NEUTRON SOURCES

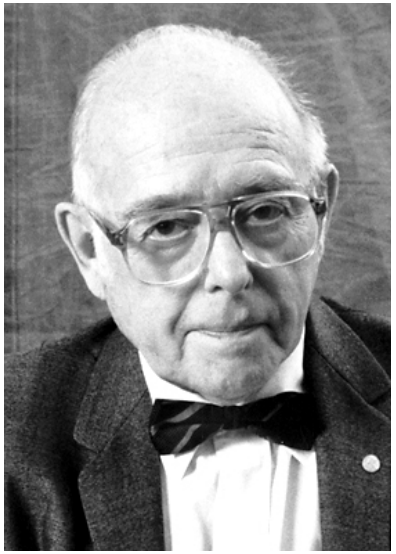
Antonino Pietropaolo
ENEA
Dipartimento di Fusione e Tecnologie per la Sicurezza Nucleare

1935

Discovery of the neutron
1932

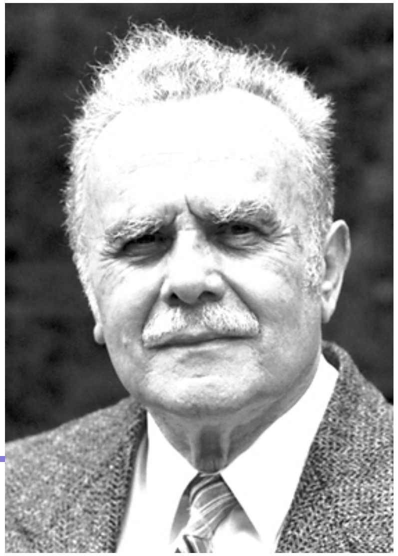
James Chadwick

1994



Clifford G. Shull

"for the development of the neutron diffraction technique"



Bertram N. Brokhouse

"for the development of neutron spectroscopy"

Main properties

Charge= 0

Barionic Number= 1

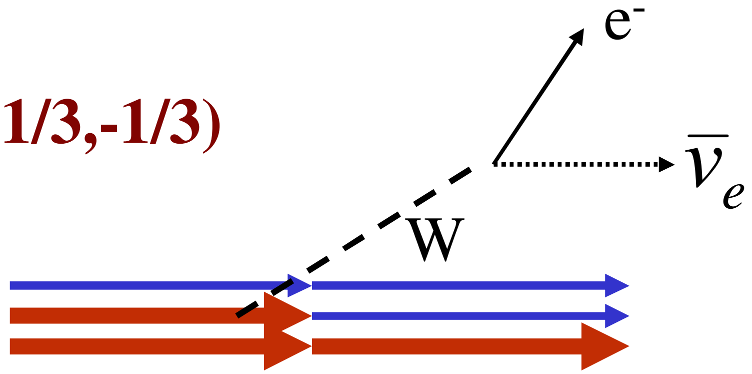
Interactions: Electroweak, strong, gravitational

Spin = $\frac{1}{2}\hbar$

Internal structure (QCD) = **udd (2/3,-1/3,-1/3)**

Weak decay ($T_{1/2}$ = 889.1 ± 2.1 sec)

