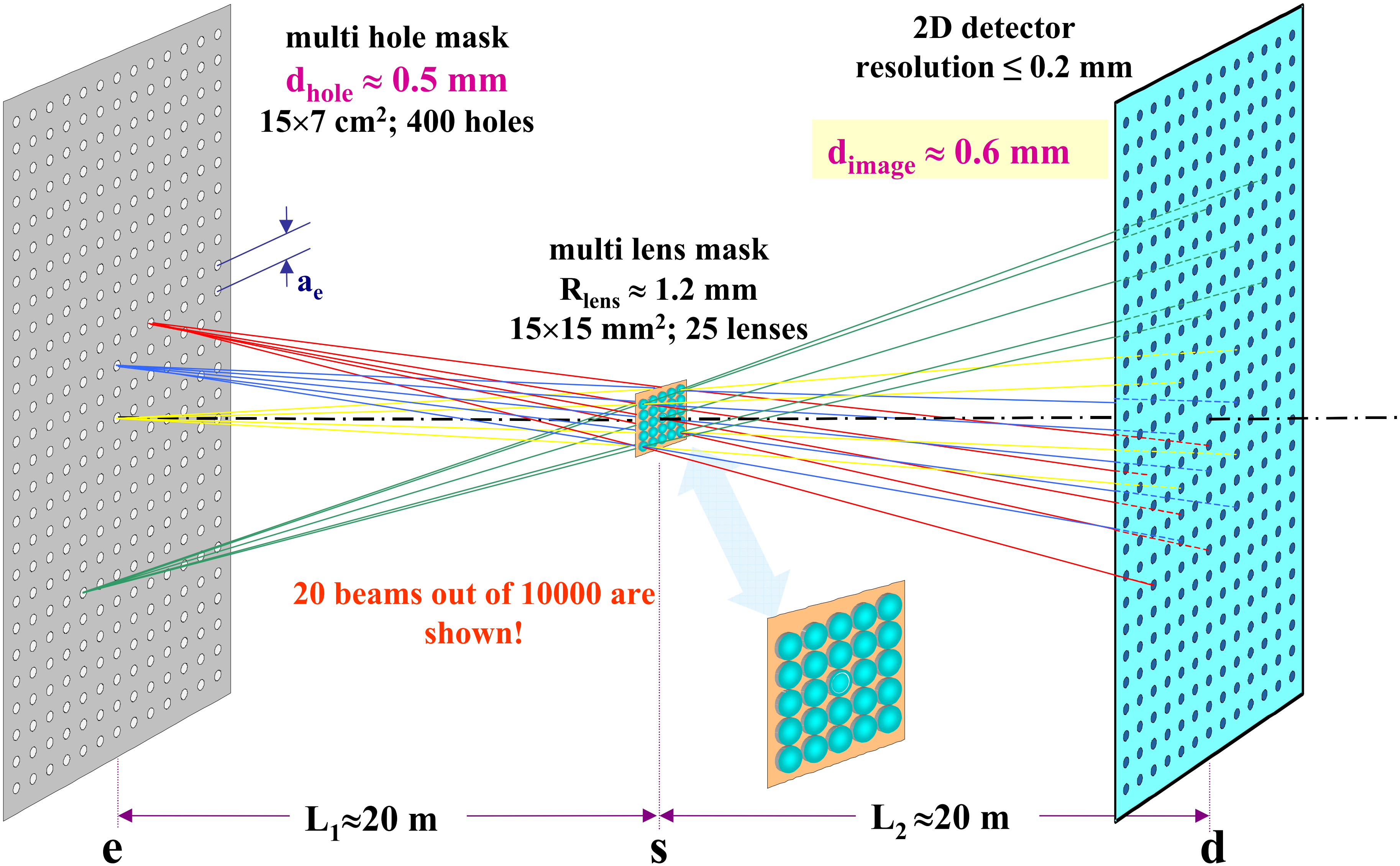
Aim: Extend beam correlation length l_C by factor 10 in 2dimensions at standard SANS machines: $l_C = 1000$ Å $\Rightarrow$ $l_C = 1$ μm

Consequence for standard SANS: $I \Rightarrow 10^{-4} I_0$ (too low!)

SAMBA uses up to 10^4 narrow beams with $l_C = 1$ μm

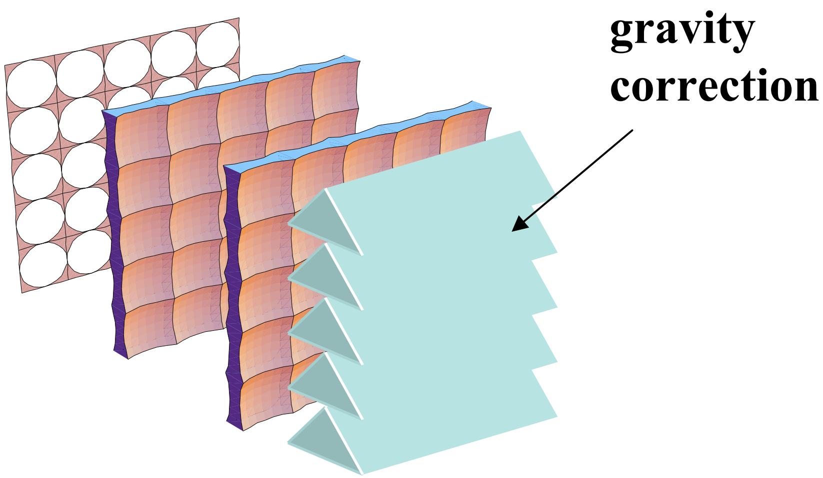
Only moderate loss in intensity but sacrifice in q-range

