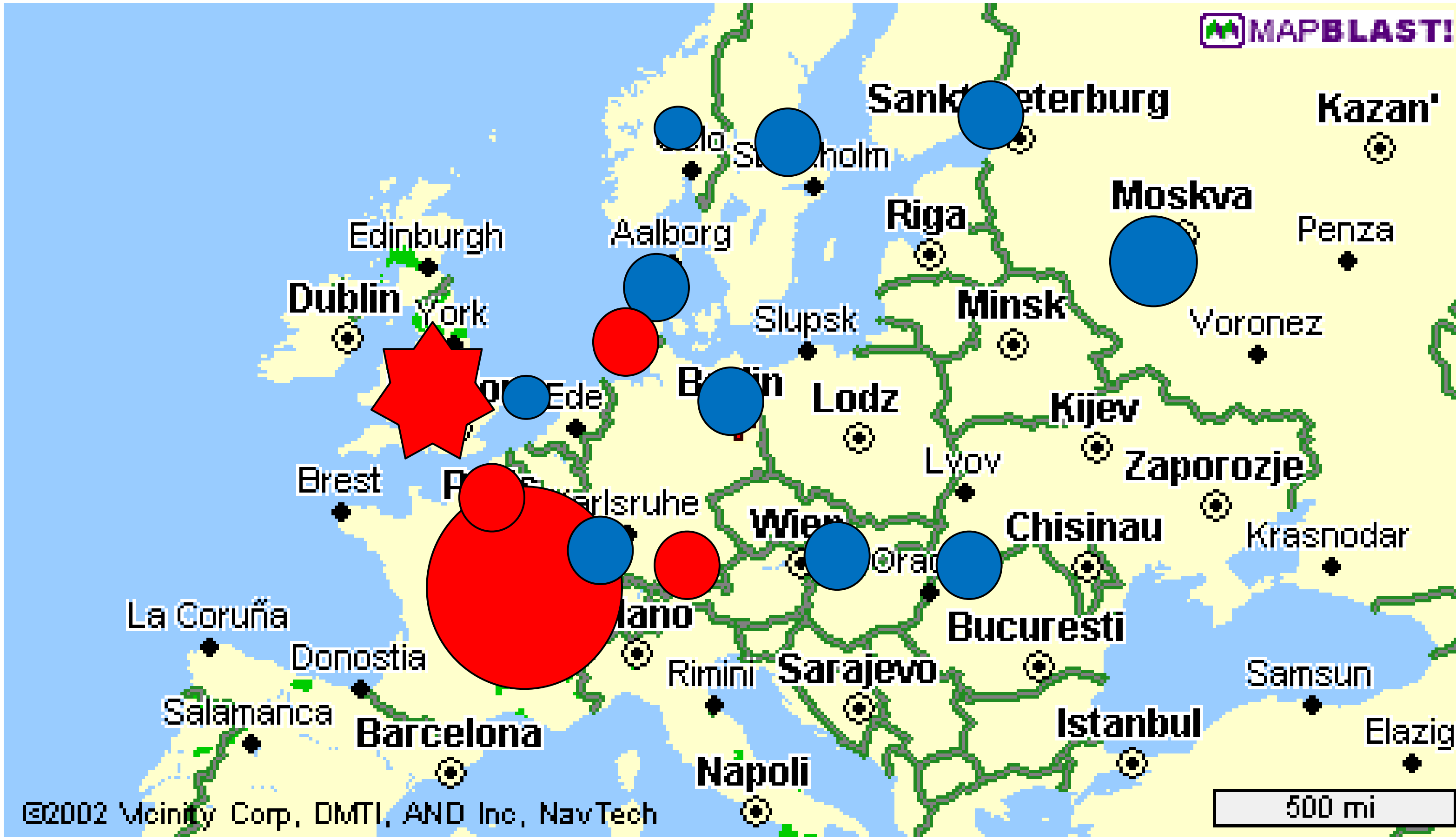
# Unique Roles of Compact Neutron Sources: Starlets Against the Backdrop of Cosmic Light

P.E. Sokol
C.K. Loong

# Neutron Scattering in Europe

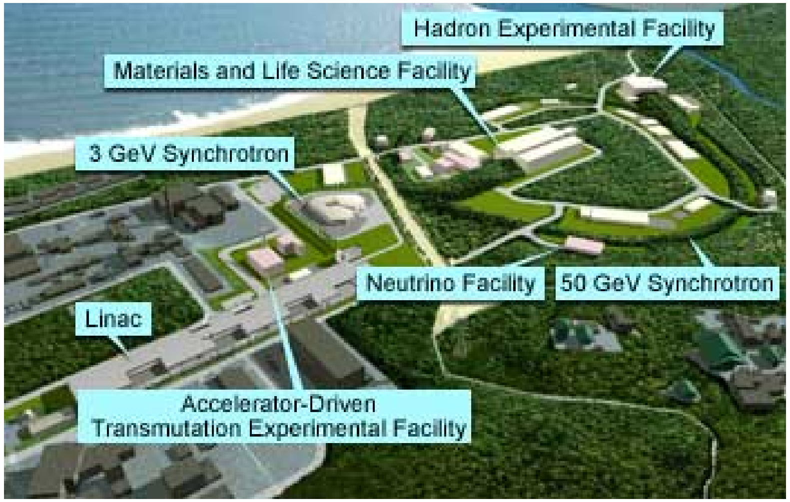



User Community – 6000-8000

Large University based community

# The "Standard Model" for New Sources

SNS





JPARC

HFIR

The US Community

Now has state-of-the art facilities comparable to/better than Europe

User Community

~800 Users

Mainly National Lab Staff

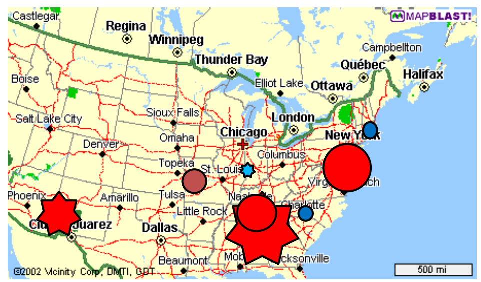
# The Need for New Sources

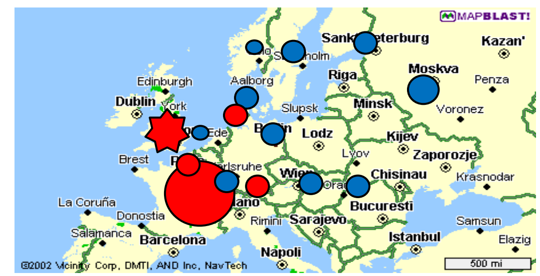
*The broad impact of having a moderate intensity accelerator-based neutron source in a university environment is of major significance to our national scientific effort. We have all seen how neutron research in Europe blossomed as a result of their university-based research teams. We have suffered significantly because of a lack of university involvement in this area.*

*NSF Reviewer*

Reactors

Pulsed Sources (short pulsed)