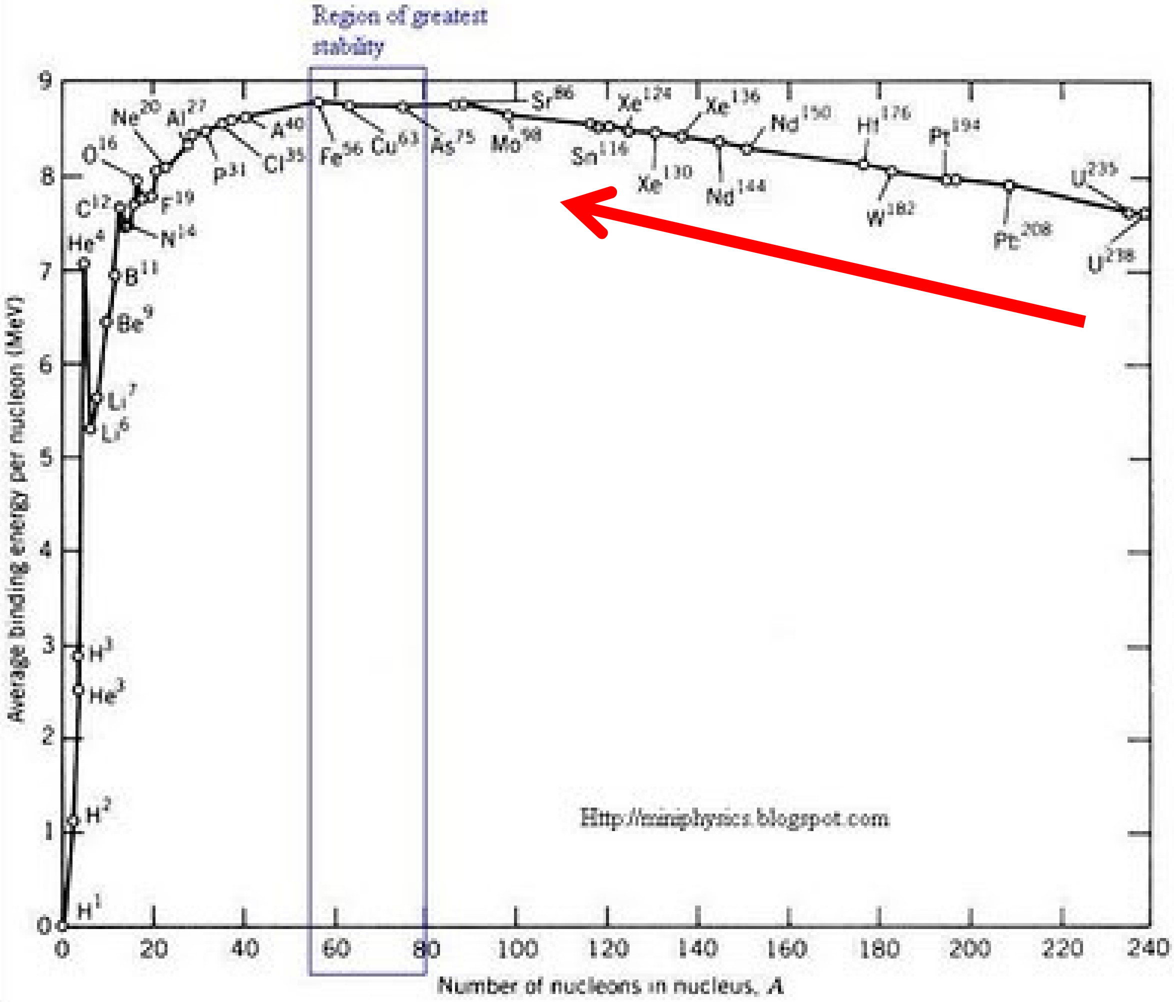
$$n \rightarrow p + e^{-} + \bar{\nu}_e$$