SAMBA in two dimensions at long base-line SANS machine:



SAMBA: Multi lens and image quality

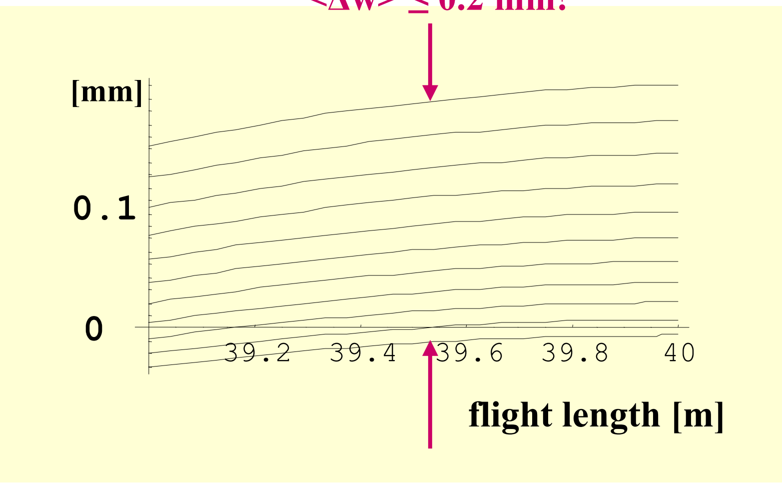
Multi lens + prisms



2 lenses R = 2.28 mm

mean spherical aberration: 0.12 mm;

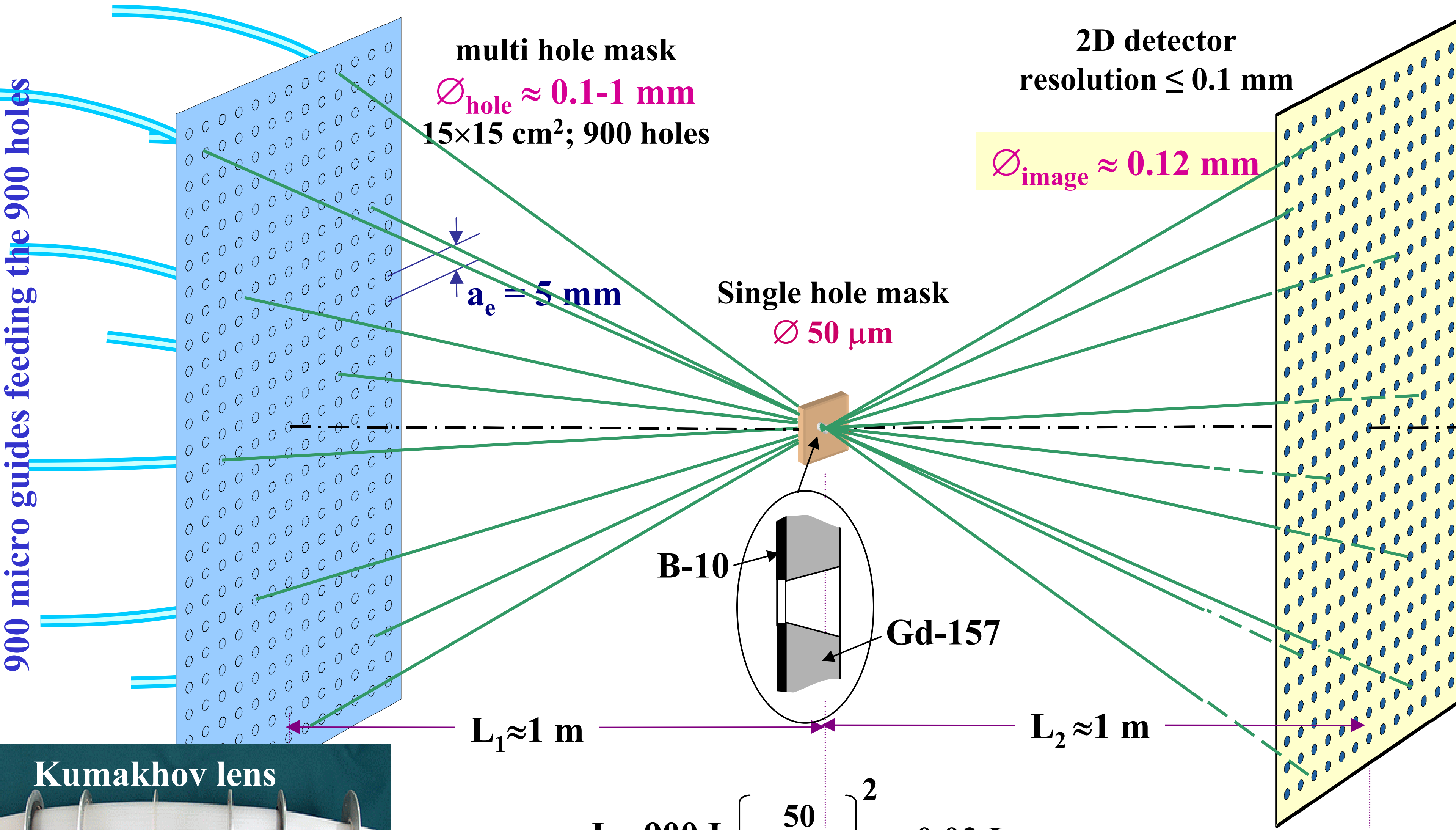
Image quality



mean distortion: 0.2mm;

Mean image width including all aberrations: 0.6 mm after 40 m flight path

2) SANS (with standard q-resolution) for 50 μm samples;



