IRIDE neutron source potentialities

Neutron Techniques for the Gentle Investigation of Matter

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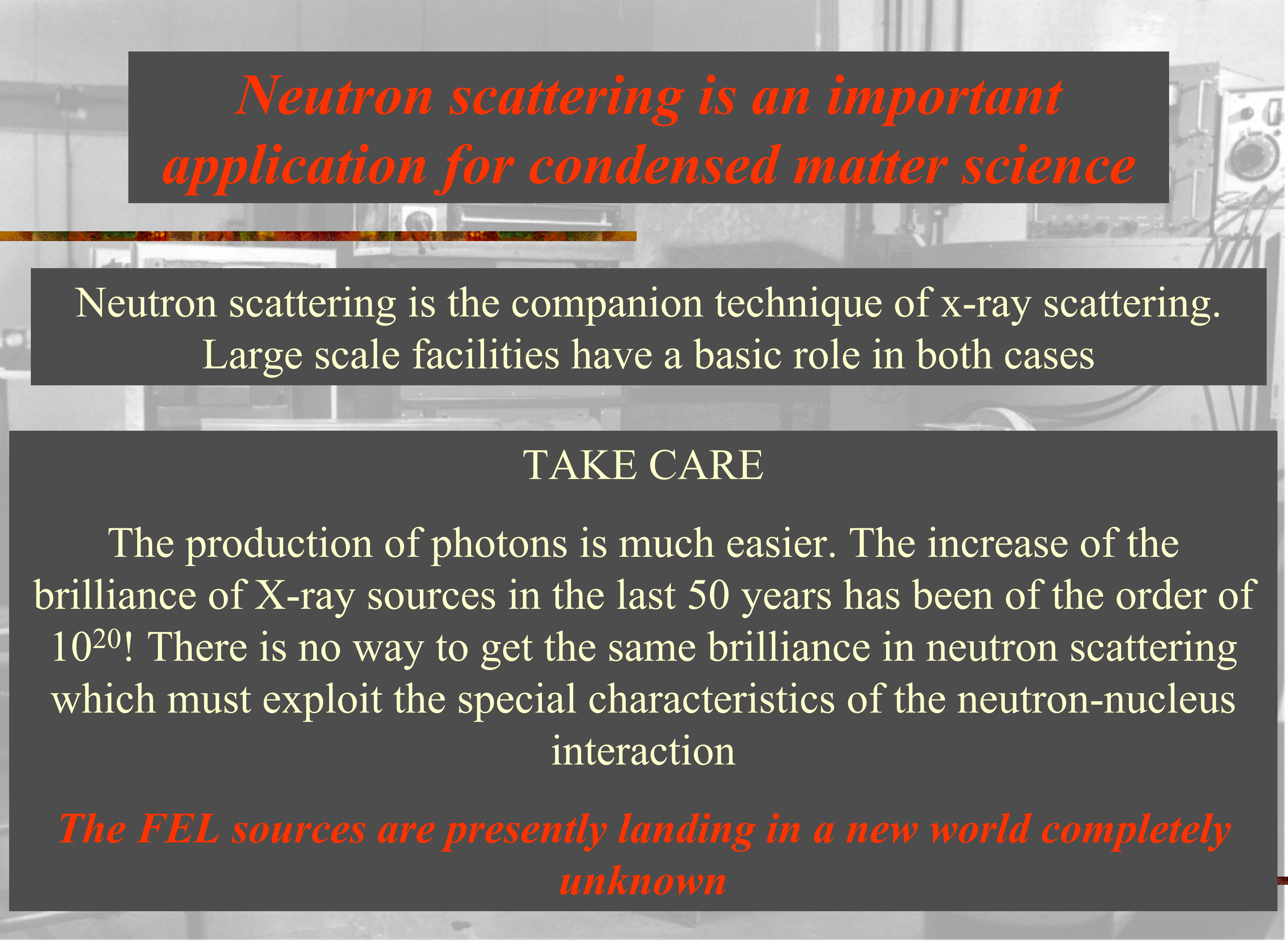
40 years of neutron scattering

Abstract

Brief history of neutron scattering

History of Italy in neutron scattering

A look into the future, where we will be, what for IRIDE?



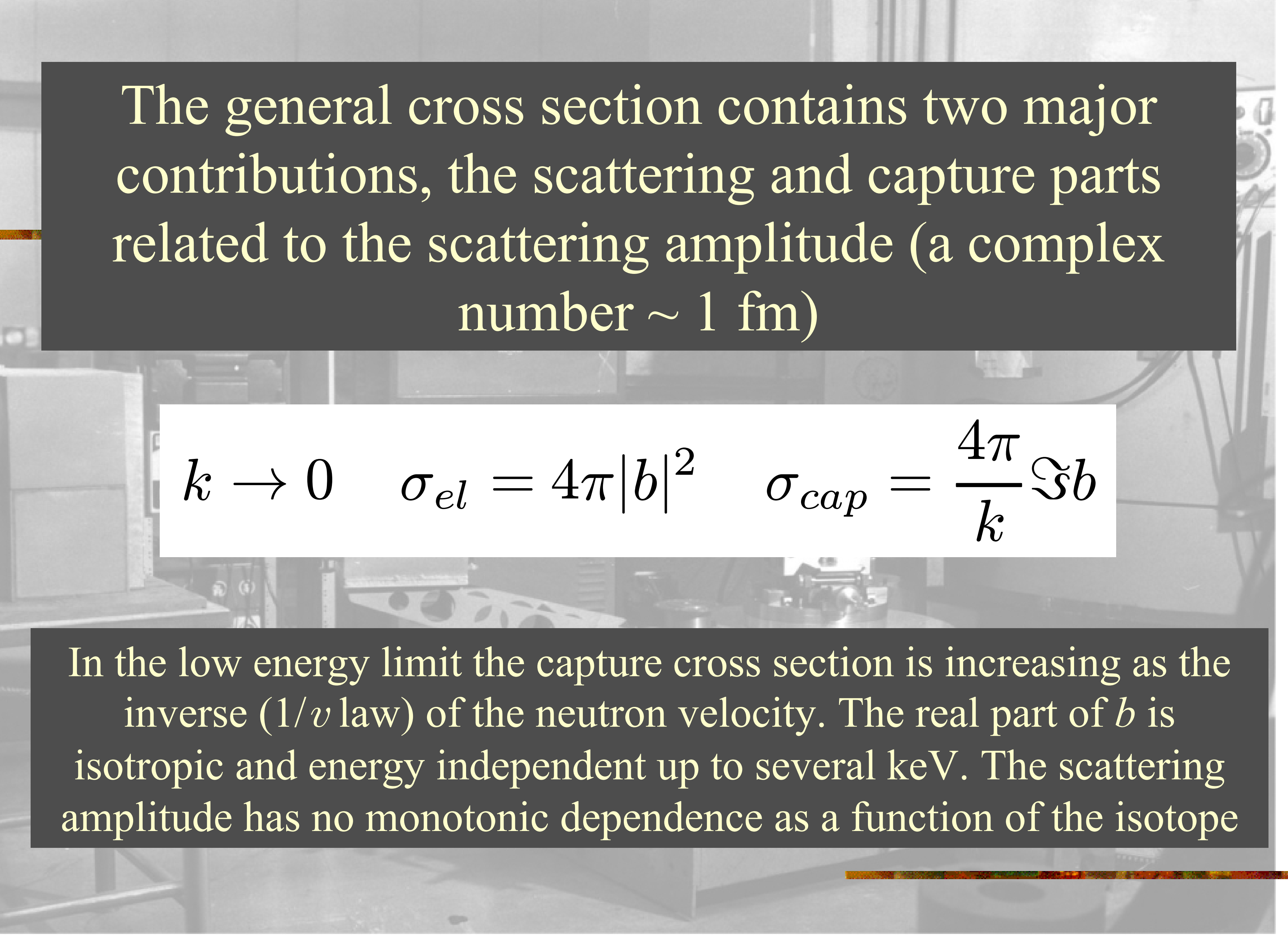
Neutron scattering is an important application for condensed matter science

Neutron scattering is the companion technique of x-ray scattering. Large scale facilities have a basic role in both cases

TAKE CARE

The production of photons is much easier. The increase of the brilliance of X-ray sources in the last 50 years has been of the order of 10^{20}! There is no way to get the same brilliance in neutron scattering which must exploit the special characteristics of the neutron-nucleus interaction

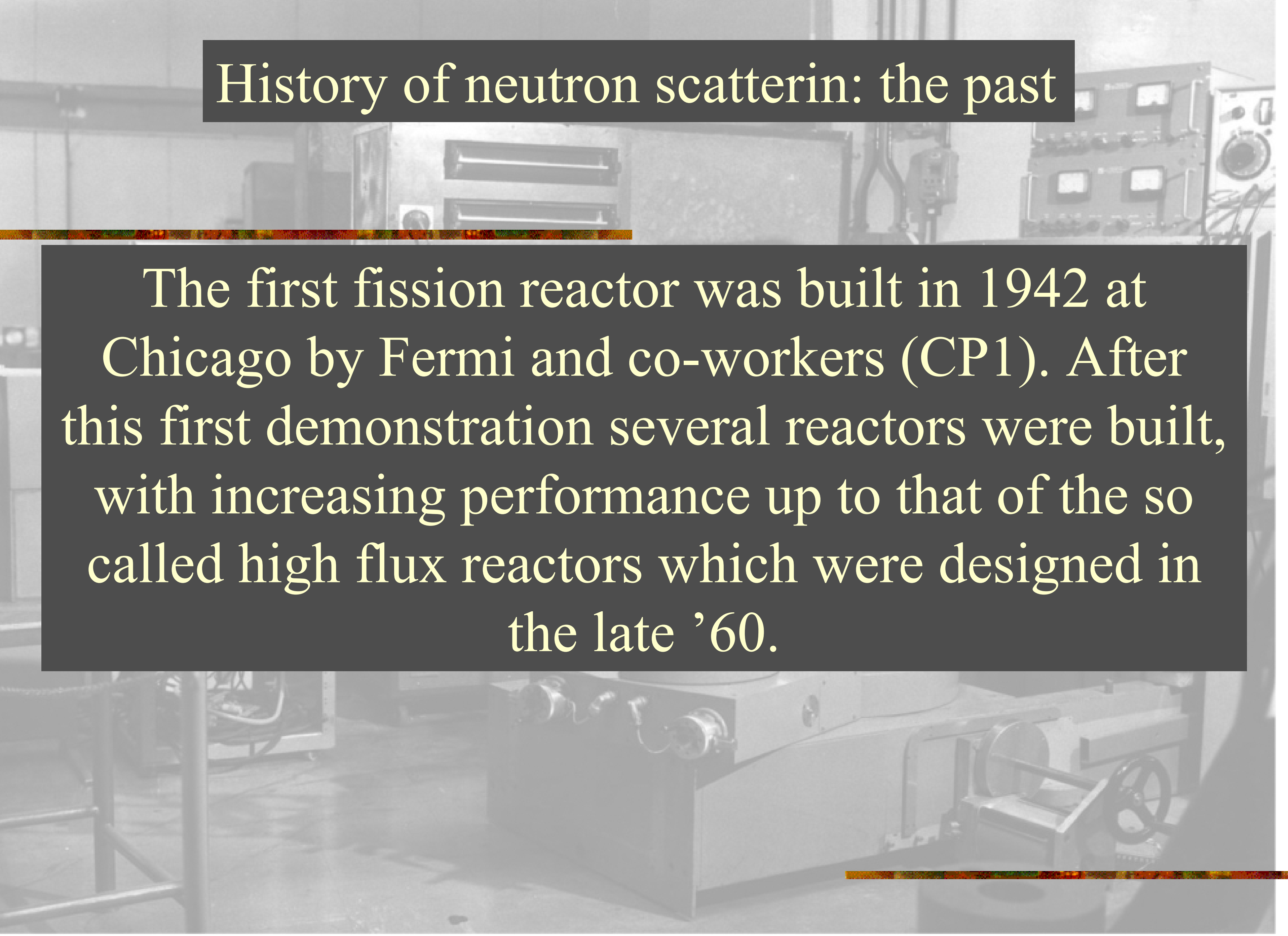
The FEL sources are presently landing in a new world completely unknown