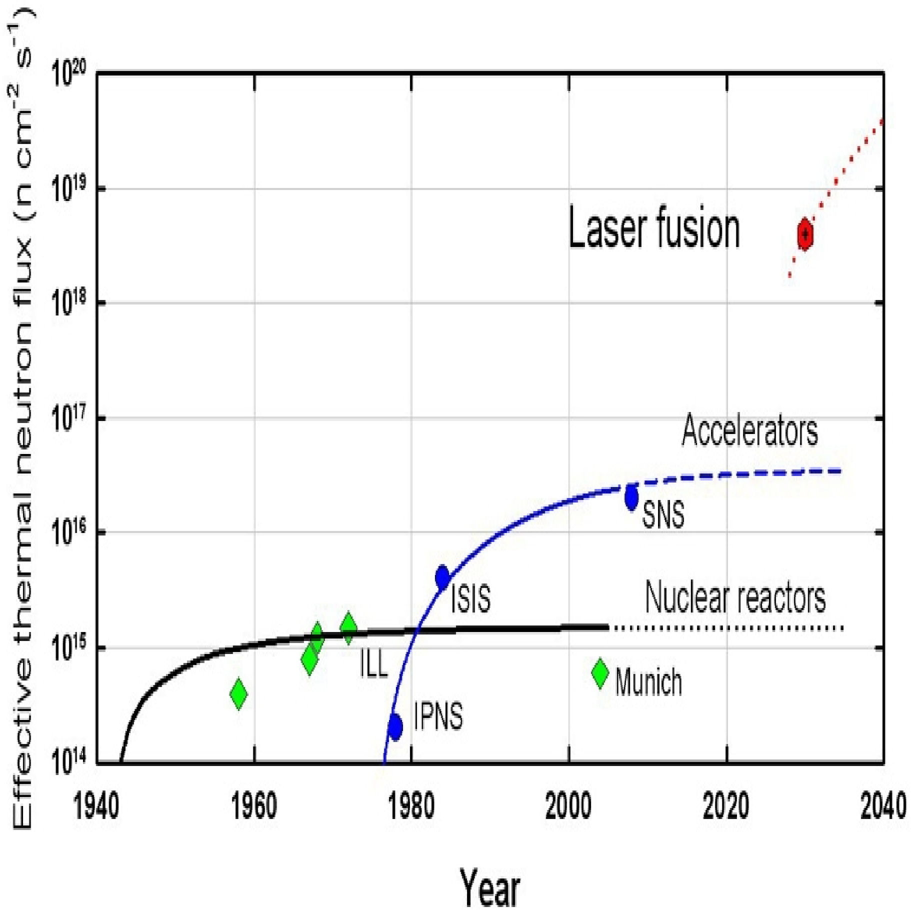

| | North America | Europe |
|---|---|---|
| National/International ($2^{nd}$/$3^{rd}$) | SNS, HFIR, LANSCE, NIST | ILL, ISIS, PSI, FRM-II, Saclay |
| University/Regional ($1^{st}$) | MURR, LENS (MIT, UNC) | Budapest, Berlin, Delft, Gatchina, Prague, Dubna,, Studsvik, Kjeller |

*A network of new small sources is needed to capitalize on the multi-billion dollar investment in large sources.*

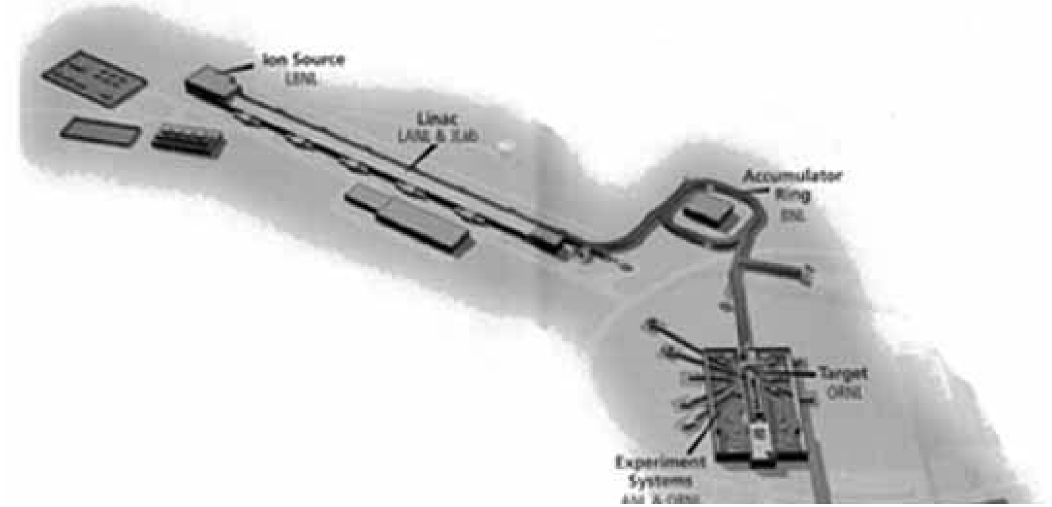
# The Next Generation

Reactors have run out of room for “growth”

Short pulsed spallation sources are reaching their limits



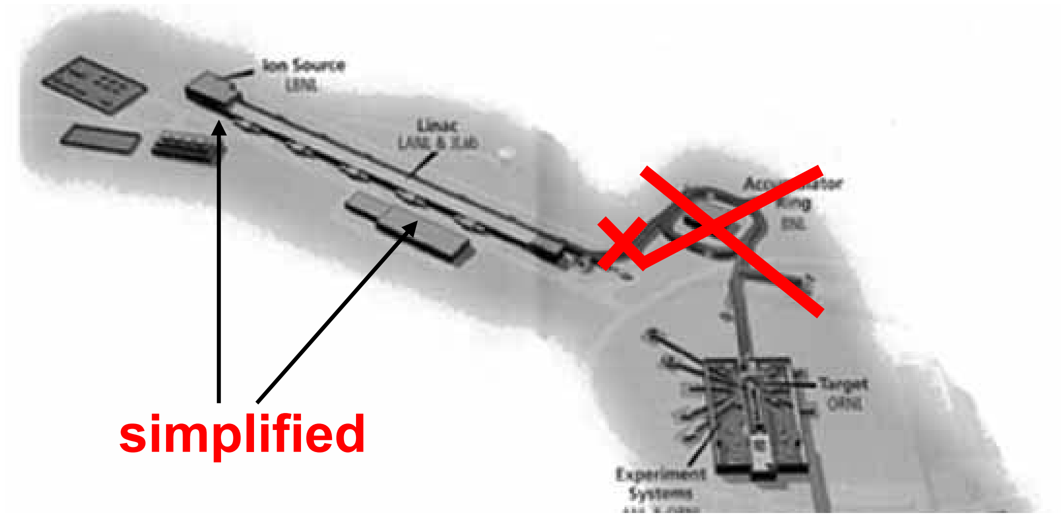
## Current generation spallation source (green field)



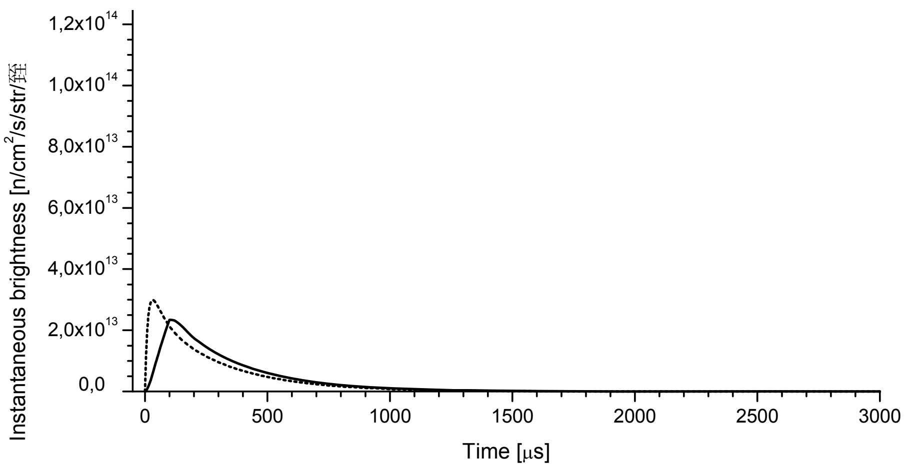

**Variety of different lay-outs for legacy accelerators (e.g., IPNS, ISIS) or combined facilities (J-PARC), other considerations (CSNS)**