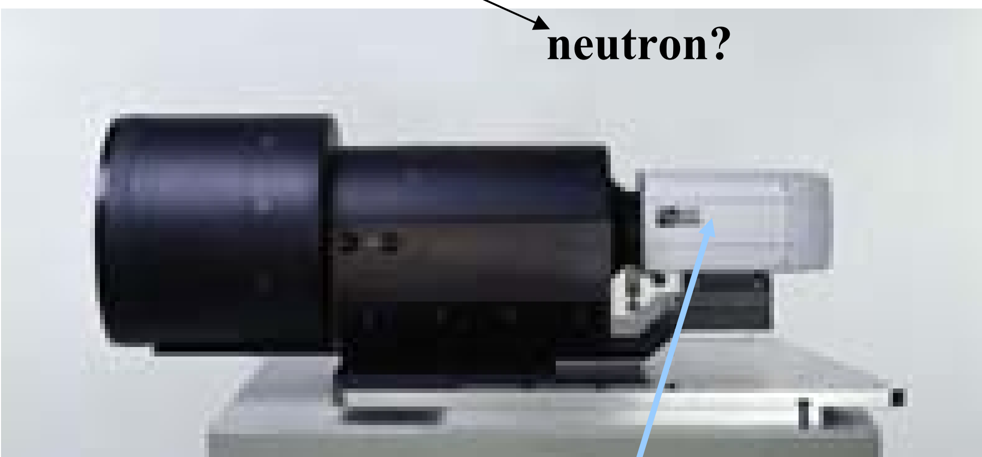
$$I = 900\, I_0 \left[\frac{50}{10000}\right]^2 = 0.02\, I_0;$$

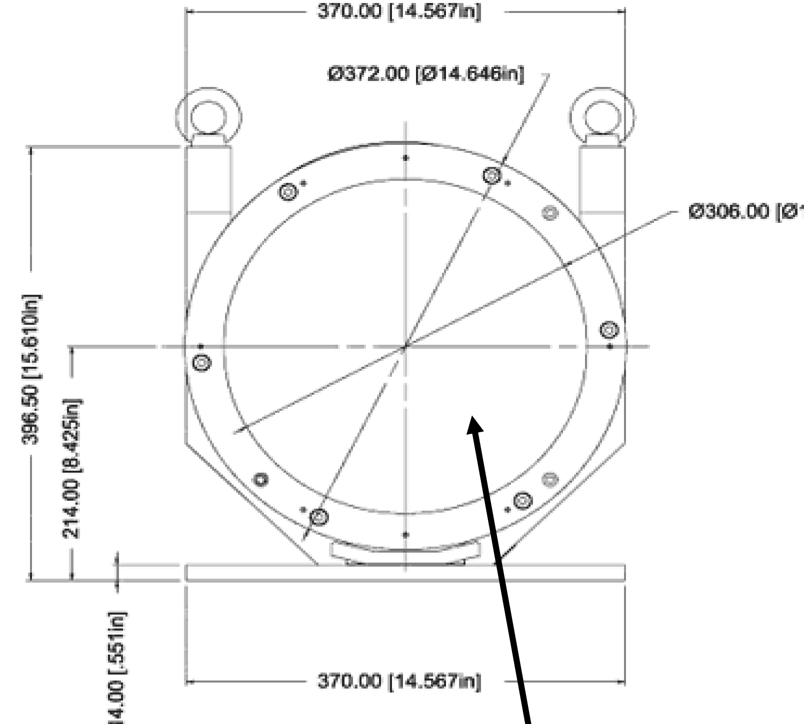
I_0 for standard SANS

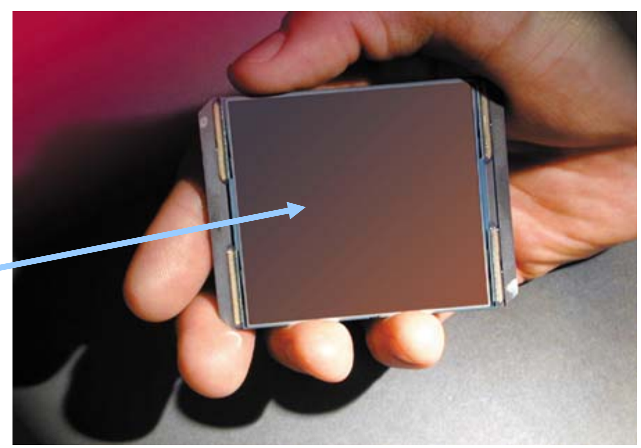
off the shelf camera system [luxury]

BRUKER ADVANCED X-RAY SOLUTIONS

neutron?