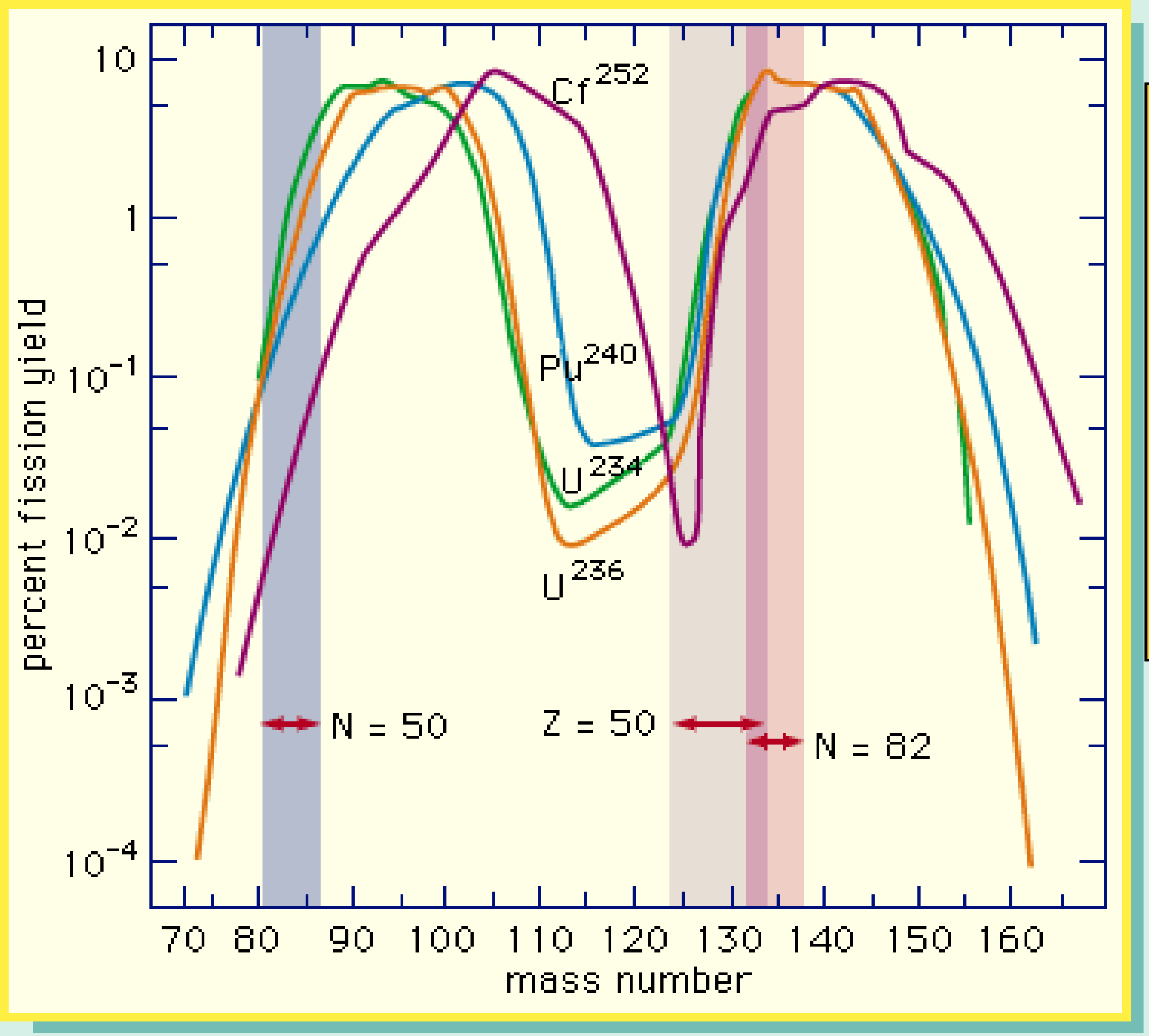
Magnetic moment: μ_m= - 0.966 236 40(23) x 10^{-26} JT^{-1}

Electric Dipole moment: |d| = 3.0 x 10^{-26} e cm

Mass = 1.6749 x 10^{-27} kg (appreciable effects in neutron interferometry)


Region of greatest stability
Average binding energy per nucleon (MeV)
Number of nucleons in nucleus, A
0
1
2
3
4
5
6
7
8
9
0
20
40
60
80
100
120
140
160
180
200
220
240
H1
H2
He3
H3
He4
Li6
Li7
Be9
B11
C12
N14
O16
F19
Ne20
Al27
P31
Cl35
A40
Fe56
Cu63
As75
Sr86
Mo98
Sn116
Xe124
Xe130
Xe136
Nd144
Nd150
Hf176
W182
Pt194
Pt208
U235
U238
Http://miniphysics.blogspot.com

The spontaneous fission



Distributions of mass numbers for different fissile nuclides:

^{252}Cf

^{240}Pu

^{234}U

^{236}U

The Fission Process

A neutron travels at high speed towards a uranium-235 nucleus.