**Instantaneous power on target (for 1 MW at 60 Hz, i.e. 17 kj in ~1 μs pulse on target): 17 x**

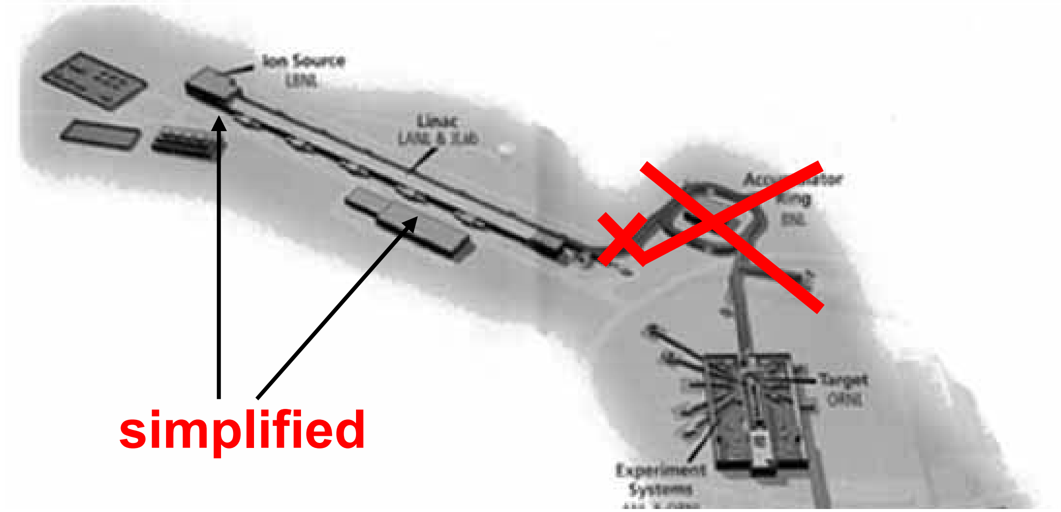
## Current generation spallation source (green field)




**Cost equivalent linear accelerator alone can produce the same cold neutron pulses by ~100 μs proton pulses (SNQ project, 1980's)**



# Next generation spallation source

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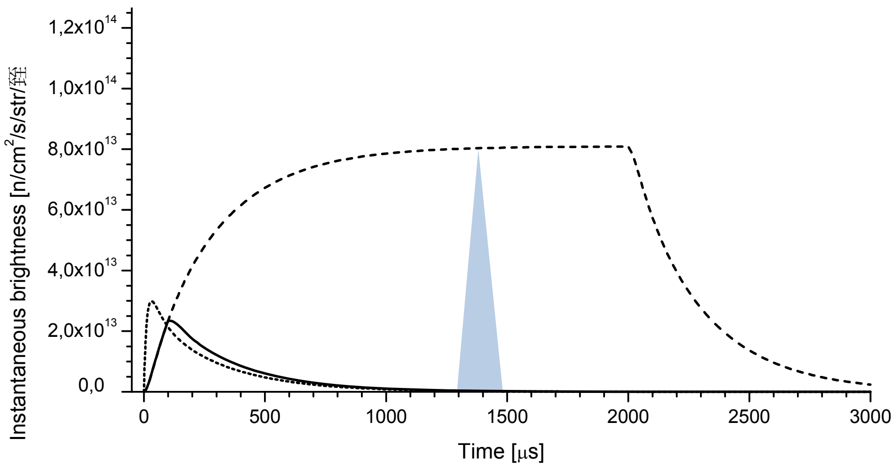
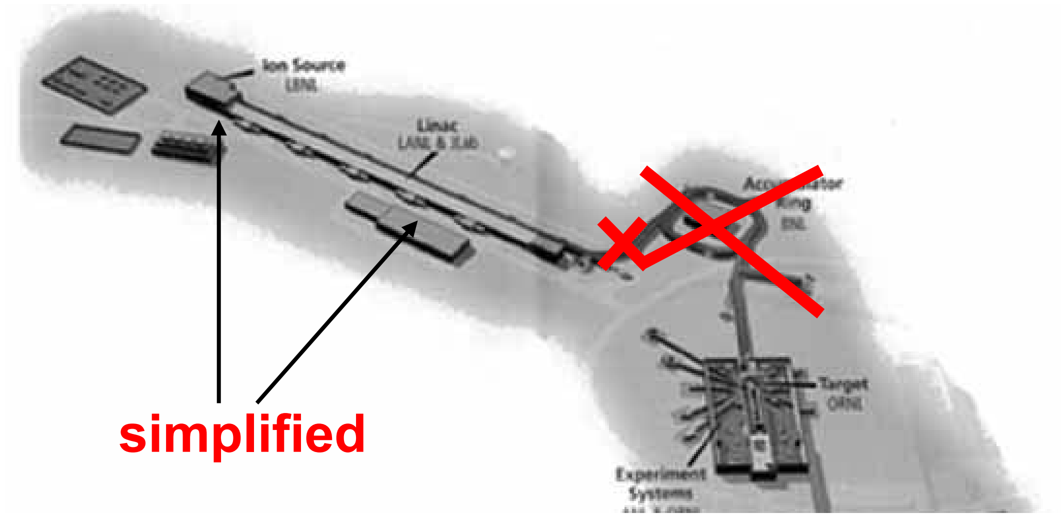



**If we find ways to control pulse parameters by neutron beam choppers (pulse length, repetition rate):**

**→ Leave the linac on for more neutrons per pulse and higher peak brightness (Long Pulse source)**

# Next generation spallation source

From Feri Mezei

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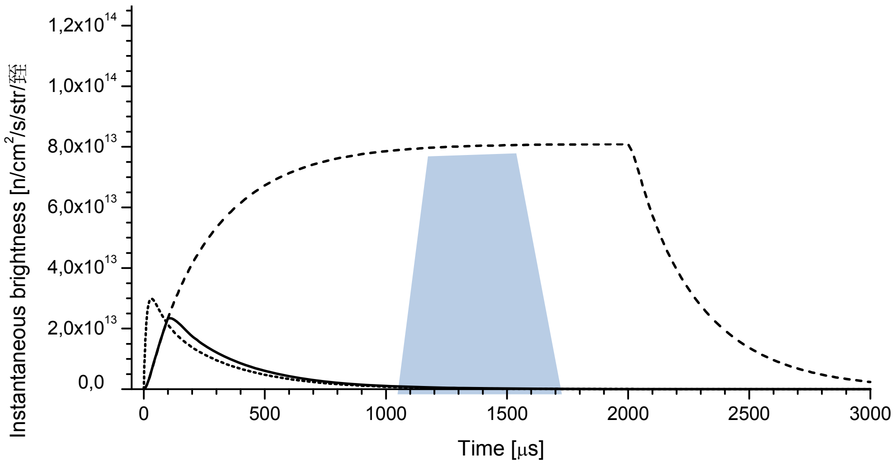