resolution:
73µ on ∅ 300 mm

CCD: 62 × 62 mm
15µ; 4096 4096

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R SCIENCE

C) Fast dynamics of (magnetic) structures; 10 μs time res. - TISANE

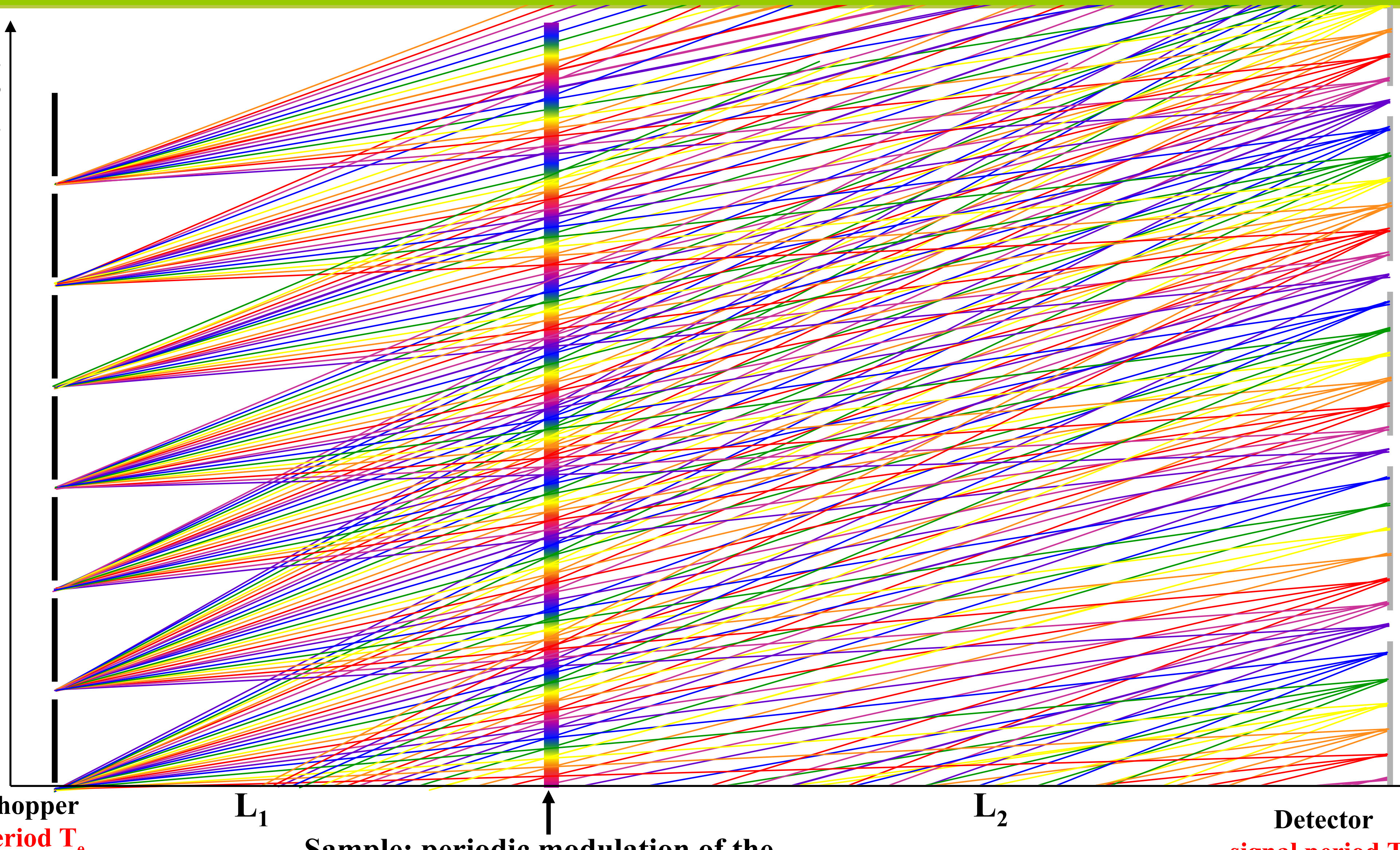
TISANE:
TIme-resolved Small Angle Neutron Experiments;

TISANE measures the time-modulation transfer function of a SANS sample for frequencies up to some hundred kHz, using a broad wavelength band;

Examples:

- **Pseudo-crystalline ordering in ferrofluids induced by B-fields; (first tests)**
- **Conformational changes of photoactive membrane-proteins**
- **ion-driven conformational changes in model-membranes**
- **Ferro-electrics ?**
- **Spintronics ?**

TISANE - principle:



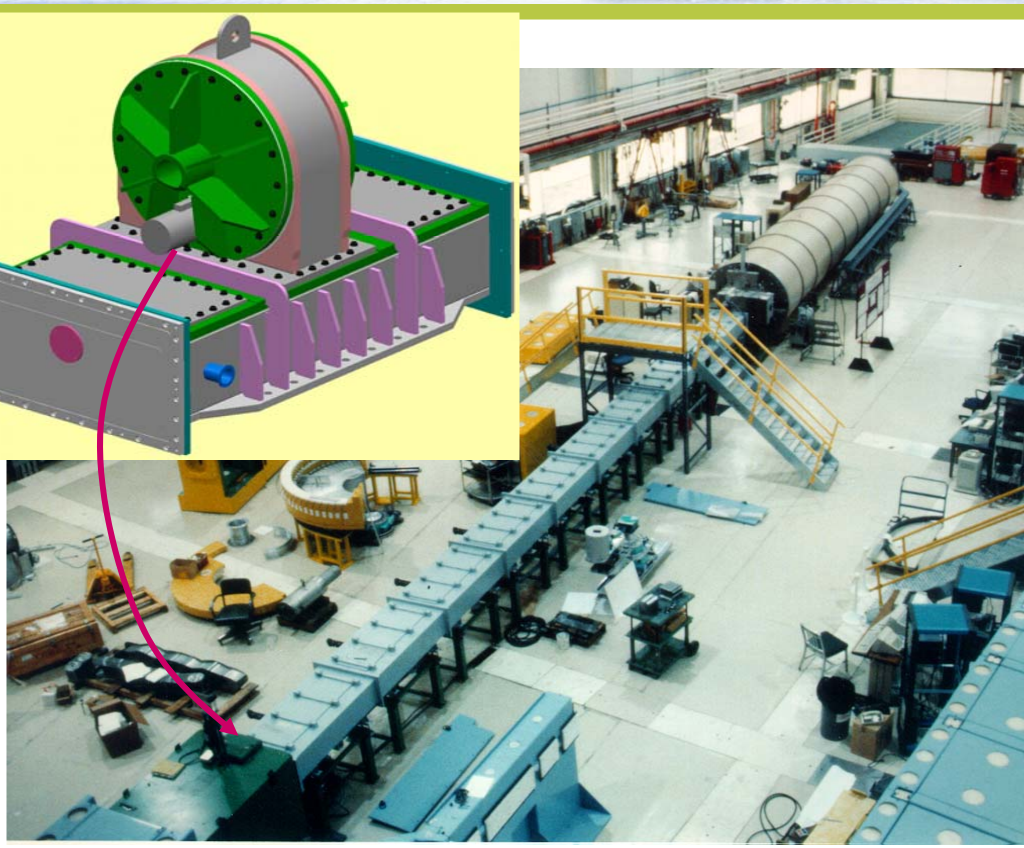
Sample; periodic modulation of the SANS properties with period T_s

Time resolution 10 µs

R.