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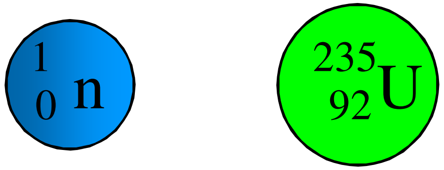

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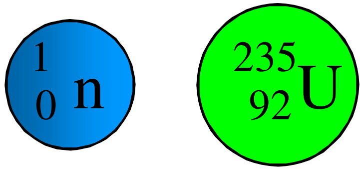
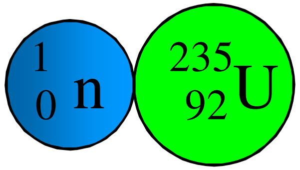


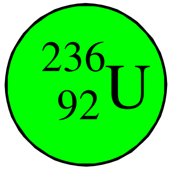
The Fission Process

The neutron strikes the nucleus which then captures the neutron.



The Fission Process

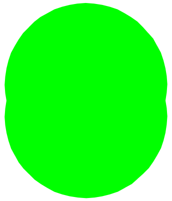
The nucleus changes from being uranium-235 to uranium-236 as it has captured a neutron.



The Fission Process

The uranium-236 nucleus formed is very unstable.

It transforms into an elongated shape for a short time.



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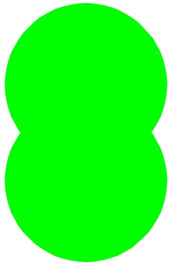

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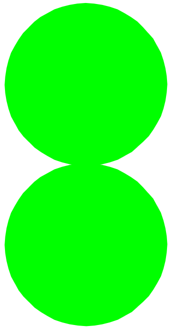
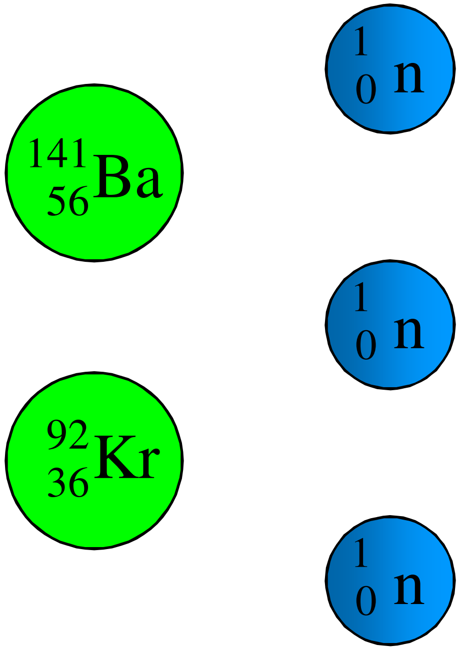


The Fission Process

It then splits into 2 fission fragments and releases neutrons.



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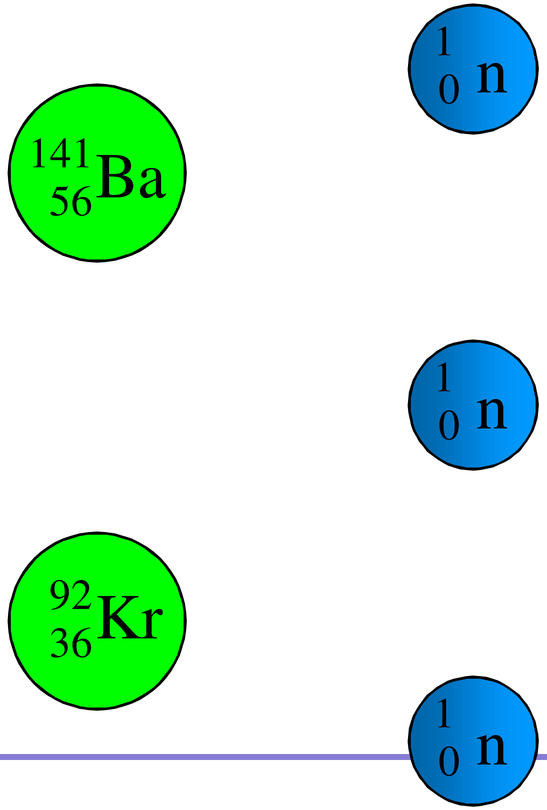