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# The Next Generation

The future is in long pulsed sources

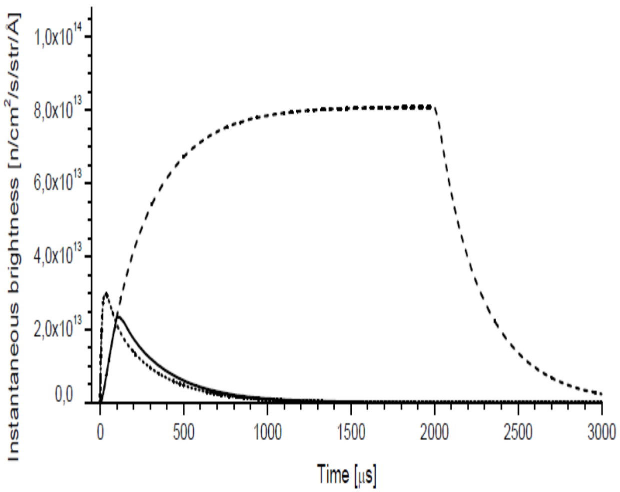
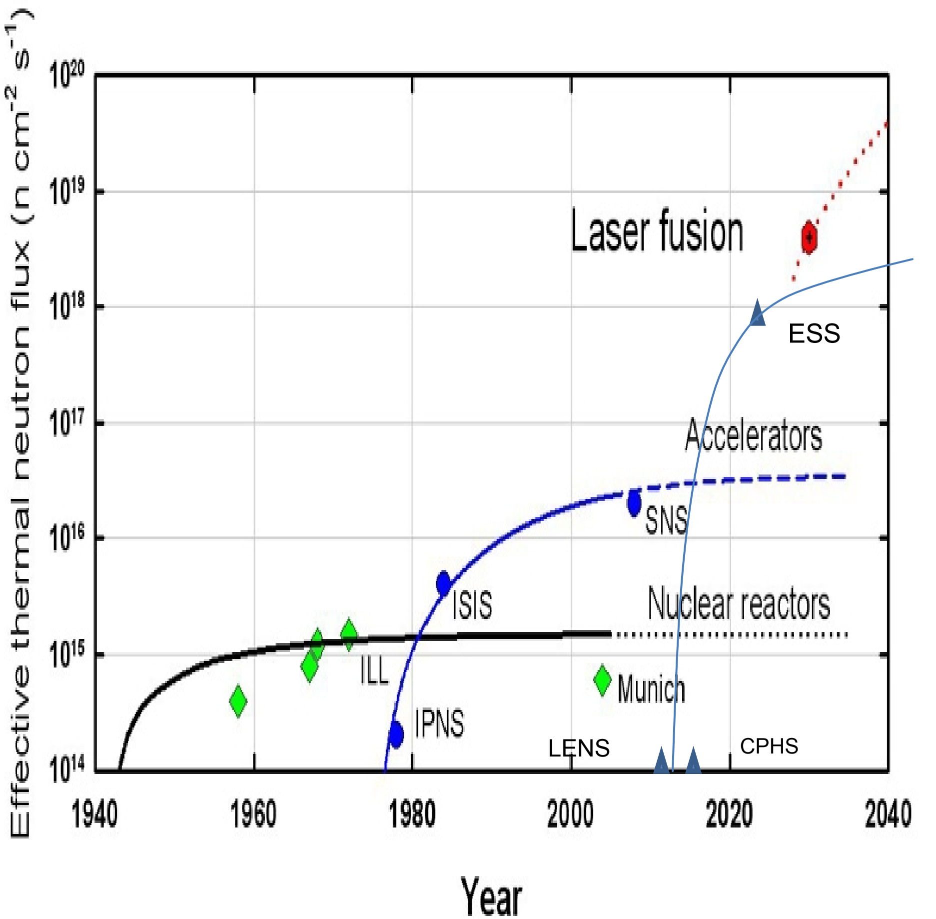



*Figure 1. Coupled cold moderator response at λ = 4 Å to different proton beam pulses: short ring accelerator pulse, 15 kj/pulse (dotted line), 100 μs long equivalent linac pulse, 15 kj/pulse (continuous line) and 2 ms long linac pulse, 300 kj/pulse (dashed line)*



# Supporting the Future

Beyond the full utilization scenario described above, the U.S. will need a new national facility, driven by the age of some of the existing facilities and the intriguing new concepts that are developing, such as very cold neutron sources for ultra-long neutron wavelengths, long pulsed sources, and novel continuous sources. *The long-term strategy must be planned during the coming decade, based upon experience with the current facilities, bearing in mind the needs of individual investigators working in CMMP and the instrumentation and facilities they need to carry out state of the art research.*

*CMMP 2010 NAS Decadal Survey*

Pulsed Sources
(long pulsed,
Very cold neutrons)



Long Pulsed Very Cold Neutron Sources

| | | |
|---|---|---|
| 1st generation | LENS | None |
| 2nd and 3rd generation | None – (SNS LWTS, ANL VCNS) | None – (ESS) |

# What are Compact Sources?

## Spallation Neutron Source

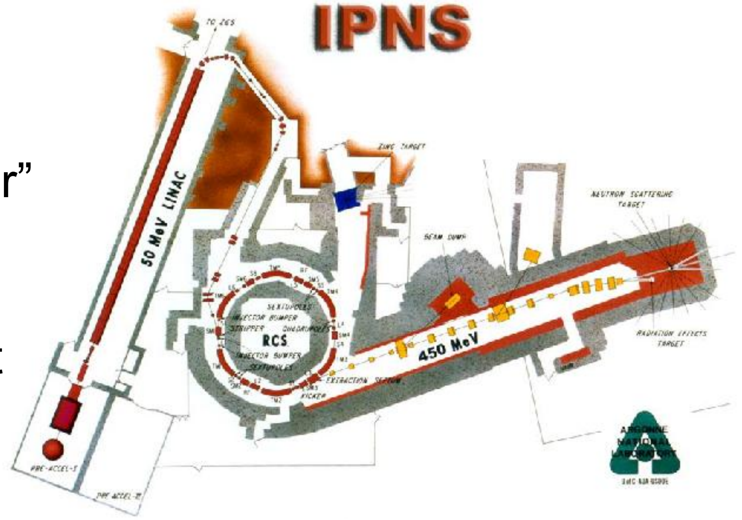
Spallation reaction in a heavy target

20 neutrons/proton 200 MeV "Barrier"

500 MeV Accelerator

15 microAmp Average current

10 kW "class" accelerator




## Compact Pulsed Source

P-n reaction in a light target (Be, Li, ..

20 protons/neutron Mev Barrier

~10 MeV Accelerator

~mA Average Current

10 kW "class" accelerator

***A University size facility!***

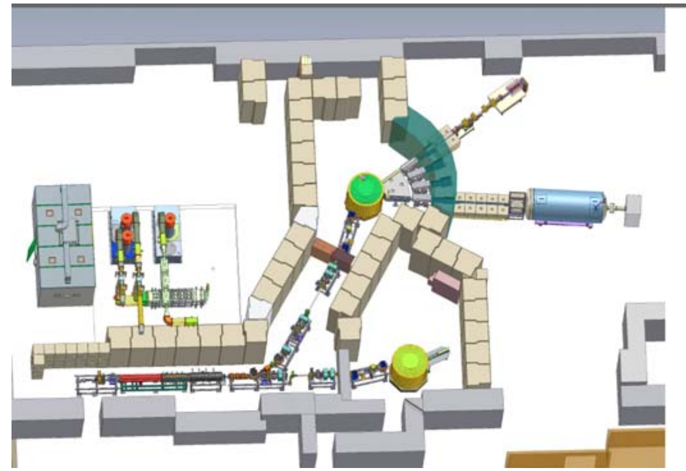
**LENS**

# The Low Energy Neutron Source

**low-energy** (p,nx) reactions ($E_p$<13MeV) in Be.

**cold moderator** (e.g. solid $CH_4$ at 1K<T<40K).

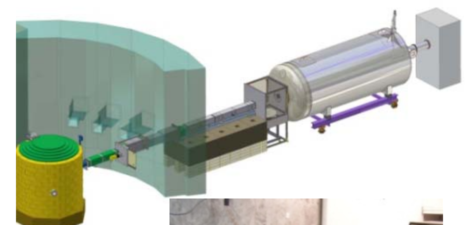
**variable pulse width** (from ~10 μs to more than 1.0 ms).