TISANE Coming on line in summer ➔ lining up projects

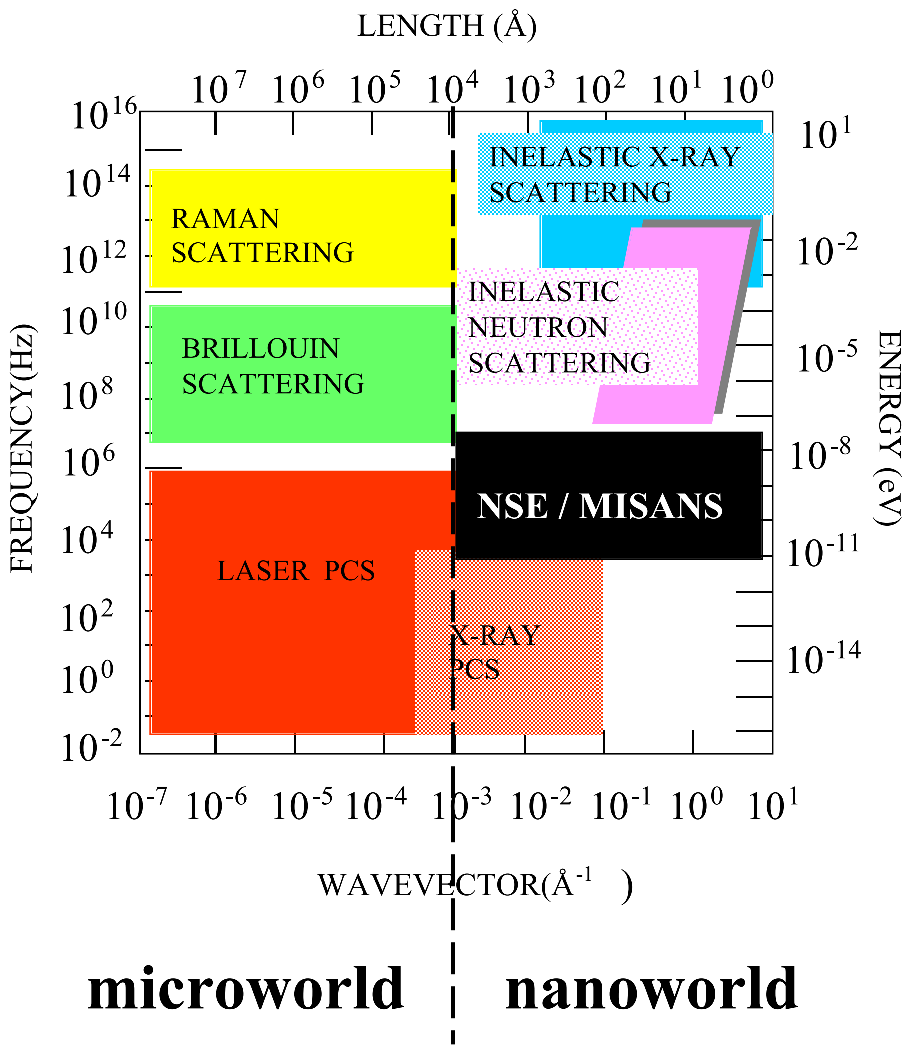
from Paul Butler, NIST



- structure in complex fluids induced by oscillatory shear (Bill Hamilton - ONRL, Lionel Porcar U. MD/NIST, Paul Butler NIST)
- biological processes, e.g. muscle contraction and membrane response to electrical fields (Ken Rubinson - CARB)
- double network polymer gels under compression loading (Wen-Li Wu – NIST Polymer)
- vortex structure as a function of oscillating driving current near the peak effect regime (Sean Ling – Brown University)
- T jump and P jump (Bill Hamilton - ORNL)