The general cross section contains two major contributions, the scattering and capture parts related to the scattering amplitude (a complex number ~ 1 fm)

$$k \to 0 \quad \sigma_{el} = 4\pi|b|^2 \quad \sigma_{cap} = \frac{4\pi}{k}\Im b$$

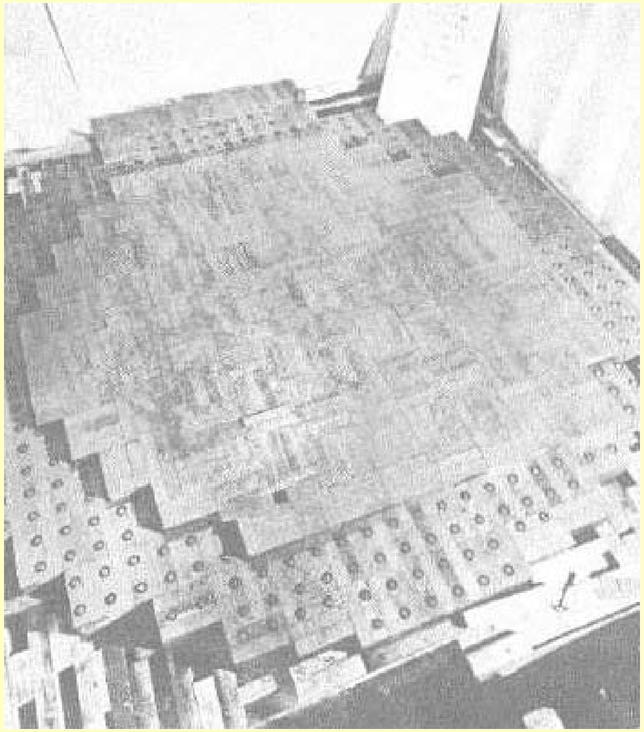
In the low energy limit the capture cross section is increasing as the inverse ($1/v$ law) of the neutron velocity. The real part of b is isotropic and energy independent up to several keV. The scattering amplitude has no monotonic dependence as a function of the isotope

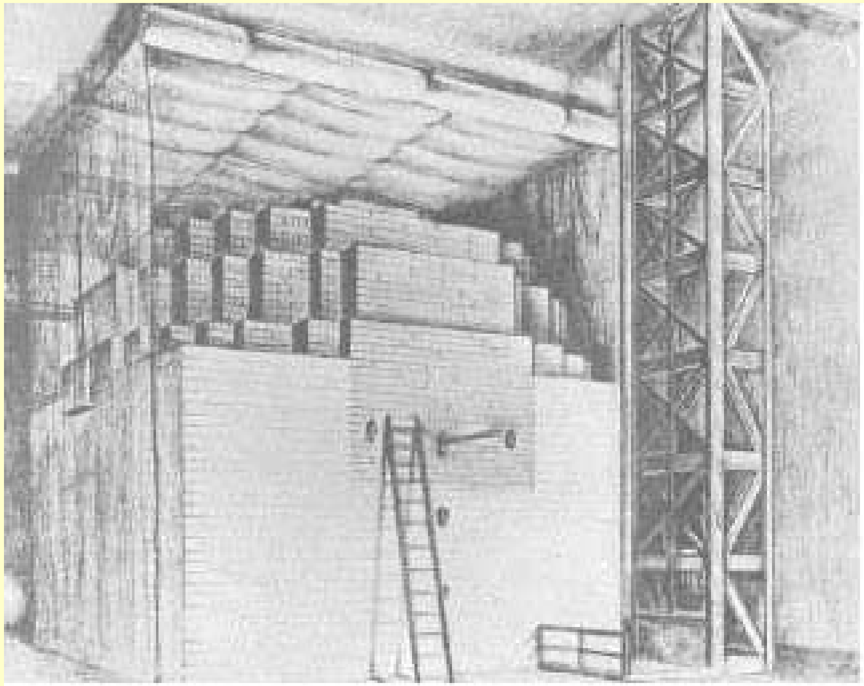


History of neutron scatterin: the past

The first fission reactor was built in 1942 at Chicago by Fermi and co-workers (CP1). After this first demonstration several reactors were built, with increasing performance up to that of the so called high flux reactors which were designed in the late ’60.

The CP1 built in 1942 was a natural uranium, graphite moderated reactor, air cooled. No biological shielding was present since the reactor power was quite low.





History of neutron scatterin: the past

1936 E. Fermi, Development of the theory of the low energy (s-wave) neutron scattering

1937 E. Fermi, use of mechanical choppers

1941 O. Halpern, M. Hamermesh, and M. H. Johnson, Theory of magnetic neutron scattering

1942 E. Fermi, First critical reactor CP1

1945 C. Shull and E. O. Wollan and coworkers, first powder diffraction, detection of antiferromagnetism,

1951 B. Brockhouse, First three axis spectrometer

1966-1967 Brookhaven, Oak Ridge, First two high flux reactors

Selected results of Shull and Wollan at Oak Ridge, 1948-1956

Laue Photography of Neutron Diffraction E. O. Wollan, C. G. Shull, and M. C. Marney, Phys. Rev. **73**, 527 – Published 1 March 1948

The Diffraction of Neutrons by Crystalline Powders E. O. Wollan and C. G. Shull, Phys. Rev. **73**, 830 – Published 15 April 1948

Neutron Diffraction Studies of Order-Disorder in Alloys C. G. Shull and Sidney Siegel, Phys. Rev. **75**, 1008 – Published 1 April 1949

Detection of Antiferromagnetism by Neutron Diffraction C. G. Shull and J. Samuel Smart, Phys. Rev. **76**, 1256 – Published 15 October 1949

Production of Highly Polarized Neutron Beams by Bragg Reflection from Ferromagnetic Crystals C. G. Shull, Phys. Rev. **81**, 626 – Published 15 February 1951

Critical Magnetic Scattering of Neutrons by Iron H. A. Gersch, C. G. Shull, and M. K. Wilkinson, Phys. Rev. **103**, 525 – Published 1 August 1956

The present era

1969 Start of the construction of ILL

1972 Start of ILL operation, a new concept in the use of condensed matter large scale facilities, an external user programme