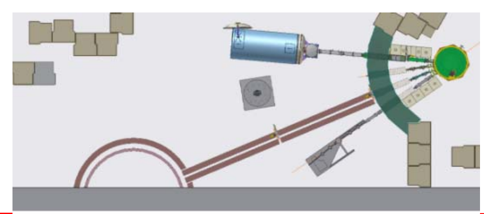


Accelerator
- 13 MeV Linac
- 30-50 mA Peak Current
- ~2 mS pulse width
- 13 kW Average Power

Target
- 10x10 $cm^2$
- 4.2 x $10^{13}$ n/s

Instruments
- SANS
- SESAME
- Fourier TOF
- LPSS Diffract.





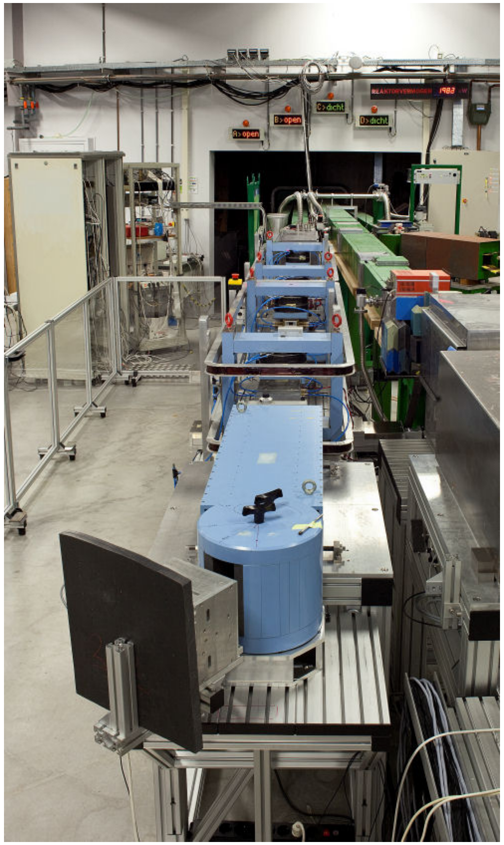
# The Role of Small Sources

**Developing New Instruments and Technology**

Increasing raw flux is hard (and expensive)

Future increases in data rate are going to come from

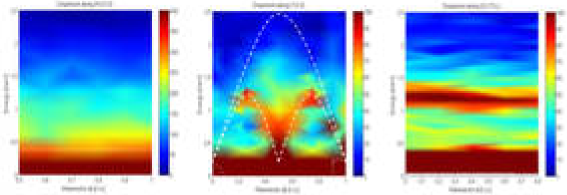
- New Instruments
- Better Optics
- More efficient moderators



**Developing (and Training) the User Community**

New facilities will need a large number of sophisticated users to fully exploit their capabilities – and justify their construction cost.

**Scientific Studies**



All three components are essential to the success of Small (and large) sources.

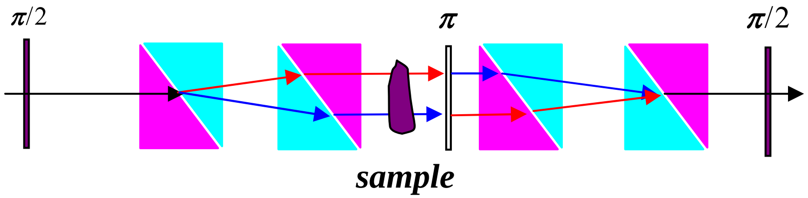
# Instrumentation Development

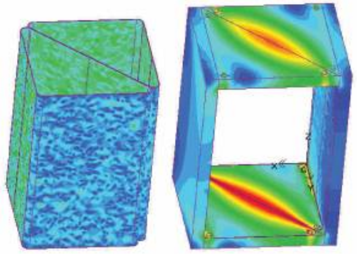
***Recommendation 4***
***Participating federal agencies promote and coordinate efforts to advance neutron scattering methods and neutron source technology needed for the future. Specifically, this includes promoting:***

- *Upgrades and enhancements to neutron scattering instruments;*
- *Research and development in neutron source (including moderator) technology;*
- *Efforts to develop new and improved neutron scattering methods; and*
- *Efforts to expand the application of neutron scattering to new areas of science.*

*OSTP Interagency Working Group on Neutron Science*

***SESAME - Decoupling resolution and intensity using an interference technique.***



# Instrumentation for Long Pulsed Sources

Many instruments at a LPSS can use the same principles as a SPSS

SANS, Reflectometry, …

Many can't!

Diffraction, TOF Inelastic, …

New techniques are needed!

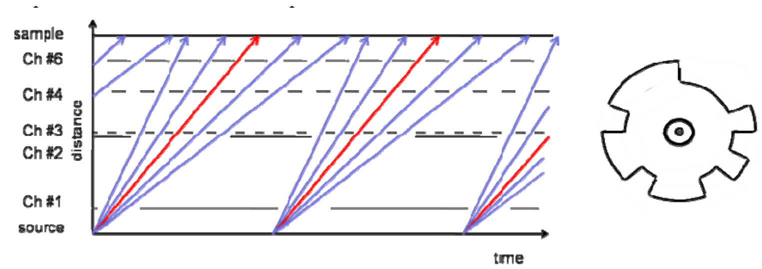
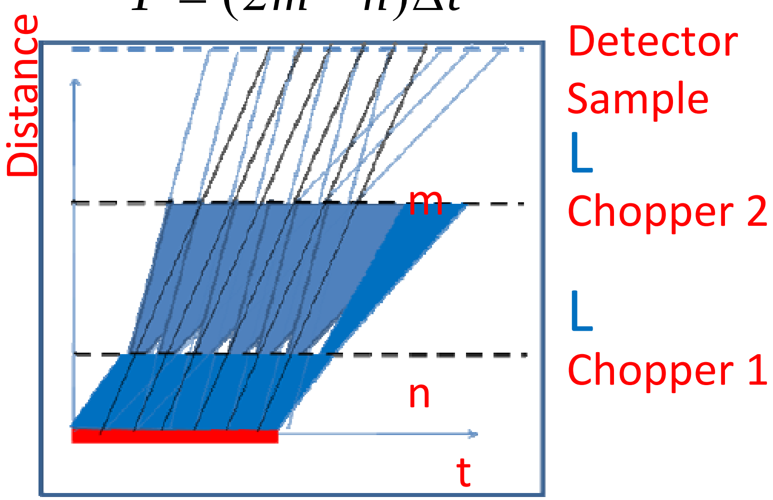



*Figure 2. Left: The principle of multiplexing chopper system for TOF spectroscopy with Repetition Rate Multiplication (RRM). Right: example of advanced selective pulse suppression chopper (chopper #5, not shown in the figure on the left, placed close to chopper #6) [6].*

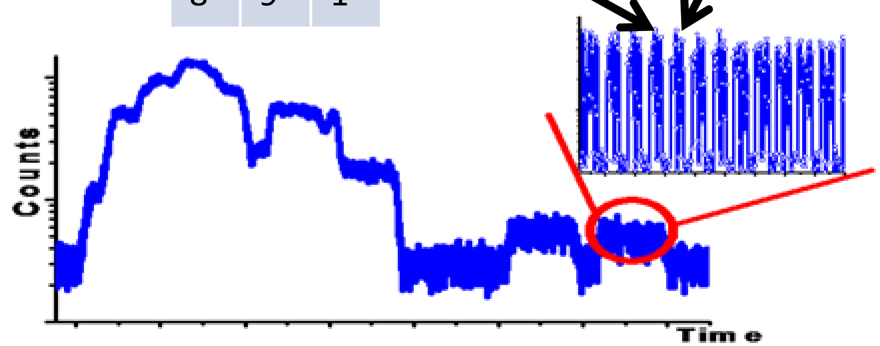
$$T = (2m - n)\Delta t$$




Each time channel contains information on multiple wavelengths

| n | m | λ |
|---|---|---|
| 4 | 7 | 3 |
| 6 | 8 | 2 |
| 8 | 9 | 1 |

| n | m | λ |
|---|---|---|
| 8 | 14 | 6 |
| 10 | 15 | 5 |
| 12 | 16 | 4 |
| 14 | 17 | 3 |
| 16 | 18 | 2 |
| 18 | 19 | 1 |