ccess to time scales inaccessible by
ny other neutron technique

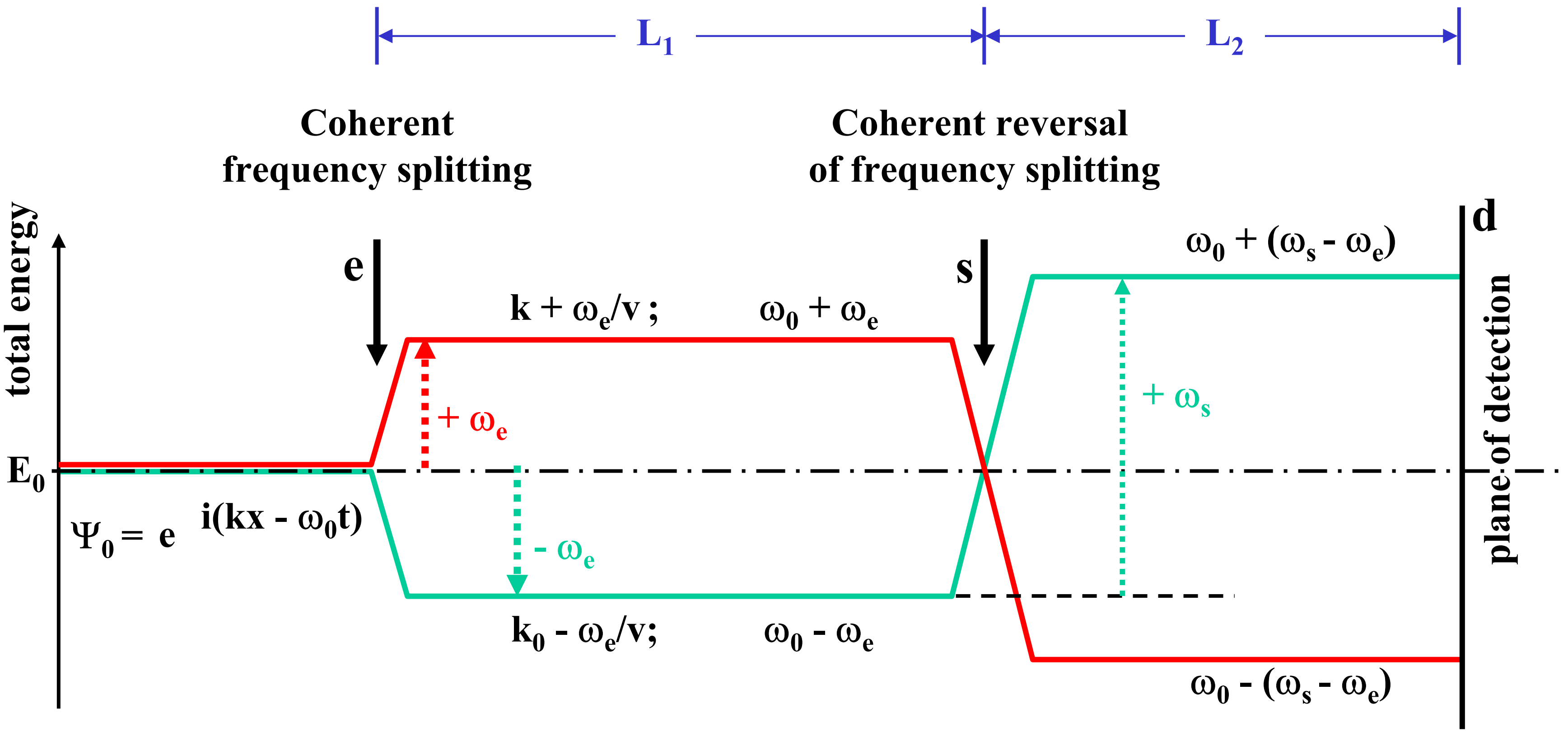
At small scattering angles, typical for SANS on large/medium nano-particles, the dynamics cannot be sensed by classical TOF methods. (time resolution!)



Field of applications:

- macro-molecules (e.g. Mycelles);
- Polymers
- Biology;

MISANS – principle; Mach-Zehnder Interferometer in Time



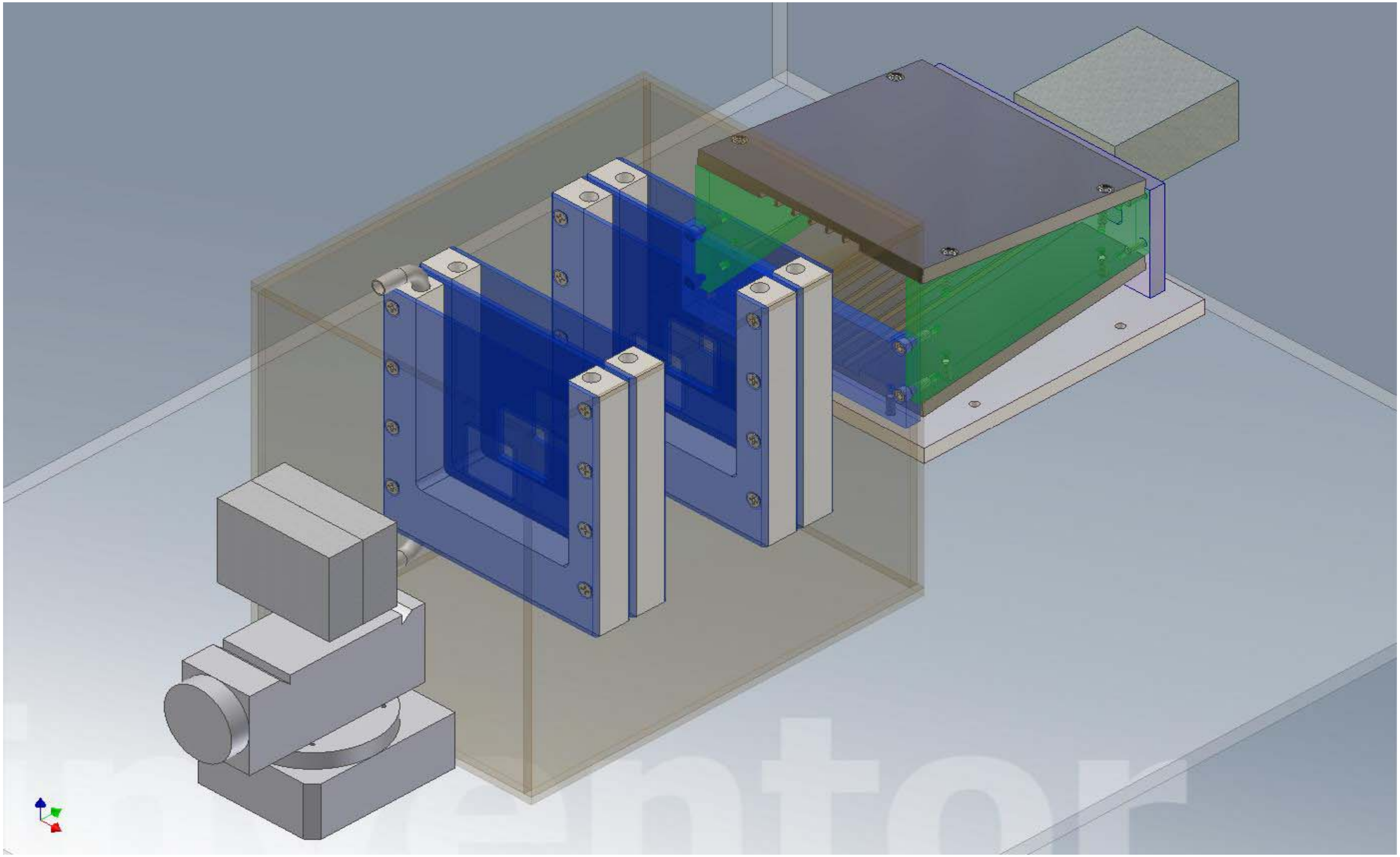
$$\Psi_{detector} = \begin{bmatrix} e^{+i(\Delta k_e L_1 - \Delta k_s L_2)} \; e^{-i(\omega_s - \omega_e)t} \\ e^{-i(\Delta k_e L_1 - \Delta k_s L_2)} \; e^{+i(\omega_s - \omega_e)t} \end{bmatrix} \Psi_0$$