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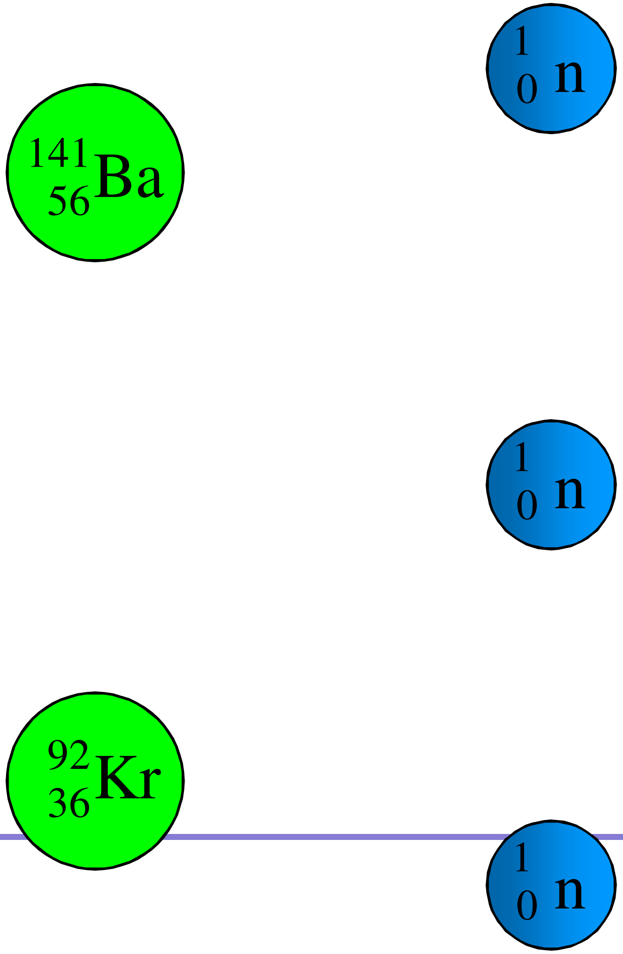

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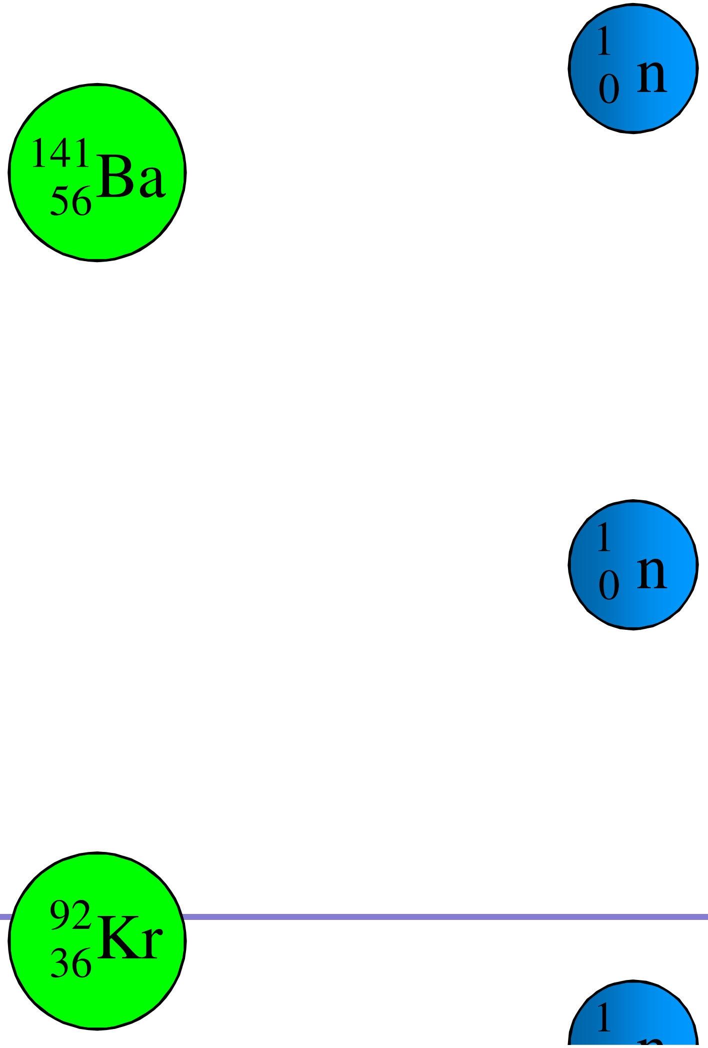