1981 Start of the IPNS pulsed source (ANL, USA)

1984 Start of the ISIS pulsed source (RAL-Lab, UK)

2005 Start of the FRM-II reactor (TUM, D)

The future

2009 Decision for the construction of the ESS

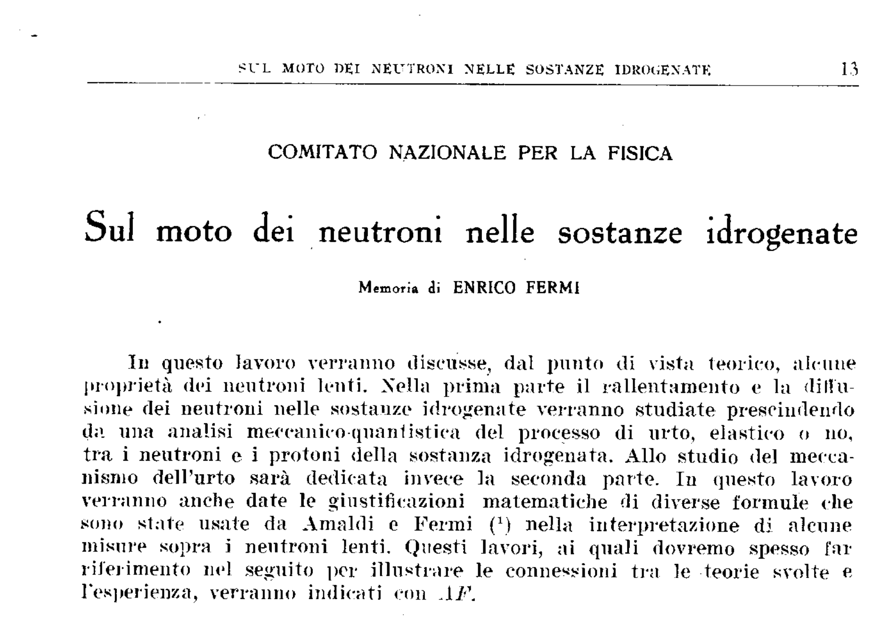
2019 Start of the operation of the ESS

2025 Start of full user programme of the ESS

???? Neutron production by inertially confined fusion

The Italian connection, old era

The discovery of the neutron scattering, 1936



SUL MOTO DEI NEUTRONI NELLE SOSTANZE IDROGENATE 13

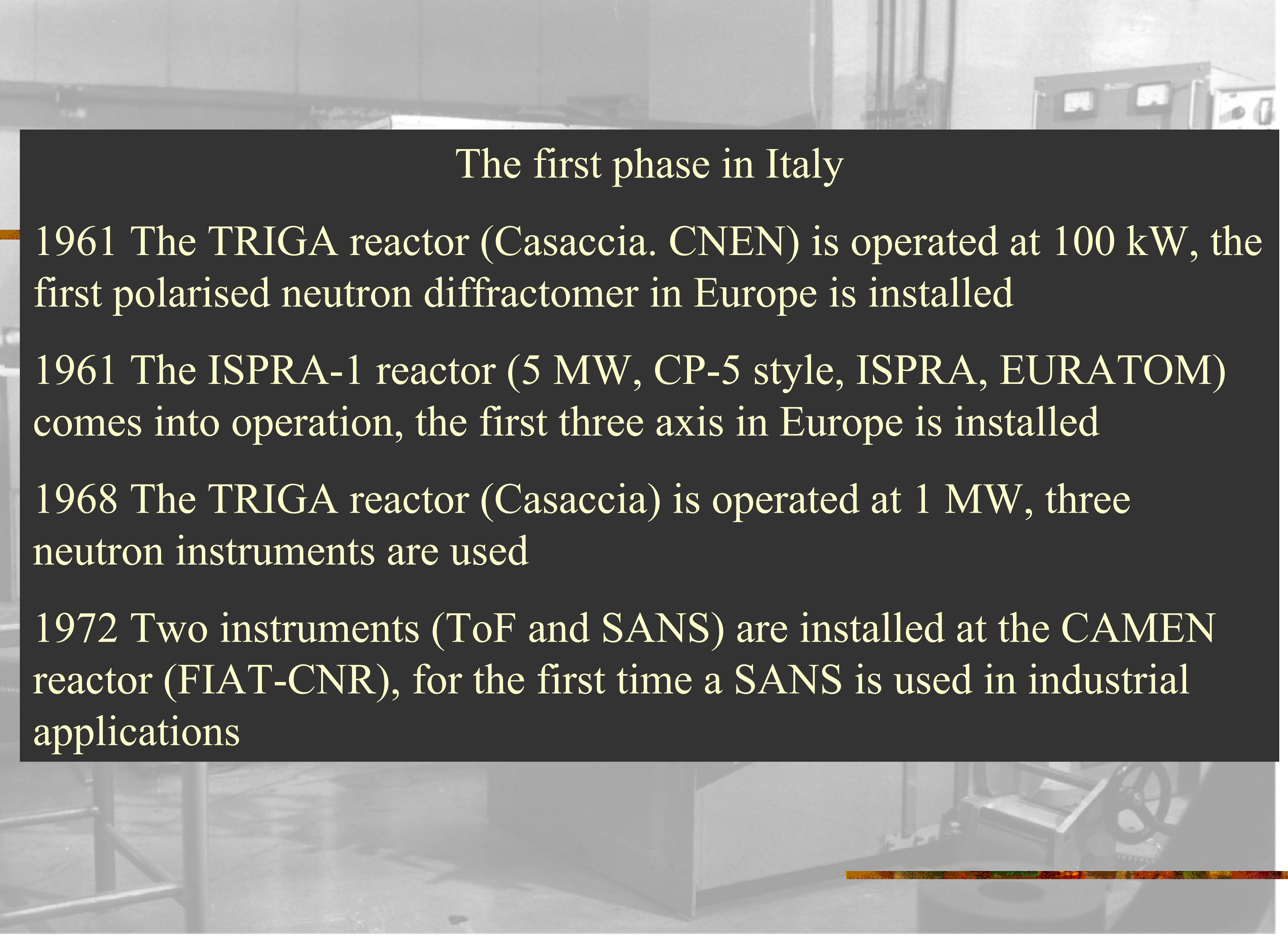
COMITATO NAZIONALE PER LA FISICA

Sul moto dei neutroni nelle sostanze idrogenate

Memoria di ENRICO FERMI

In questo lavoro verranno discusse, dal punto di vista teorico, alcune proprietà dei neutroni lenti. Nella prima parte il rallentamento e la diffusione dei neutroni nelle sostanze idrogenate verranno studiate prescindendo da una analisi meccanico-quantistica del processo di urto, elastico o no, tra i neutroni e i protoni della sostanza idrogenata. Allo studio del meccanismo dell'urto sarà dedicata invece la seconda parte. In questo lavoro verranno anche date le giustificazioni matematiche di diverse formule che sono state usate da Amaldi e Fermi (1) nella interpretazione di alcune misure sopra i neutroni lenti. Questi lavori, ai quali dovremo spesso far riferimento nel seguito per illustrare le connessioni tra le teorie svolte e l'esperienza, verranno indicati con *AF*.

Beginning of neutron scattering. This paper (On the motion of neutrons in the hydrogenated substances) introduces the so called *Fermi pseudopotential*, the basic tool for a quantitative interpretation of a neutron experiment



The first phase in Italy

1961 The TRIGA reactor (Casaccia. CNEN) is operated at 100 kW, the first polarised neutron diffractomer in Europe is installed

1961 The ISPRA-1 reactor (5 MW, CP-5 style, ISPRA, EURATOM) comes into operation, the first three axis in Europe is installed

1968 The TRIGA reactor (Casaccia) is operated at 1 MW, three neutron instruments are used

1972 Two instruments (ToF and SANS) are installed at the CAMEN reactor (FIAT-CNR), for the first time a SANS is used in industrial applications

The new phase

1972 The EURATOM in Ispra stops the operation of the reactor

1972 The CNEN (now ENEA) stops the neutron scattering activity

1974 The CNR enters the game giving access to the TRIGA reactor

1974 The LISONE project is presented: photo production using the 70 MeV sector (40 kW) of the ADONE injector, not accepted

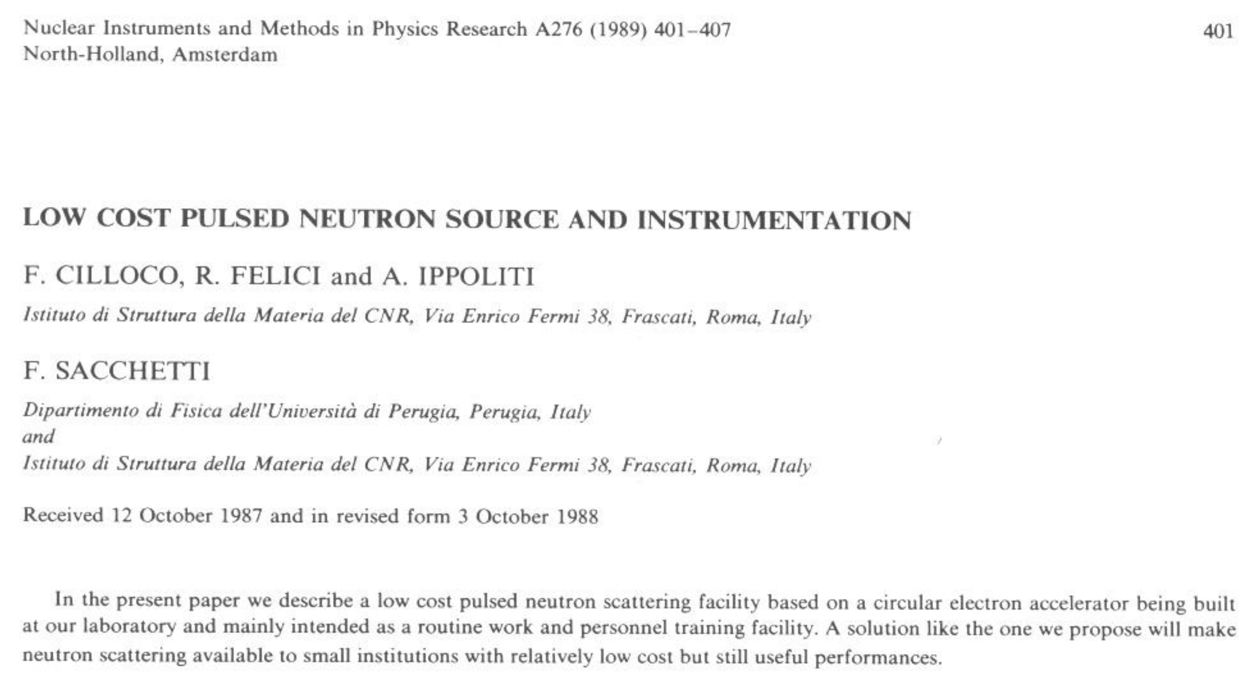
1981 Collaboration at the ELIOS source in Harwell (90 MeV short pulse LINAC, 40 kW, dedicated)

1984 Agreement between CNR and RAL to open the access to ISIS

1997 Agreement between INFM and ILL to open the access to HFR in Grenoble

2011 Start of collaboration with ESS (support from MIUR)

LISONE-2, test source using the neutron photo-production



Nuclear Instruments and Methods in Physics Research A276 (1989) 401–407
North-Holland, Amsterdam

LOW COST PULSED NEUTRON SOURCE AND INSTRUMENTATION

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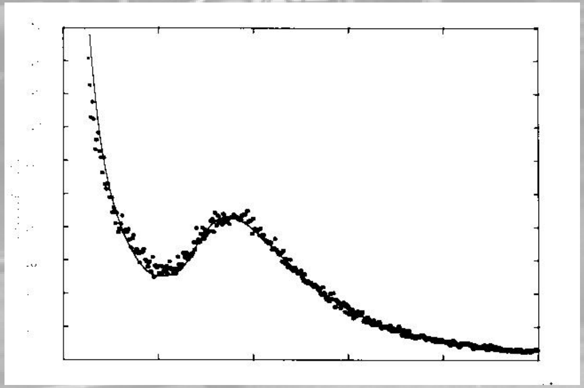
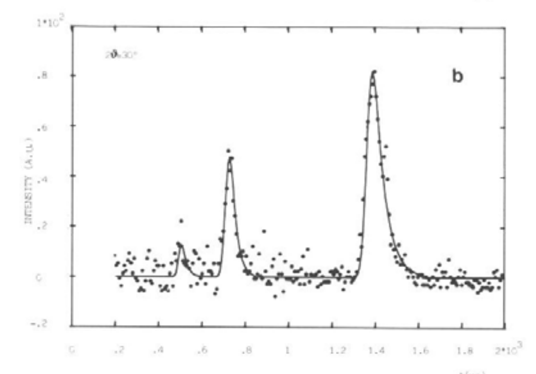
In the present paper we describe a low cost pulsed neutron scattering facility based on a circular electron accelerator being built at our laboratory and mainly intended as a routine work and personnel training facility. A solution like the one we propose will make neutron scattering available to small institutions with relatively low cost but still useful performances.