$\Delta k_e = \omega_e/v$;

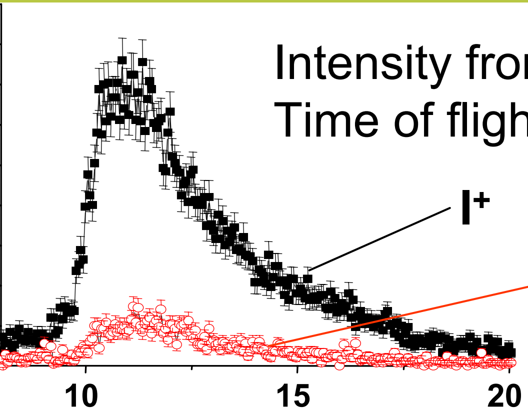
$\Delta k_s = (\omega_s - \omega_e)/v$;

For $\omega_e L_1 = (\omega_s - \omega_e) L_2$, $\Psi_{detector}$ gets independent from v. $\Rightarrow$ beats in time with $\omega_d = (\omega_s - \omega_e)$

MISANS – first tests at ANL (pulsed source)

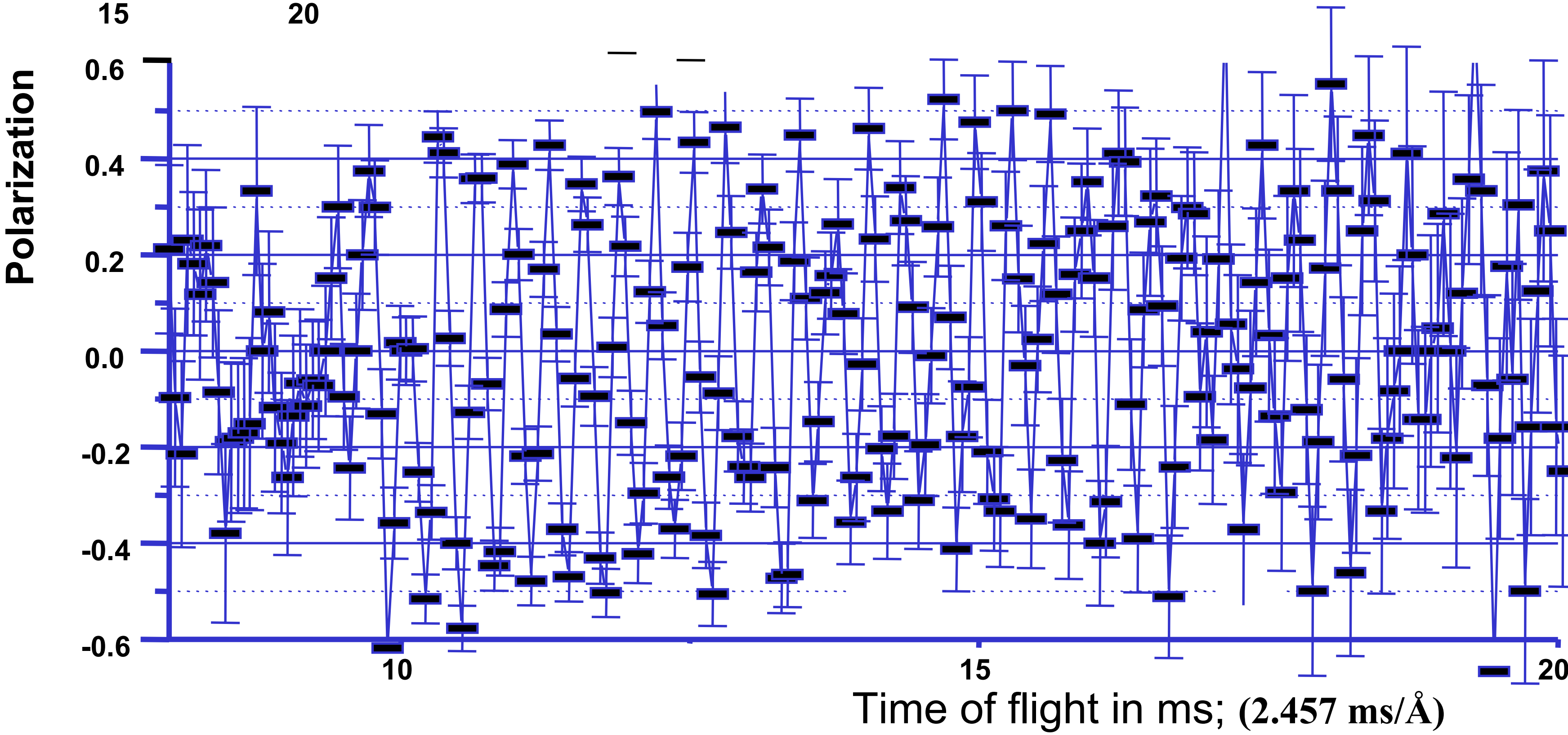


MISANS – first signals;



Intensity from pulsed source;
Time of flight in ms; **(2.457 ms/Å)**

MIEZE signal at 2kHz (+ Larmor precession)
Signal frequency limited by detector response;



Outlook

1) Cancer Therapy using nano technology

2) How to boost neutron brilliance at existing sources?
for single shots in time-resolved reactions
or for smaller samples

3) Beyond the SNS?

« Nanoparticles reveal tiny cancerous tumors »

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Europe's Premier Nanomedicine Conference of 2005
2005
5th-9th September Edinburgh, Scotland
EuroNanoForum

ecially designed nanoparticles can reveal tiny cancerous tumors that are invisible by ordinary ans of detection, according to a study by researchers at Washington University School of dicine in St. Louis.

cause nanoparticles can be engineered to carry a variety of substances, they also may be able iver cancer-fighting drugs to malignant tumors as effectively as they carry the imaging materia t spotlight cancerous growth.

e spherical nanoparticles can carry about 100,000 molecules of the metal used to provide ntrast in MRI images. This creates a high density of contrast agent, and when the particles bind pecific area, that site glows brightly in MRI scans.

this study, MRI scans picked up tumors that were only a couple of millimeters (about one twent h of an inch) wide.