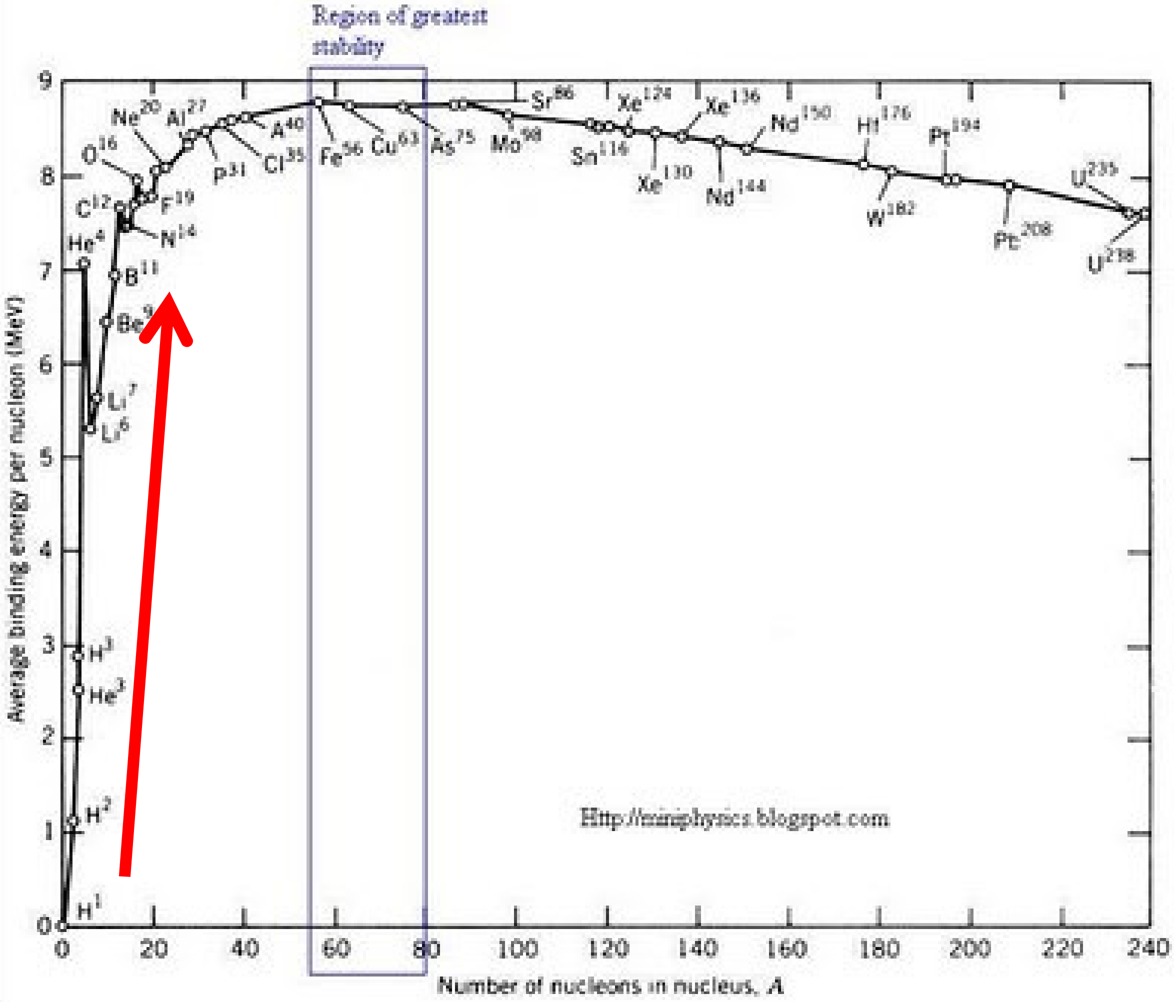
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Cl35
A40
Fe56
Cu63
As75
Sr86
Mo98
Sn116
Xe124
Xe130
Xe136
Nd144
Nd150
Hf176
W182
Pt194
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U235
U238
Http://miniphysics.blogspot.com