# Innovation

*All of the examples that they give pose interesting scientific questions and most are well-suited to LENS. However all of the proposed science could be done today at the large neutron scattering centers in the US. Thus the justification for this source cannot rest on its contribution to condensed science alone. In fact, I believe that the most important contribution of this source would be in the areas of neutron production and instrumentation development.*

*NSF Reviewer*

Magnetic Lenses

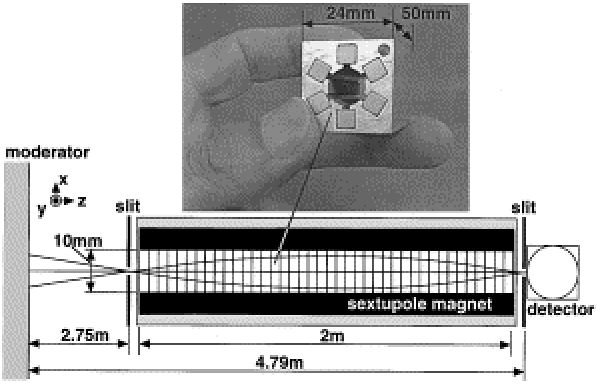
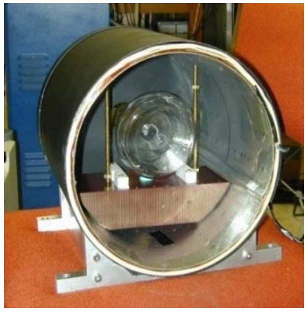
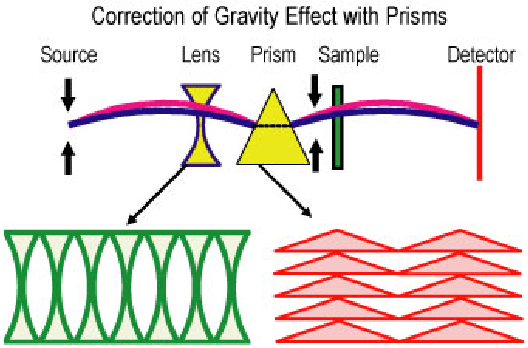



Fig. 1. Setup of the experiment at the electron linac facility of Hokkaido University. A 2 m sextupole magnet comprised of 40 units of aluminum blocks. Each block contained six pieces of NEOMAX48 [4], 5×5×50 mm, as shown in the photograph. Shimizu et al

***Polarized $^3$He cell (11 cm diameter)***



Lenses



# Moderator Development

*Perhaps the single most important advance that could come out of LENS is the development of a source of very long wavelength neutrons. This offers the possibility of some very innovative and novel scientific advances that gives access to larger scale structures that are not accessible at any neutron source in the country.*

*NSF Reviewer*

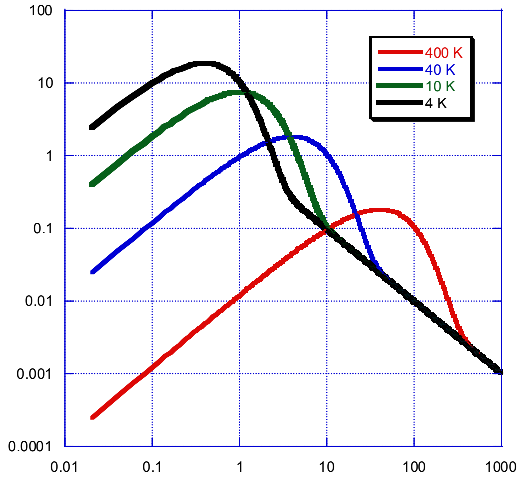
## *LENS Goal – a 4 K Moderator Effective Temperature*

Peak wavelength

$$\lambda \propto T^{-1/2}$$

Peak flux

$$I \propto T^{-1}$$




International Cold Moderator Working Group

- Jack Carpenter (ANL)
- Phil Ferguson (ORNL)
- Eric Iverson (ORNL)
- Gunther Muhrer (LANL)
- Stewart Ansell (ISIS)
- Mike Snow (IU)
- Paul Sokol (IU)
- Dave Baxter (IU)

*Improved Capabilities opening new frontiers*

# Developing the User Community

## The breadth and depth of neutron scattering research—recent research highlights

**Advances in Unconventional Iron-Based Superconductors**

In mid-March 2008 Pengcheng Dai, researcher in the Neutron Scattering Science Division (NSSD) and joint professor of condensed matter science at the University of Tennessee, attended a conference in his native China. He asked a fellow scientist familiar with a paper in the February 23, 2008, issue of the *Journal of American Chemical Society* why he and his colleagues were so excited. The scientist called the paper "fantastic" and said that the paper reports the discovery in Japan of a new iron-based superconducting material.

After reading the paper, Dai shared their excitement. After obtaining some "made in China" samples of the superconductor's iron-based parent compound, he returned to ORNL to analyze the material's magnetic structure using neutron scattering. The experiments employed instruments at HFIR and the National Institute of Standards and Technology (NIST) research reactor in Maryland.

At about the same time, ORNL staff Michael McGuire and Athena Safa-Sefat became the first team in the United States to report that they had synthesized powders and crystals made of the iron-based material. In addition, ORNL's Mark Lumsden and Andy Christianson, both in NSSD, were performing neutron scattering experiments on ORNL-made samples.

The original discovery of superconductivity in an iron-based material was made in February 2008 by Japanese scientist Y. Kamihara and colleagues. They initially reported that an iron-based material can conduct electricity without resistance at 4 Kelvin (4 degrees Celsius above absolute zero). The elements in

the first known iron-ba
are iron, arsenic, oxyge
num. When LaFeAsO w
Japanese discovered th
superconducting at 26

Landmark research about a newly discovered superconducting material will lead to more efficient, less-expensive products in fields such as energy, transportation, and medicine.

**Researching a Cure for Huntington's Disease**

Huntington's disease (HD) is a genetic condition that causes certain brain cells to waste away, eventually robbing its victims of their ability to control their muscles. In its early stages, it can cause clumsiness, forgetfulness, and impaired speech. In its more advanced stages, it can take away a person's ability to walk, talk, and swallow. Available drugs for this neurological disease, first described in 1872 by American physician George Huntington, help patients manage the symptoms of HD, but they don't slow or stop the disease.

While there is no cure for HD, there is hope. Scientists at ORNL and the University of Tennessee (UT) Medical Center are using modern tools to better understand the mechanisms behind this neurological disease. Like Alzheimer's and Parkinson's diseases, HD is caused by a specific protein, huntingtin, that misbehaves. For all cases of HD, a defective gene codes for the troublesome protein.

Each protein is made of a combination of amino acids in a sequence dictated by a gene. In a person suffering from HD, the HD protein in many brain cells contains an abnormally long sequence of 40 or more glutamine amino acids in succession. This abnormal repeat sequence results in the formation of fibrils (thin, threadlike fibers) that cause brain cells to deteriorate and die. In

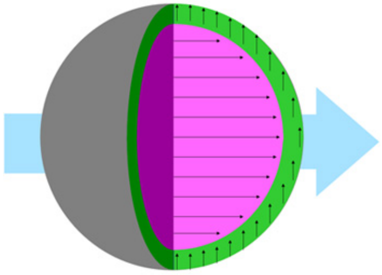
the Bio-SANS instrument at HF
Dean Myles, introduced him to a
researcher, Professor Valerie Ber
ing the protein specifically involv
disease.