nall, rapidly growing tumors cause growth of new blood vessels, which feed the tumors. To get particles to bind to tumors, the researchers equipped them with tiny "hooks" that link only to mplementary "loops" found on cells in newly forming blood vessels. When the nanoparticles oked the "loops" on the new vessels' cells, they revealed the location of the tumors.

These Nanoparticles may not be poisonous and may be used as jumbo-carriers for B-10
Revival of BNCT ?

How to boost the brilliance at existing sources?

It needs a higher phase space density in the source. ⇒ cooling

By cooling from 300 K to 4 K, the phase space density increases by 600!

Solid D2 at 4K produce UCN; Storage in bottle for 1000 s → Extraction and beam shaping by Wanderfeld → Final acceleration by moving crystal to cold/thermal n;

Beyond the SNS?

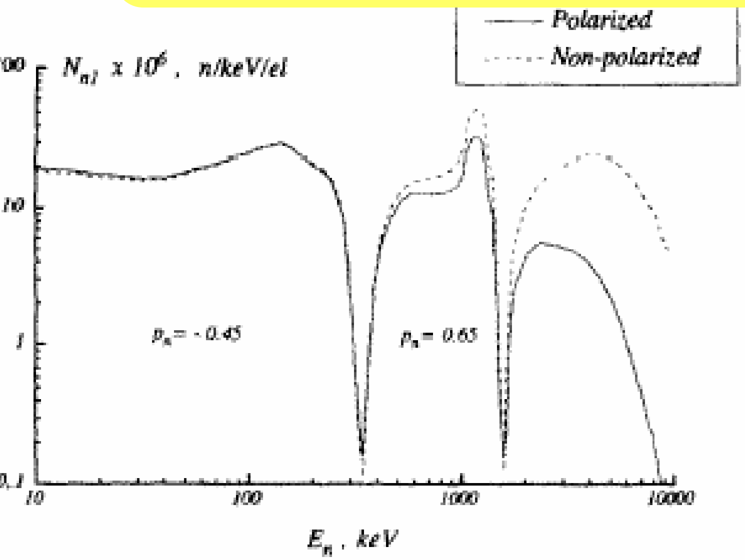
Nuclear Instruments and Methods in Physics Research A 405 (1998) 225–228

A method for producing polarized neutrons by the magnetic bremsstrahlung γ-radiation

I.P. Eremeev[a], A.L. Barabanov[b],*

[a]International Business Nucleonic, Moscow, Russia
[b]Russian Research Centre "Kurchatov Institute", Moscow, Russia

e^- → wiggler → γ → Be(γ,n) → n



. 1. The spectra of polarized (solid curve) and non-polarized
shed curve) photoneutrons produced in the ^{9}Be target by
cularly and linearly polarized MB γ-rays, respectively.

MB polarization	Linear	Circular
Q_γ	0	0.90
$N_{\gamma 1}$, q/el	35.4	16.6
$\Phi_{\gamma 1}$, q/cm^2 el	435	175
P_n	0	0.45–0.65
N_{n1}, n/el	0.18	0.045
$\dot{\Phi}_{n1}$, n/cm^2 s el	3.7×10^8	4.6×10^7
N_n, n/bunch	1.1×10^{11}	2.8×10^{10}
$\dot{\Phi}_n$, n/cm^2 s	2.3×10^{20}	2.9×10^{19}
$\langle \dot{N}_n \rangle$, n/s mA	1.1×10^{15}	2.8×10^{14}
$\langle \dot{\Phi}_n \rangle$, n/cm^2 s mA	1.2×10^{15}	1.5×10^{14}