Microtron
20 MeV,

0.5-2.4 kW

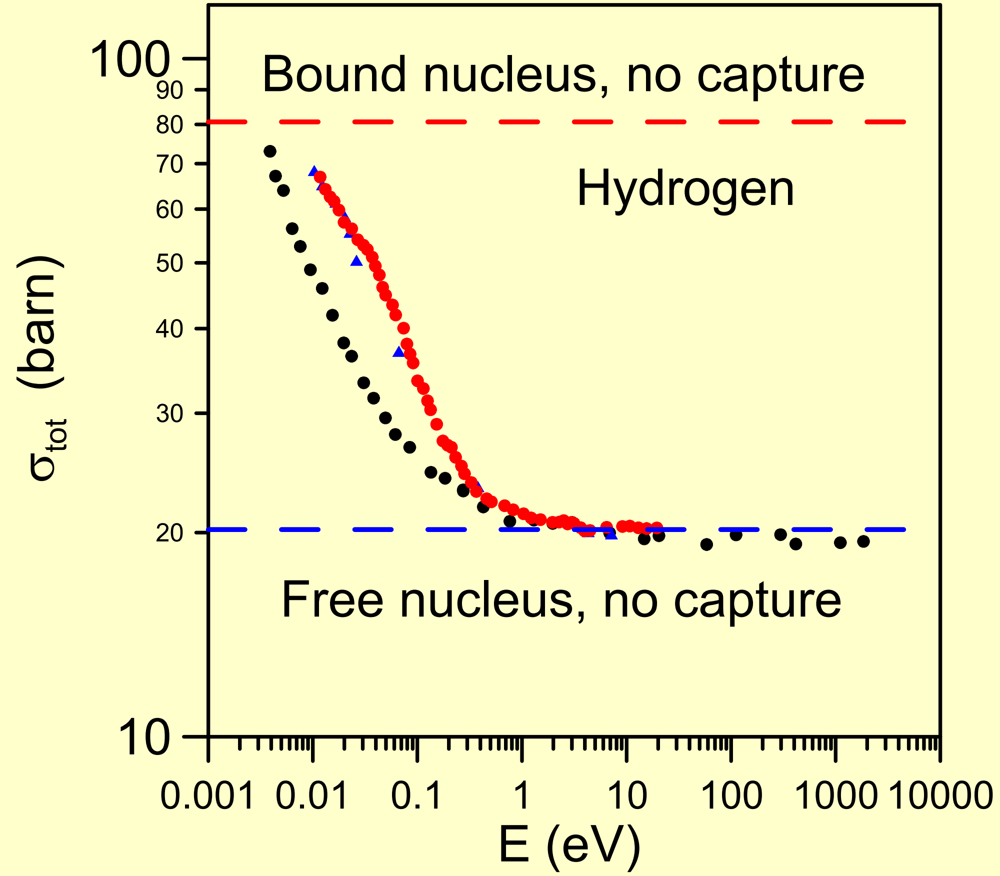
1 M$ 1986





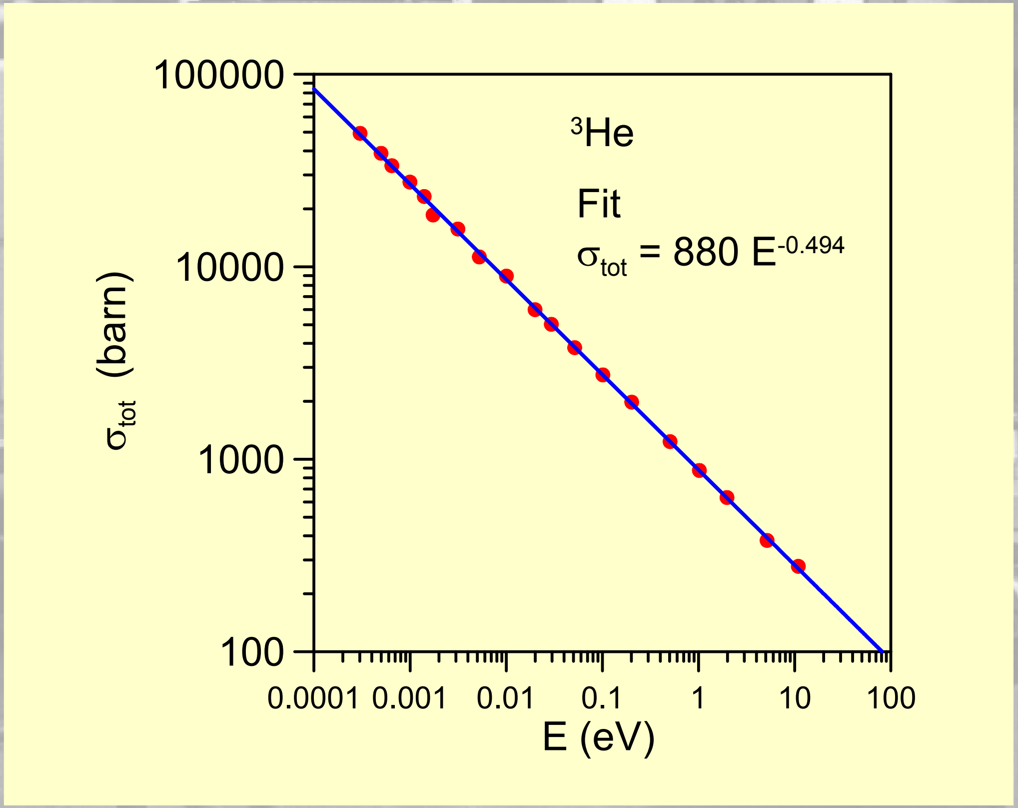
LISONE-2 at 10 W

A different behaviour is seen in different nuclei and different conditions.



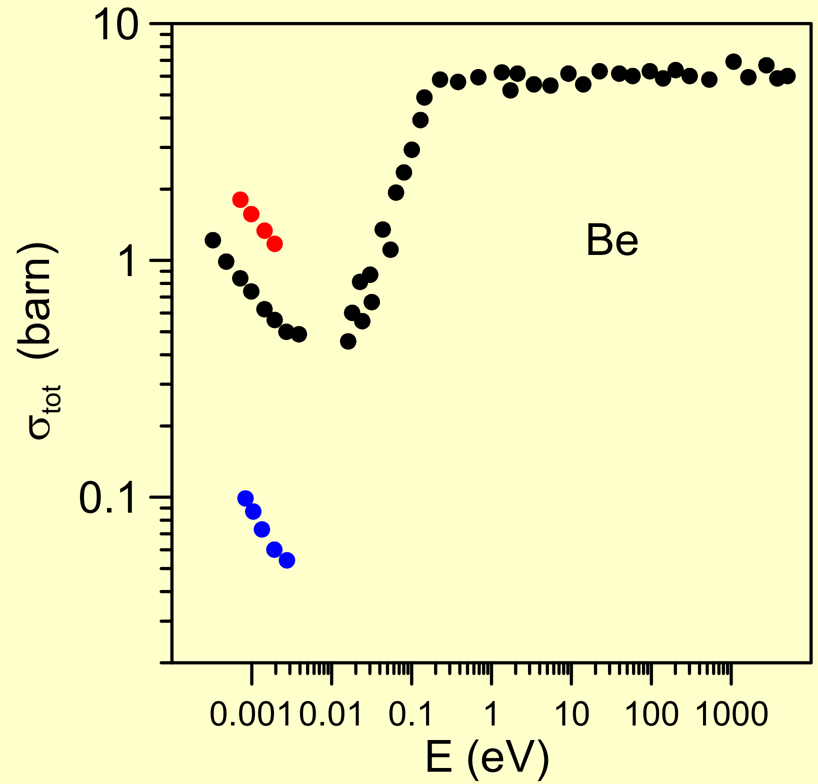
The cross section of hydrogen, as other elements, depends strongly on the energy and the thermodynamic state.

A very important nucleus is (was) the ^{3}He. Notice, liquid ^{3}He is the only Fermi liquid in nature.



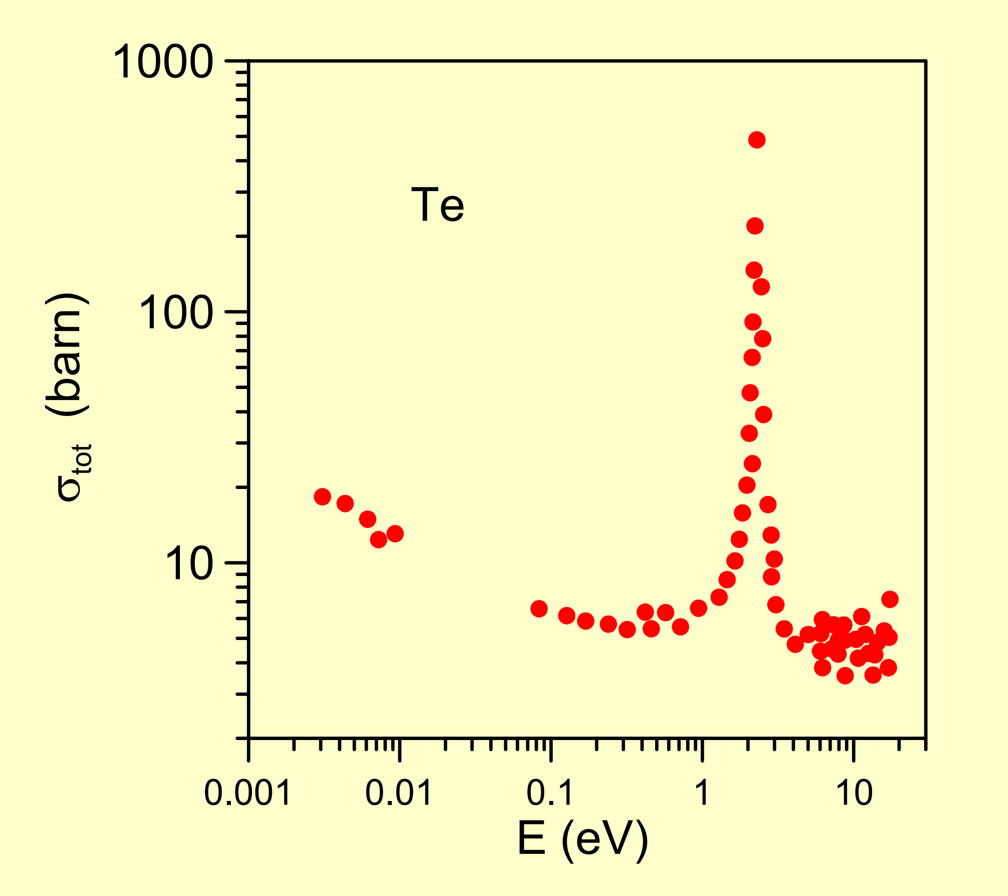
The cross section of ^{3}He is almost purely capture and very high. This isotope is (was) well suited for *neutron detection. This isotope is scarcely commercially available.*

Another important example is that of Be.



Beryllium is typical example of the effect of the Bragg scattering. The capture cross section is the smallest of various elements and there is sharp edge at about 5 meV is due to the first Bragg peak.

A typical example of a system showing a sharp resonance is tellurium.