At the Graduate School of Medic
Center, Berthelier's group seeks t
mechanisms of protein folding an
correct and incorrect folding of a
amino acids into a three-dimensi
researchers decipher how these p
to normal physiology and disease
biophysical, and cell biology appr

In their current work on HD, the
makes an aggregate toxic. By ide
pounds that are capable of alteri
aggregates, they think they will b
the functional role of pre-fibrilla

*Two-dimensional SANS pattern from polyglutamine fibrils.*

Neutrons provide 'core' understanding of magnetic nanoparticles



- Our educational infrastructure at the graduate level must keep pace with these investments in our neutron sources:
  - Need to attract and train new users of these facilities capable of designing experiments to answer increasingly sophisticated scientific questions
  - Need to train experts in the techniques of neutron scattering who may eventually become instrument scientists (APS report)

# Education

- Neutron scattering research is almost exclusively done at a few large facilities

- no equivalent to the lab x-ray machine for neutrons
- very few small neutron sources compared to Europe

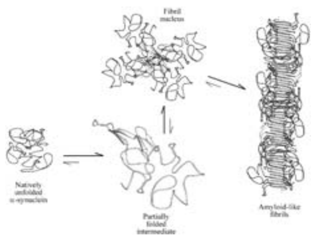
- The scientific areas addressed by neutron scattering are very broad - educational efforts must be interdisciplinary as the background of students are quite different
- Neutron scattering probes both the **structure** and **dynamics** of condensed matter; these two capabilities are often intertwined – most users employ only structural methods as these methods are much higher throughput
- Computational methods are frequently essential in interpreting the data

# LENS as a Support Facility

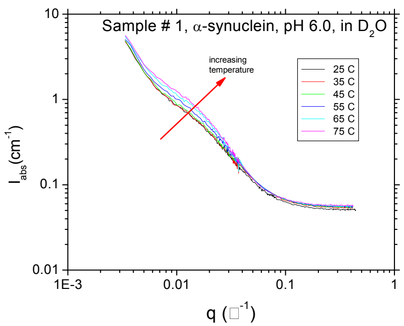
*The fact that LENS can achieve such an intensity makes it clear that good experiments can be done with it (because IPNS does experiments now that impact scientific frontiers). On the other hand, one should be careful to recognize that the IPNS is a first-generation source and the that the SNS will be a third-generation source. Thus LENS really will be a "feeder Source" for the SNS rather than an internationally competitive neutron source – somewhat in the same sense that a rotating anode is a powerful laboratory source of x-rays which allows some forefront experiments as well as the preparation of state-of-the-art experiments at synchrotron x-ray sources.*

*NSF Reviewer*

**BIOLOGY – Uversky (IUMS)**
**and Kaiser (LENS)**
**Intrinsically disordered proteins, such as α-synuclein, are thought to be responsible for neurodegenerative disorders (Parkinson's disease, Alzheimer's, ...)**



Molecular model of the α-synuclein aggregation leading to the formation of insoluble fibrils




SANS data taken at NIST

# LENS as a Research Facility

*LENS is a low intensity neutron source. The time-averaged intensity will be comparable to the current IPNS at Argonne National Laboratory. There is an excellent scientific case for smaller neutron facilities, especially in universities, that complement the high flux, tightly scheduled neutron facilities in national laboratories.*

*NSF Reviewer*

<u>*An ideal study for LENS*</u>

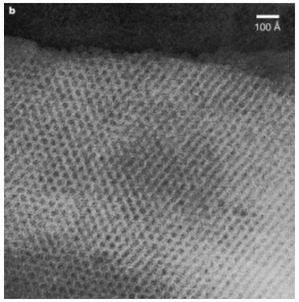
Observation of the density minimum in deeply supercooled confined water

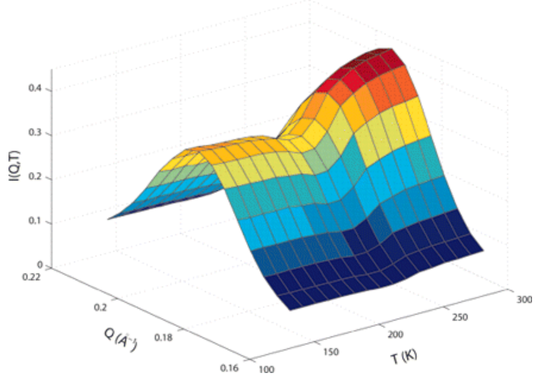
Chen et al, PNAS 104, 9547 (2007)

- Bulk water is anomalous at freezing
  shows a density maximum at 4 C
- Freezing is suppressed in confined water
- Density minimum at -63 C for confined water

Why LENS?

Strong Scatterer
Large Sample
Challenging Sample Environment



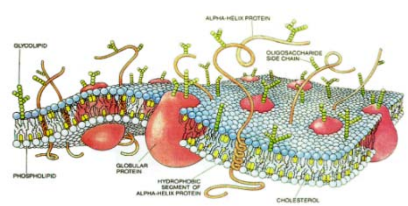
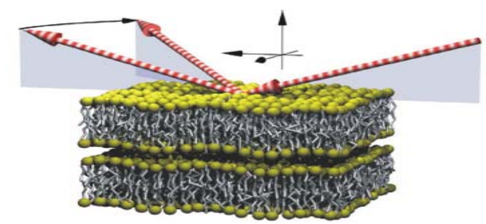

SANS Data from NIST

# LENS as a Unique Facility

*Experiments that can be done uniquely at LENS include feasibility studies, higher risk instrument development and preliminary experimentation.*

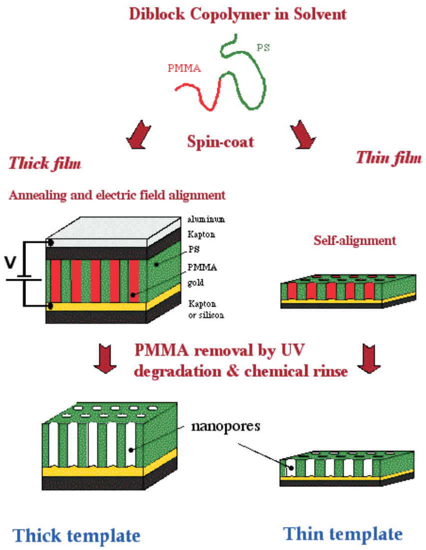
*NSF Reviewer*

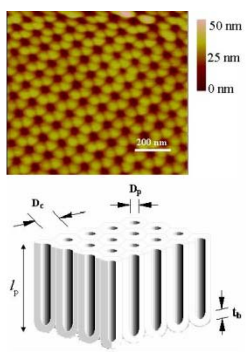
The Spin Echo Scattering Angle Measurment (SESAME) instrument at LENS will offer unique opportunities to measure long correlation lengths. Initially, such measurements will only be possible at LENS.