Nuclear Fusion

In nuclear fusion, two nuclei with low mass numbers combine to produce a single nucleus with a higher mass number.

$$ {}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n + \text{Energy} $$

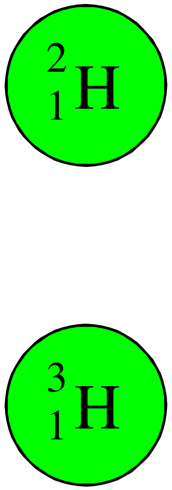
The Fusion Process

The Fusion Process

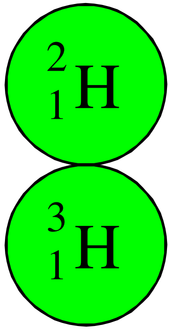
$^{2}_{1}\mathrm{H}$

$^{3}_{1}\mathrm{H}$

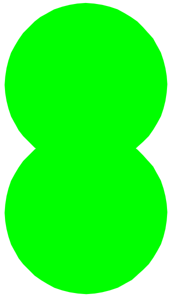
The Fusion Process



The Fusion Process



The Fusion Process



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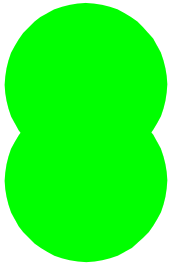

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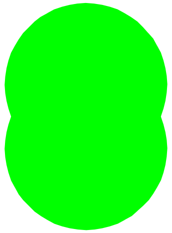

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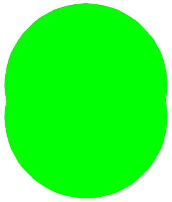

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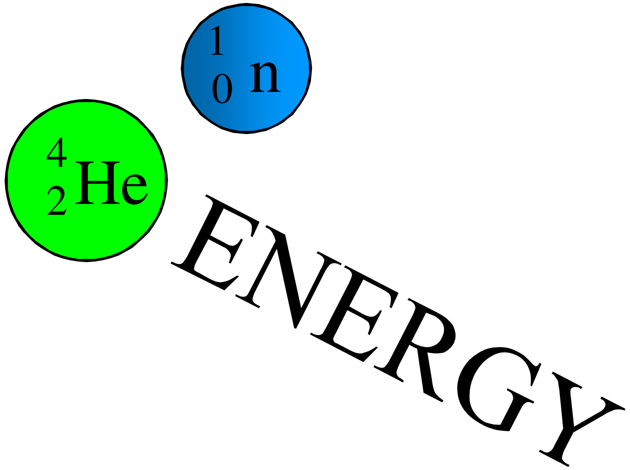

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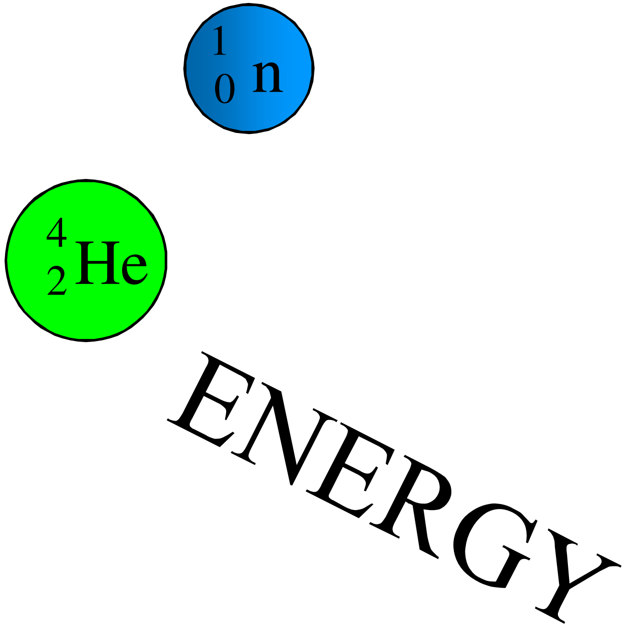