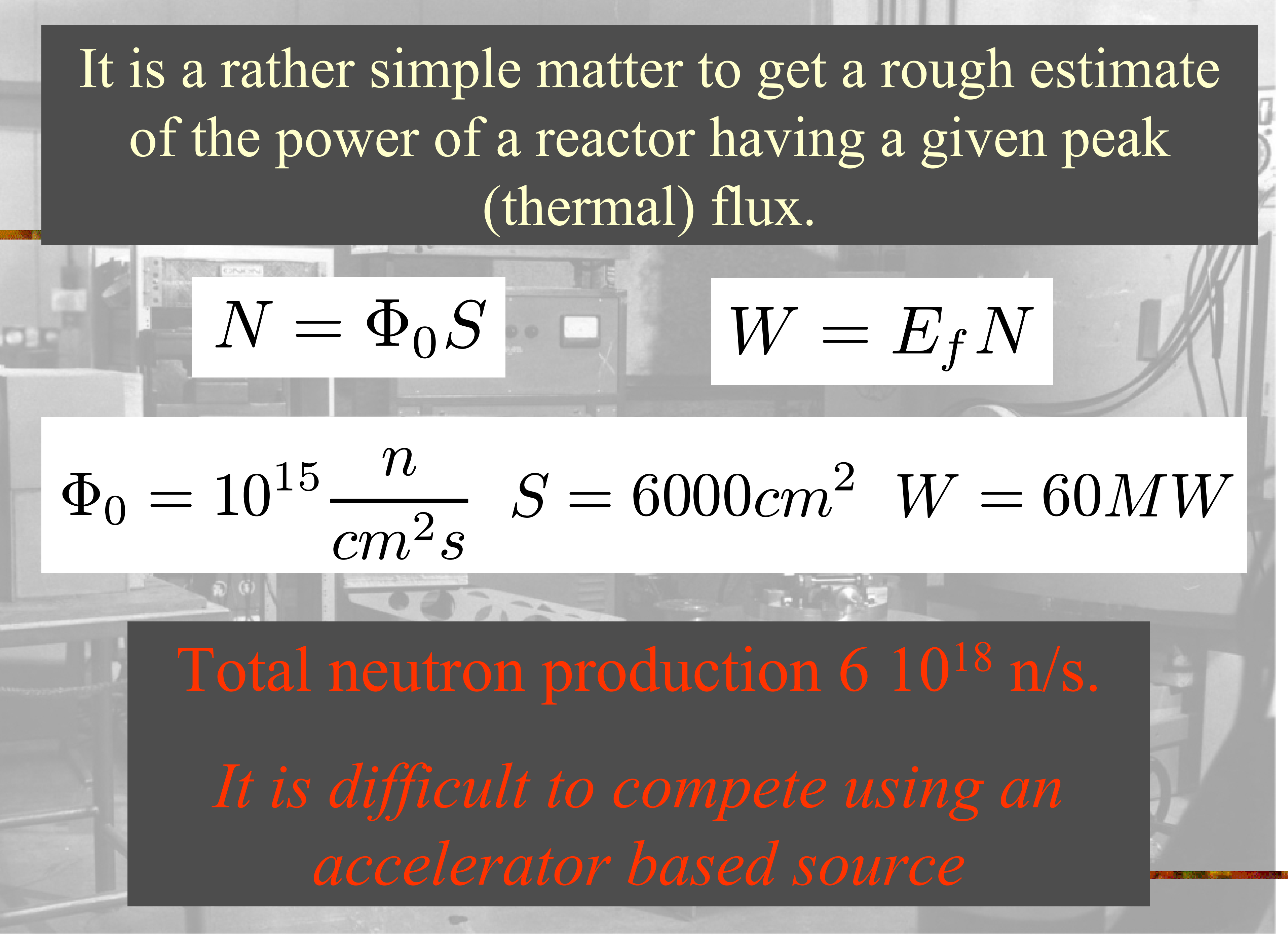


The peak observed at about 2.5 eV is a typical sharp resonance. Sharp resonances are present in almost all elements in a wide energy range.

To perform condensed matter experiments the typical wavelength is 1 Å.

Therefore the typical neutron energy is 81.797 meV or 19.795 THz, while the neutron velocity is 0.3956 cm/μs. It is evident that the measurement of the neutron velocity, ToF, allows a simple and direct determination of the neutron wavelength. Of course the other simple way to determine the neutron wavelength, and hence all related quantities, is the Bragg diffraction.

To date, two main nuclear reactions are employed to produce a large flux of neutrons: ***fission*** and ***spallation*** reactions. The IRIDE photo production has been rarely used in the past because it is easy but inefficient.



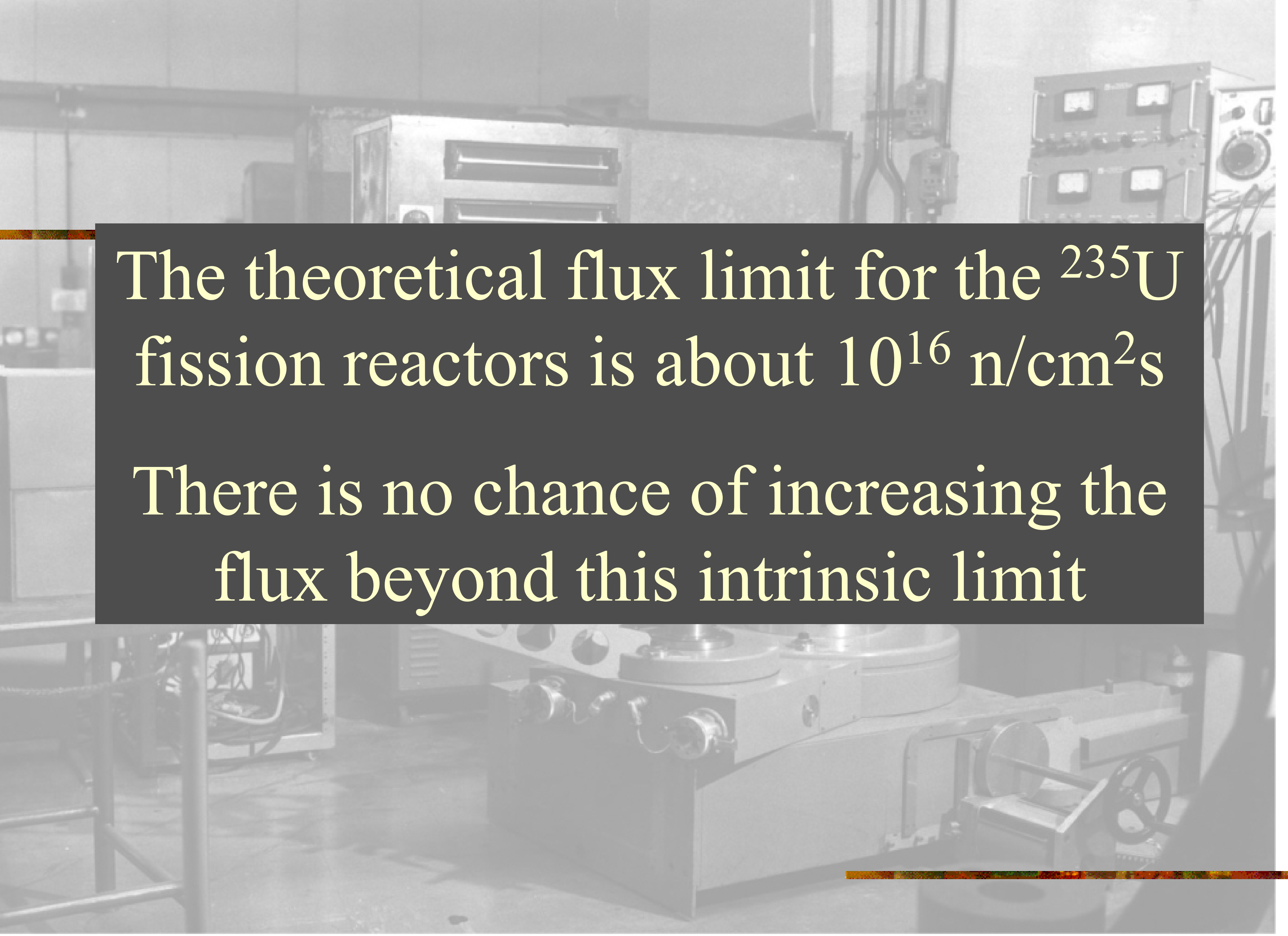
It is a rather simple matter to get a rough estimate of the power of a reactor having a given peak (thermal) flux.

$$N = \Phi_0 S \qquad W = E_f N$$

$$\Phi_0 = 10^{15} \frac{n}{cm^2 s} \quad S = 6000 cm^2 \quad W = 60 MW$$

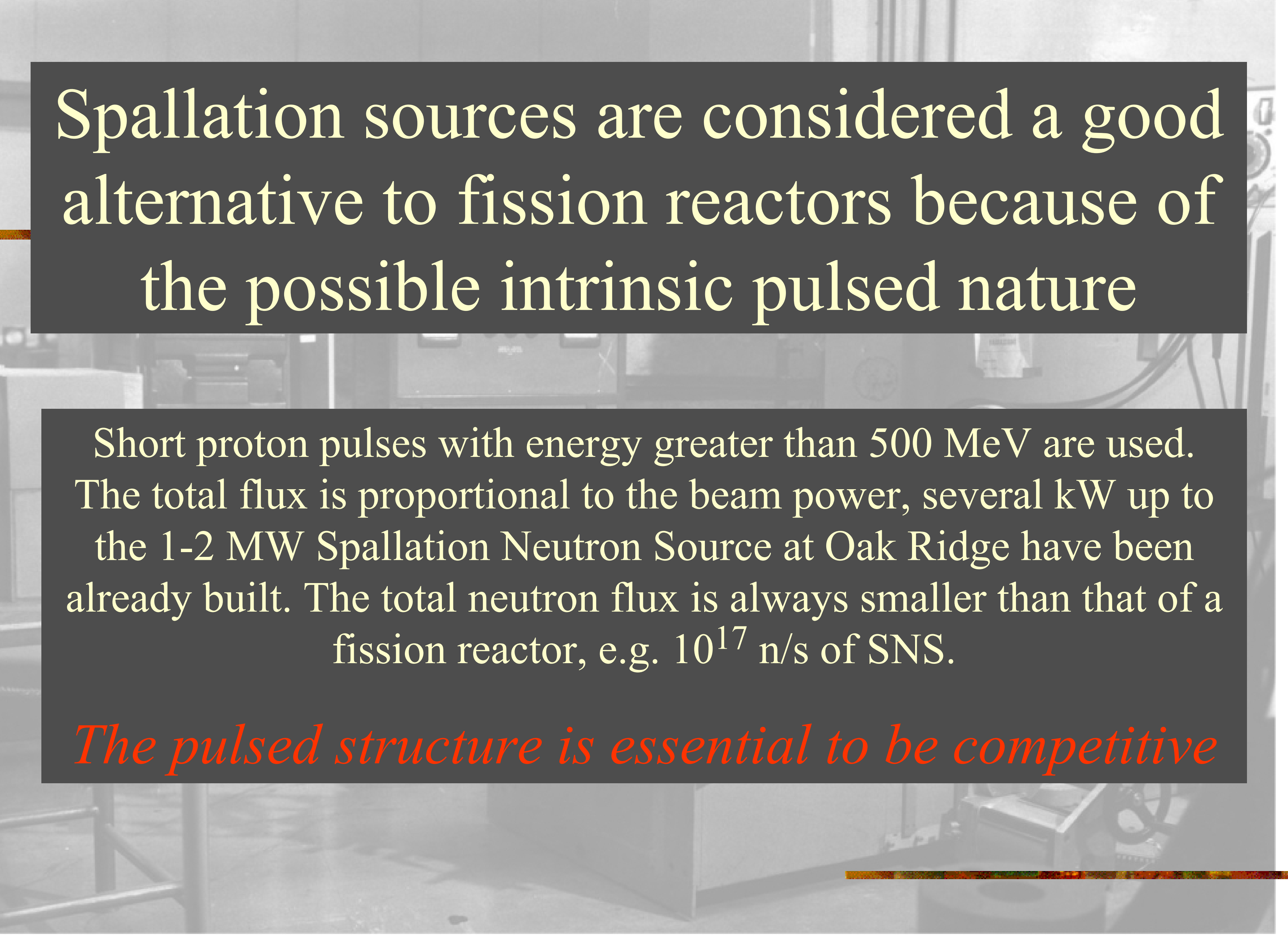
Total neutron production 6 10^{18} n/s.