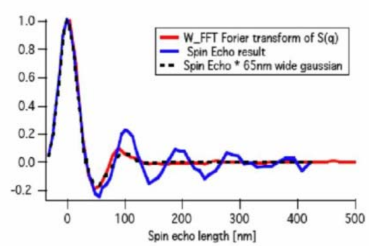



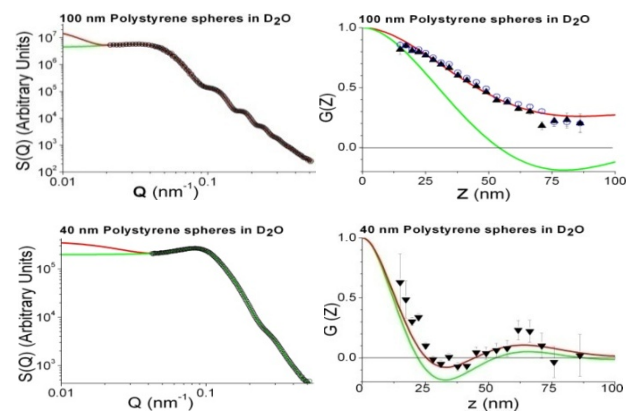
Potential application: in-plane structure of membranes

Structure of nanopatterned films



# New Opportunities

## Radiography

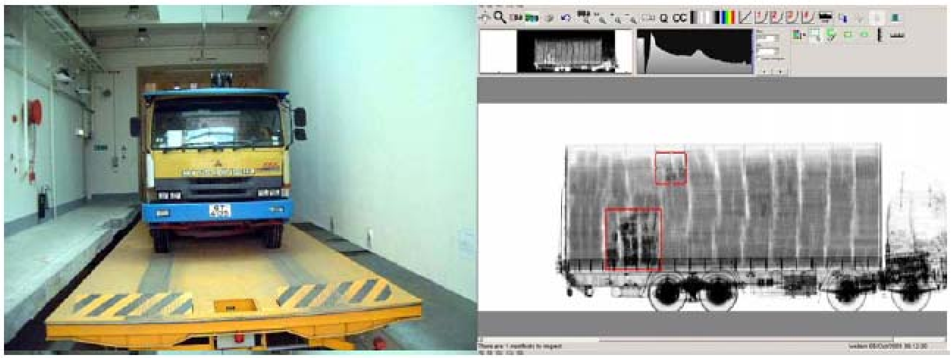
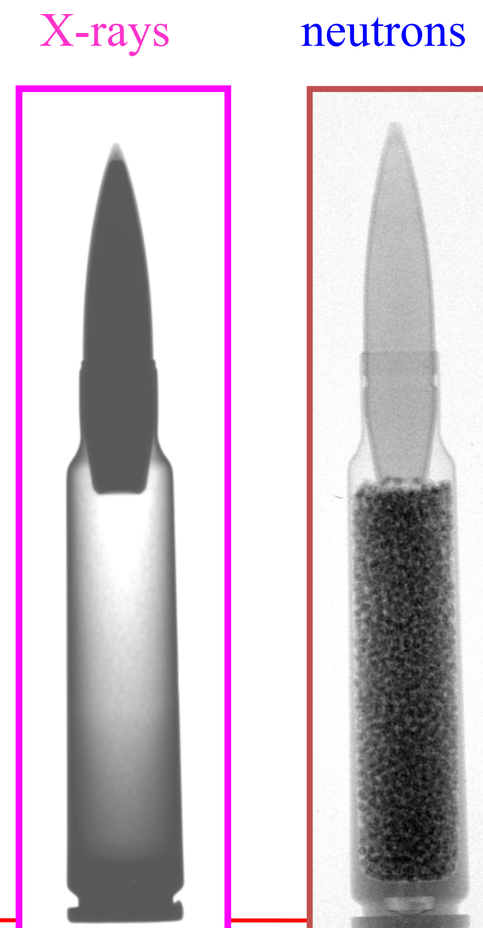


Figure 3. Rapiscan Series 2000 high energy x-ray inspection shows a truck moving through the inspection tunnel. Smuggled contraband is shown among legitimate cargo.

Figure 5. Aracor Eagle® relocatable x-ray inspection system inspecting a fully loaded truck.

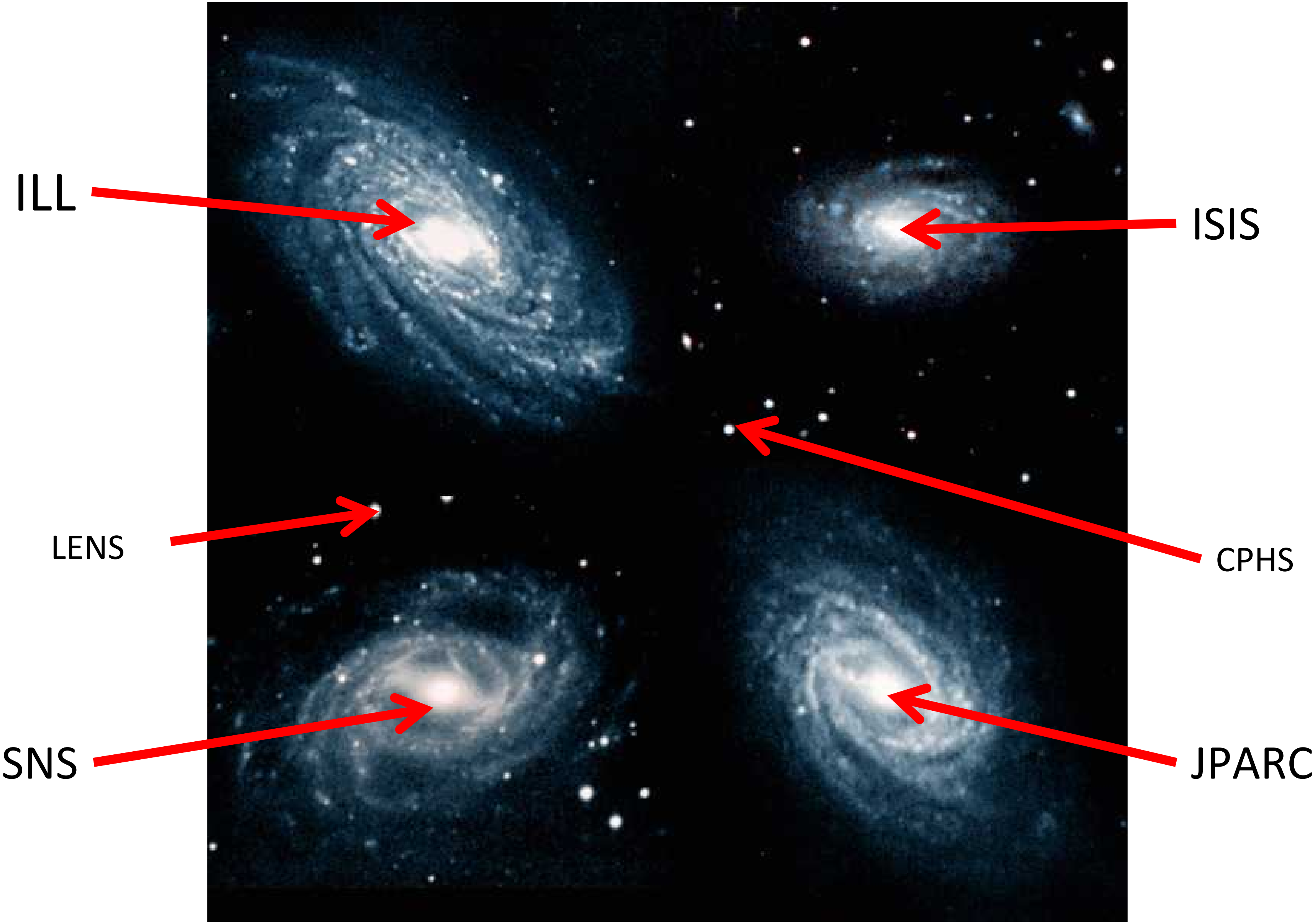





Note: individual gun powder grains can be distinguished

# Conclusions

- **Compact Accelerator Based Neutron Sources offer a unique opportunity**
  - **In developing the user community**
  - **In developing new instrumentation**
  - **In cutting edge science**
  - **In opening new markets.**
- **This is a very exciting time!**


ILL
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CPHS
SNS
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