It is difficult to compete using an accelerator based source



The theoretical flux limit for the ^{235}U fission reactors is about 10^{16} n/cm^{2}s

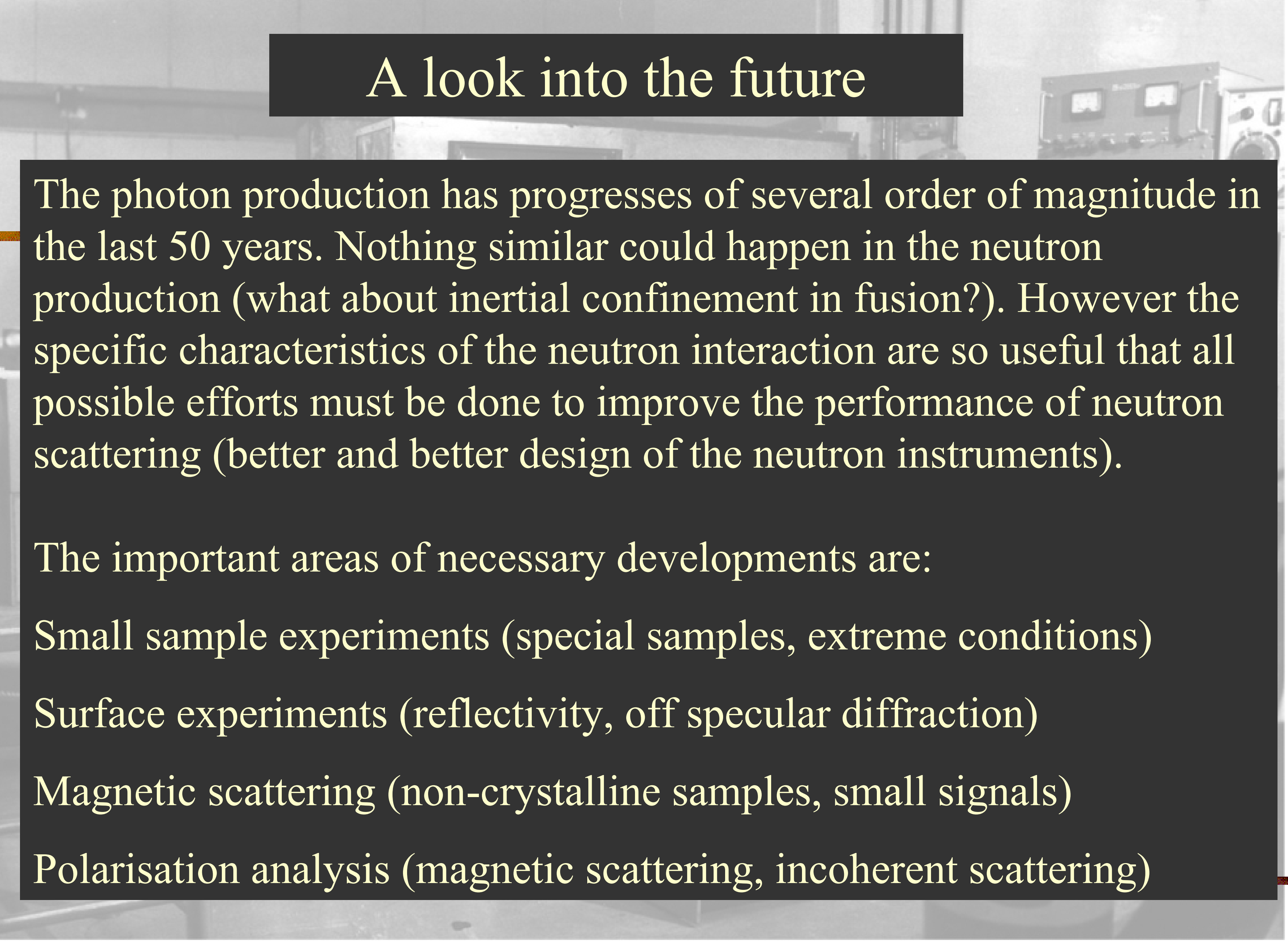
There is no chance of increasing the flux beyond this intrinsic limit



Spallation sources are considered a good alternative to fission reactors because of the possible intrinsic pulsed nature

Short proton pulses with energy greater than 500 MeV are used. The total flux is proportional to the beam power, several kW up to the 1-2 MW Spallation Neutron Source at Oak Ridge have been already built. The total neutron flux is always smaller than that of a fission reactor, e.g. 10^{17} n/s of SNS.

The pulsed structure is essential to be competitive



A look into the future

The photon production has progresses of several order of magnitude in the last 50 years. Nothing similar could happen in the neutron production (what about inertial confinement in fusion?). However the specific characteristics of the neutron interaction are so useful that all possible efforts must be done to improve the performance of neutron scattering (better and better design of the neutron instruments).

The important areas of necessary developments are:

Small sample experiments (special samples, extreme conditions)

Surface experiments (reflectivity, off specular diffraction)

Magnetic scattering (non-crystalline samples, small signals)

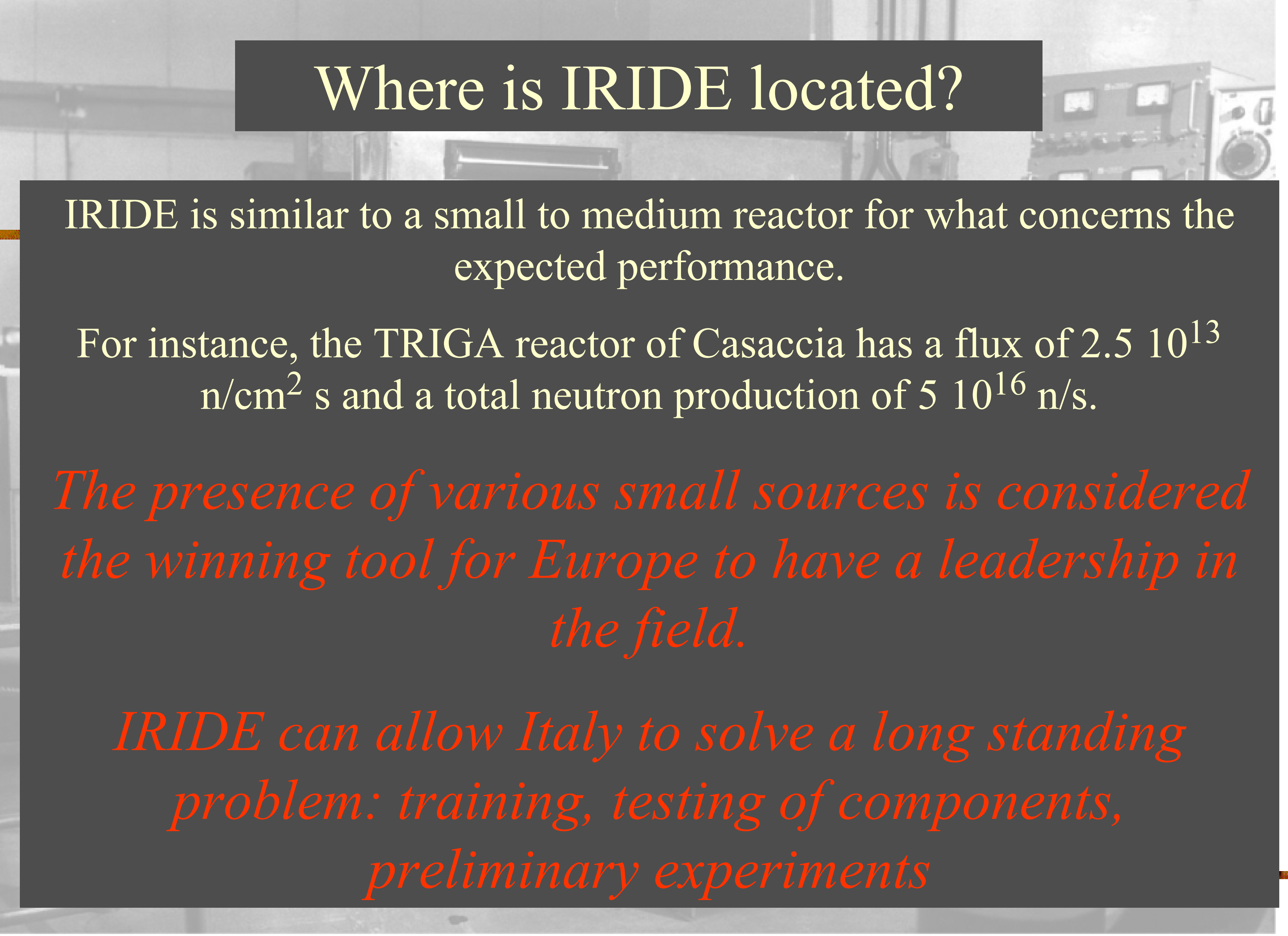
Polarisation analysis (magnetic scattering, incoherent scattering)

The ESS is a new concept in the neutron sources

The ESS is a long pulse spallation source. A linear proton accelerator produces neutron pulses 3 ms long with a repetition rate of 14 Hz and an average power of 5 MW.

In short pulse spallation sources the neutron are (under) moderated by thin moderators and the efficiency is rather low. The long pulse of ESS can be moderated by a thick high efficiency moderator, the average thermal neutron flux is equal to that of ILL while the peak flux is 35 times higher. A proper use of this high flux will produce an unprecedented increase of the neutron scattering possibilities.

Total neutron production 10^{18} n/s, similar to a medium flux reactor!



Where is IRIDE located?

IRIDE is similar to a small to medium reactor for what concerns the expected performance.

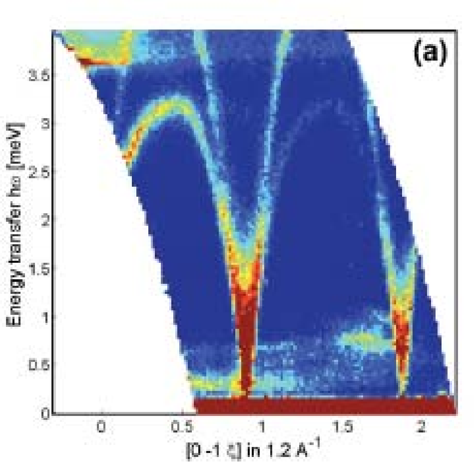
For instance, the TRIGA reactor of Casaccia has a flux of 2.5 10^{13} n/cm^2 s and a total neutron production of 5 10^{16} n/s.

The presence of various small sources is considered the winning tool for Europe to have a leadership in the field.

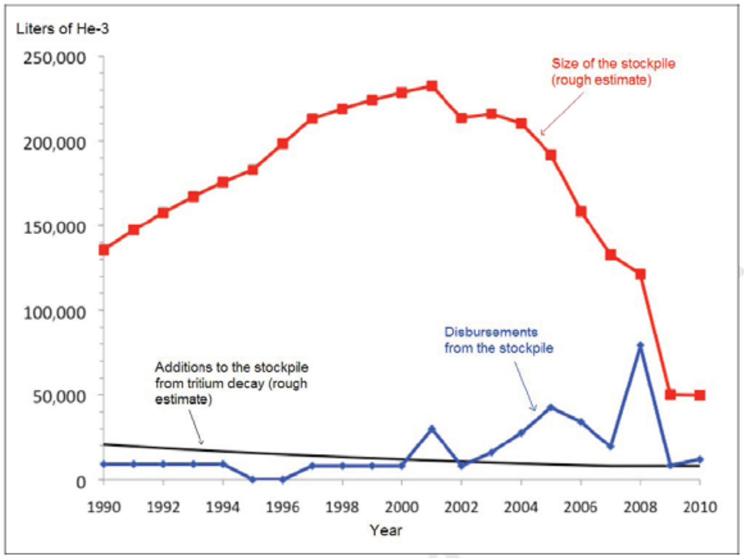
IRIDE can allow Italy to solve a long standing problem: training, testing of components, preliminary experiments

Detectors in the new era, the development and testing is very important

A ^{3}He detectors of this sort will be very difficult in Europe in the near future

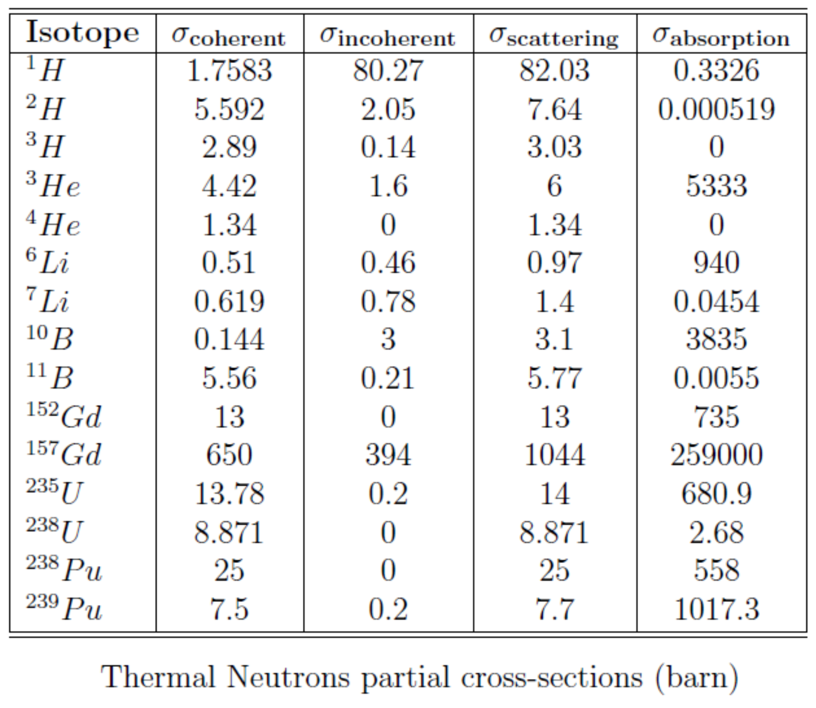


Size of the Helium-3 Stockpile, 1990-2010



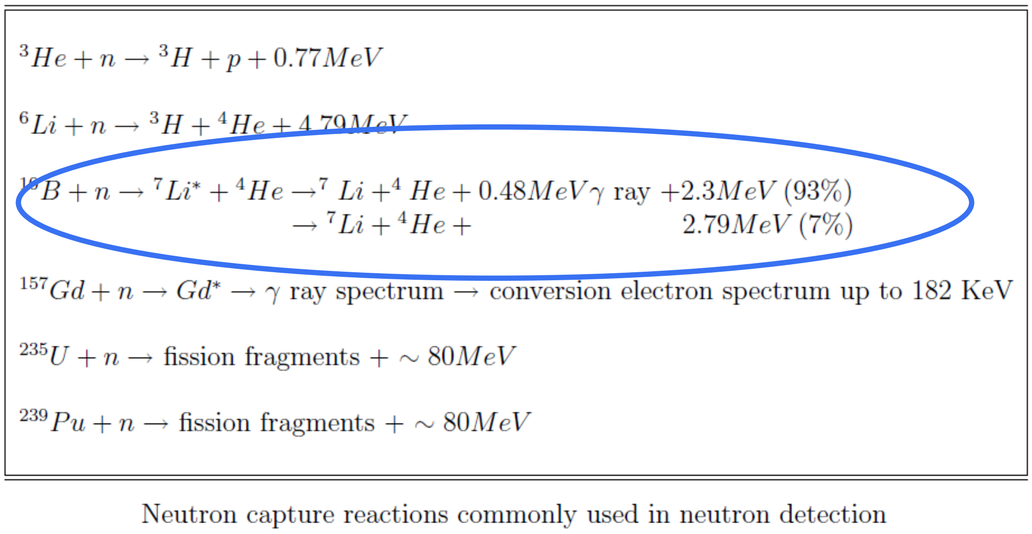
Source: Adapted from Steve Fetter, Office of Science and Technology Policy, "Overview of Helium-3 Supply and Demand," presentation at the American Association for the Advancement of Science Workshop on Helium-3, April 6, 2010.

^{3}He alternatives, a national neutron source will allow Italian groups to enter into the detector business



Isotope	σ_{coherent}	$\sigma_{\text{incoherent}}$	$\sigma_{\text{scattering}}$	$\sigma_{\text{absorption}}$
^1H	1.7583	80.27	82.03	0.3326
^2H	5.592	2.05	7.64	0.000519
^3H	2.89	0.14	3.03	0
^3He	4.42	1.6	6	5333
^4He	1.34	0	1.34	0
^6Li	0.51	0.46	0.97	940
^7Li	0.619	0.78	1.4	0.0454
^{10}B	0.144	3	3.1	3835
^{11}B	5.56	0.21	5.77	0.0055
^{152}Gd	13	0	13	735
^{157}Gd	650	394	1044	259000
^{235}U	13.78	0.2	14	680.9
^{238}U	8.871	0	8.871	2.68
^{238}Pu	25	0	25	558
^{239}Pu	7.5	0.2	7.7	1017.3

Thermal Neutrons partial cross-sections (barn)



$$^3He + n \rightarrow {}^3H + p + 0.77MeV$$

$$^6Li + n \rightarrow {}^3H + {}^4He + 4.79MeV$$

$$\begin{aligned} {}^{10}B + n \rightarrow {}^7Li^* + {}^4He \rightarrow {}^7Li + {}^4He + 0.48MeV\gamma \text{ ray } &+ 2.3MeV\ (93\%) \\ \rightarrow {}^7Li + {}^4He + &\ 2.79MeV\ (7\%) \end{aligned}$$

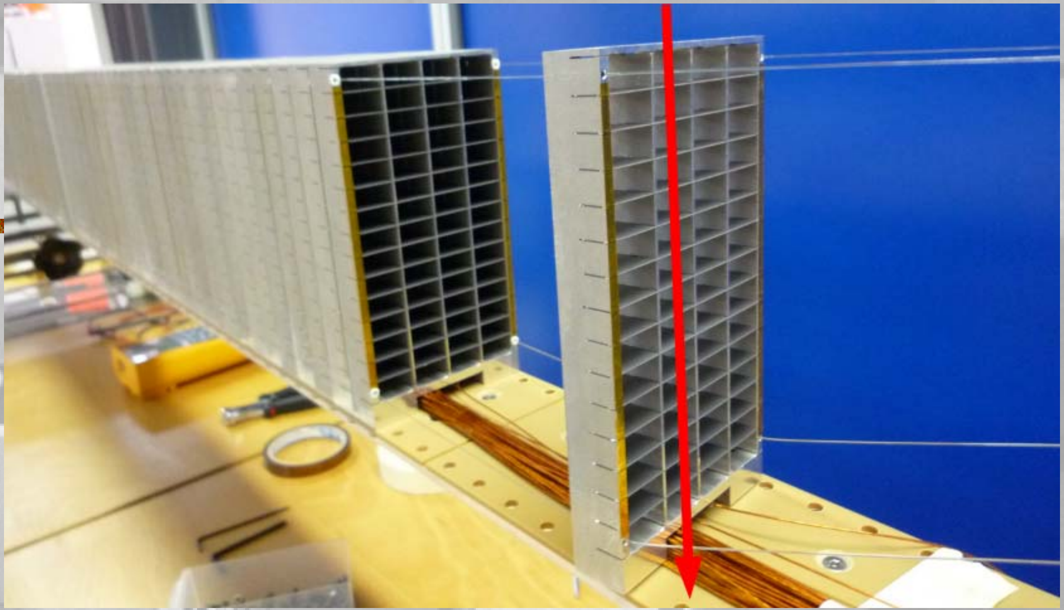
$$^{157}Gd + n \rightarrow Gd^* \rightarrow \gamma \text{ ray spectrum} \rightarrow \text{conversion electron spectrum up to 182 KeV}$$

$$^{235}U + n \rightarrow \text{fission fragments} + \sim 80MeV$$

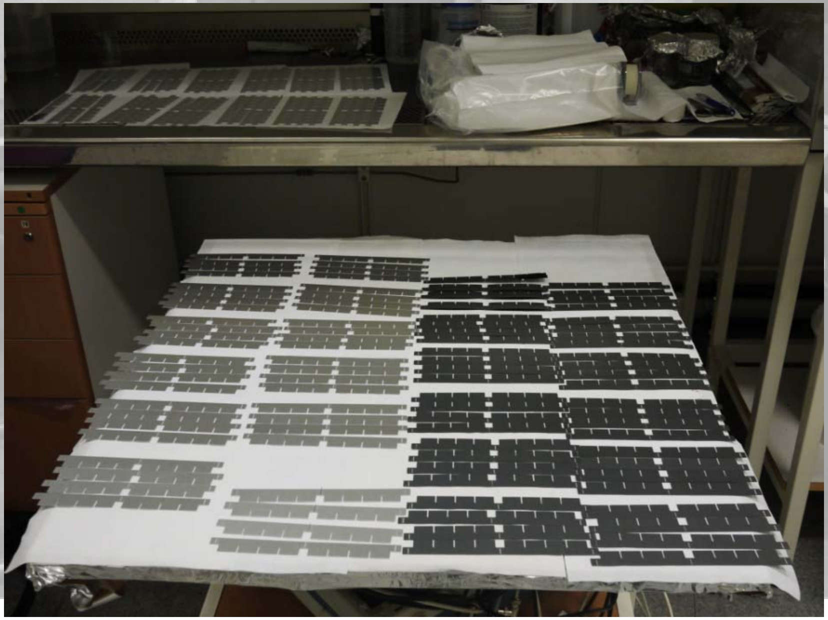
$$^{239}Pu + n \rightarrow \text{fission fragments} + \sim 80MeV$$

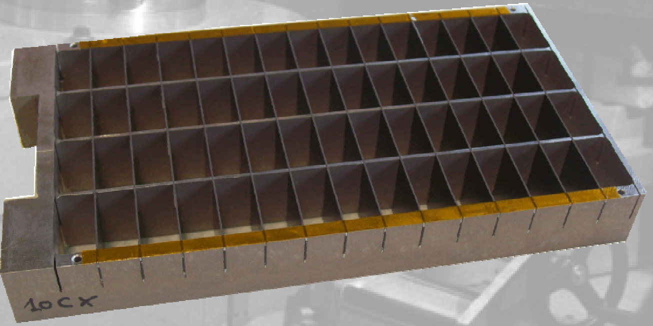
Neutron capture reactions commonly used in neutron detection

The boron reaction has an adequate cross section and high energy in the final state. The only gaseous compound is BF_3, rather toxic.



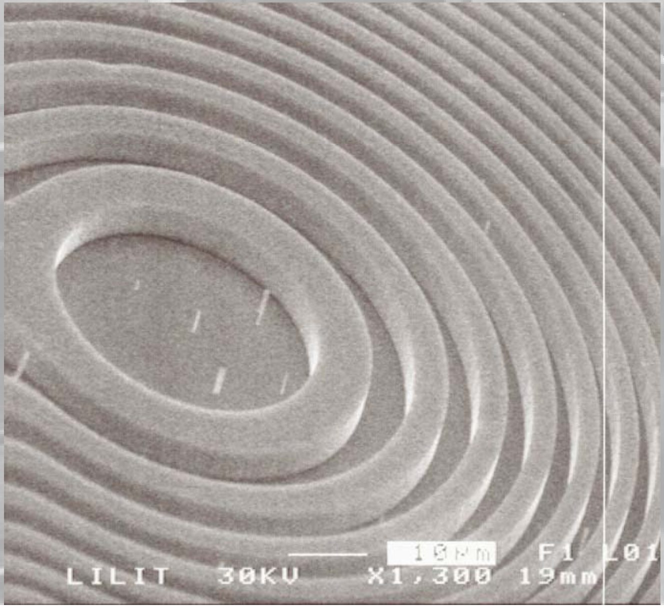
A collaboration between ILL and ESS produced a preliminary device which could be used in real large area detectors



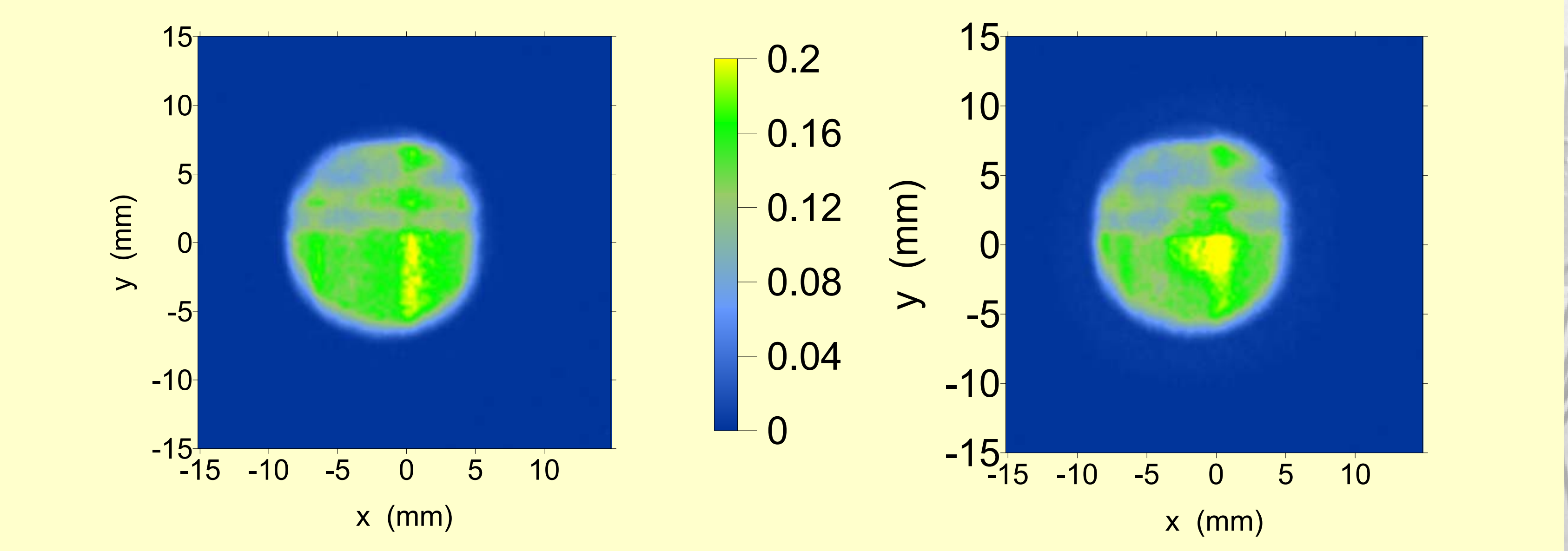


Testing of neutron optics devices is a very important area of development

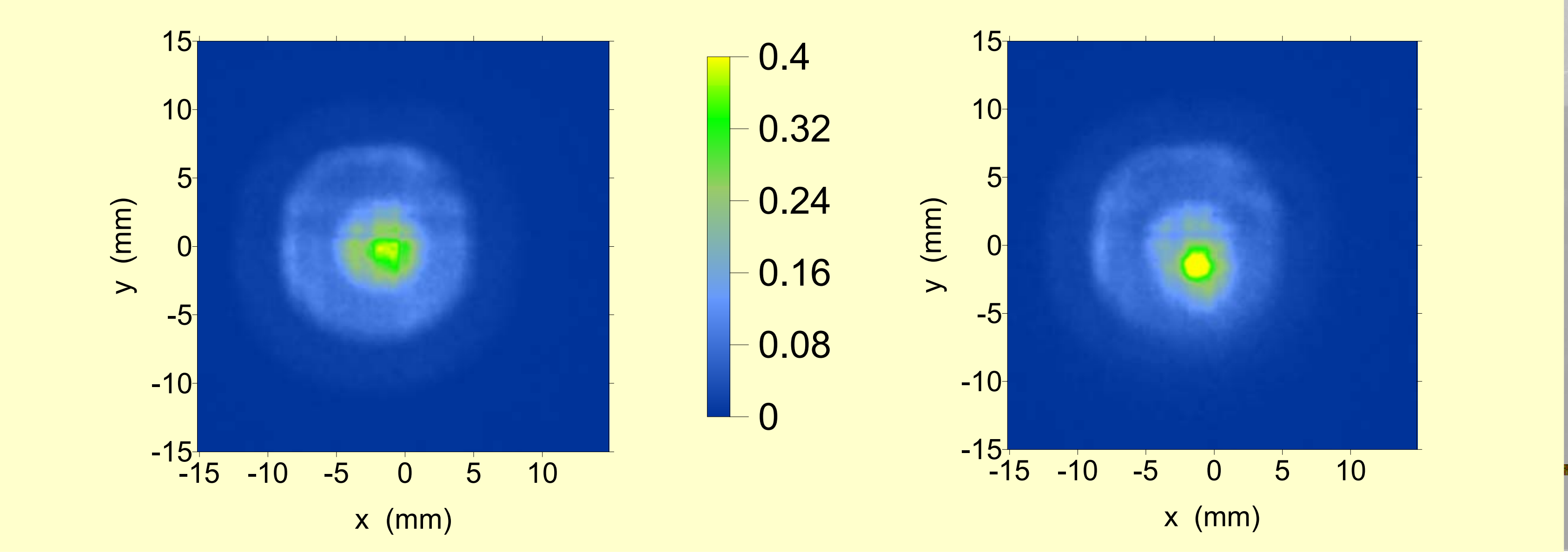
Future focusing techniques. Fresnel zone plates. Still too small for neutron applications, nano-technology being improved, research is needed. A focal distance of 4 m at 5.2 Å of a lens with 5 mm diameter is already possible. Be careful, the Liouville theorem limits the use of concentrating tools



SEM picture of the ZP

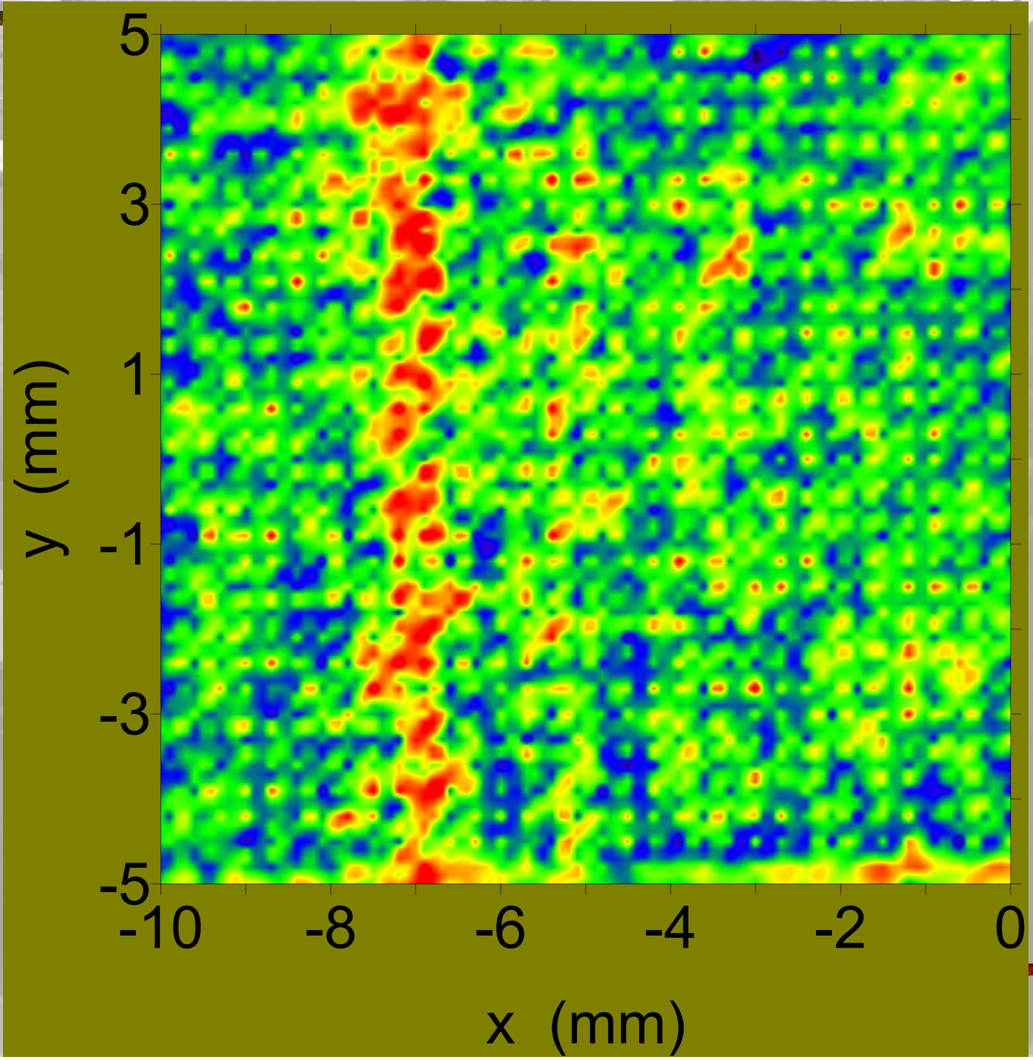


Empty beam, 1 ZP, 2 ZP, 3 ZP



Is neutron microscopy possible in the μm range?

ZP matrix, 100 μm neutron spots (here resolution limited) produced from a 1 mm hole at 6.5 Å wavelength. The same matrix at 100 m from the source will produce 3 μm neutron spots



IRIDE neutron source

Training and test sources are very important, however less demanding preliminary experiments are possible. See for instance the Delft reactor (2 MW) which gets support from the EU within the access program and it is a well recognized facility.

It is important to have a good equilibrium between investment and results.

Italy has the fourth European neutron user community (number of scientists and scientific production) but the investment is about 10% of that of France, all in charge of the CNR (about 8 M€/year) for the access.

It is not possible to stop the progress

The knowledge is always better than the ignorance

E. Fermi