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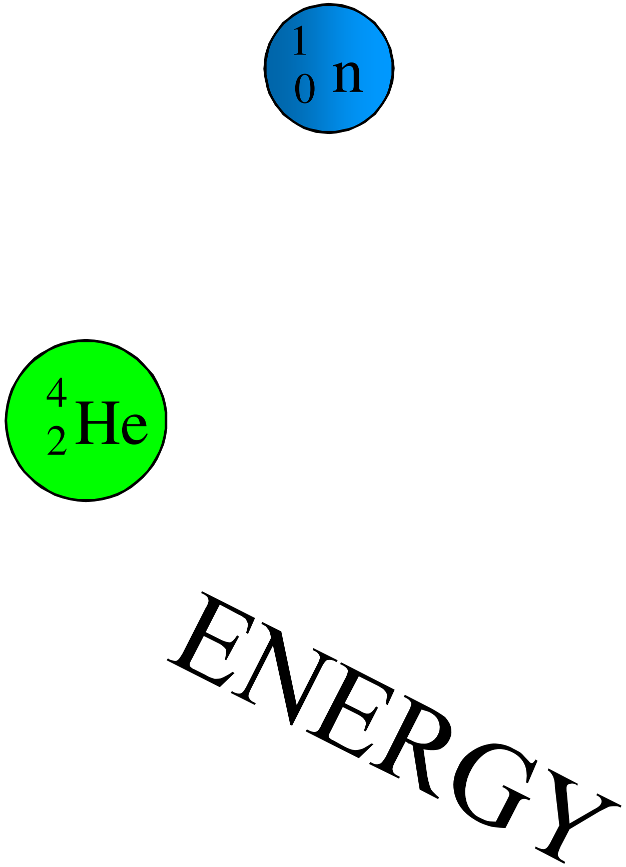
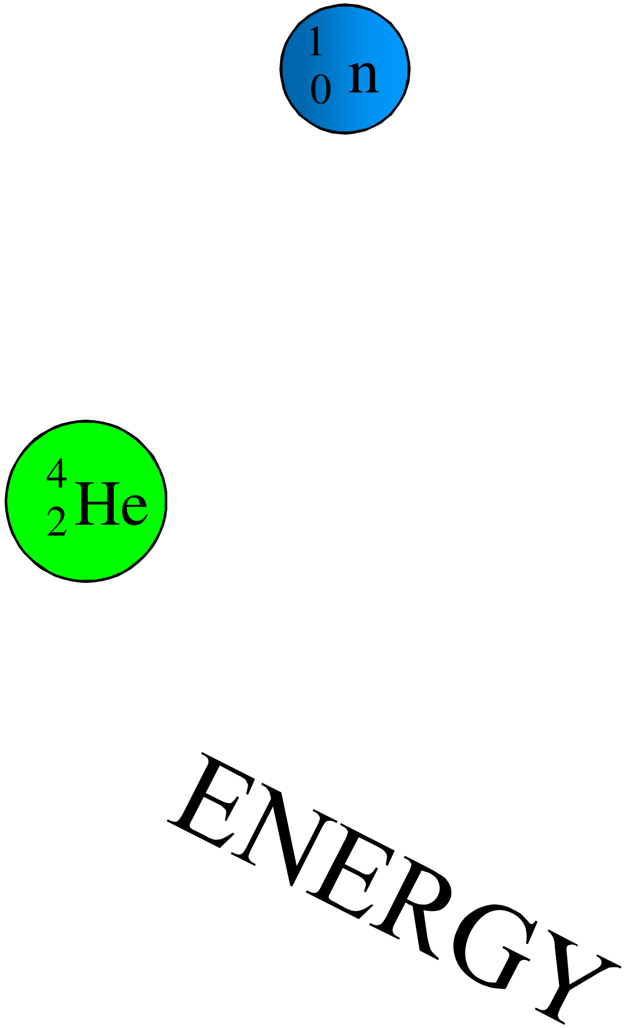


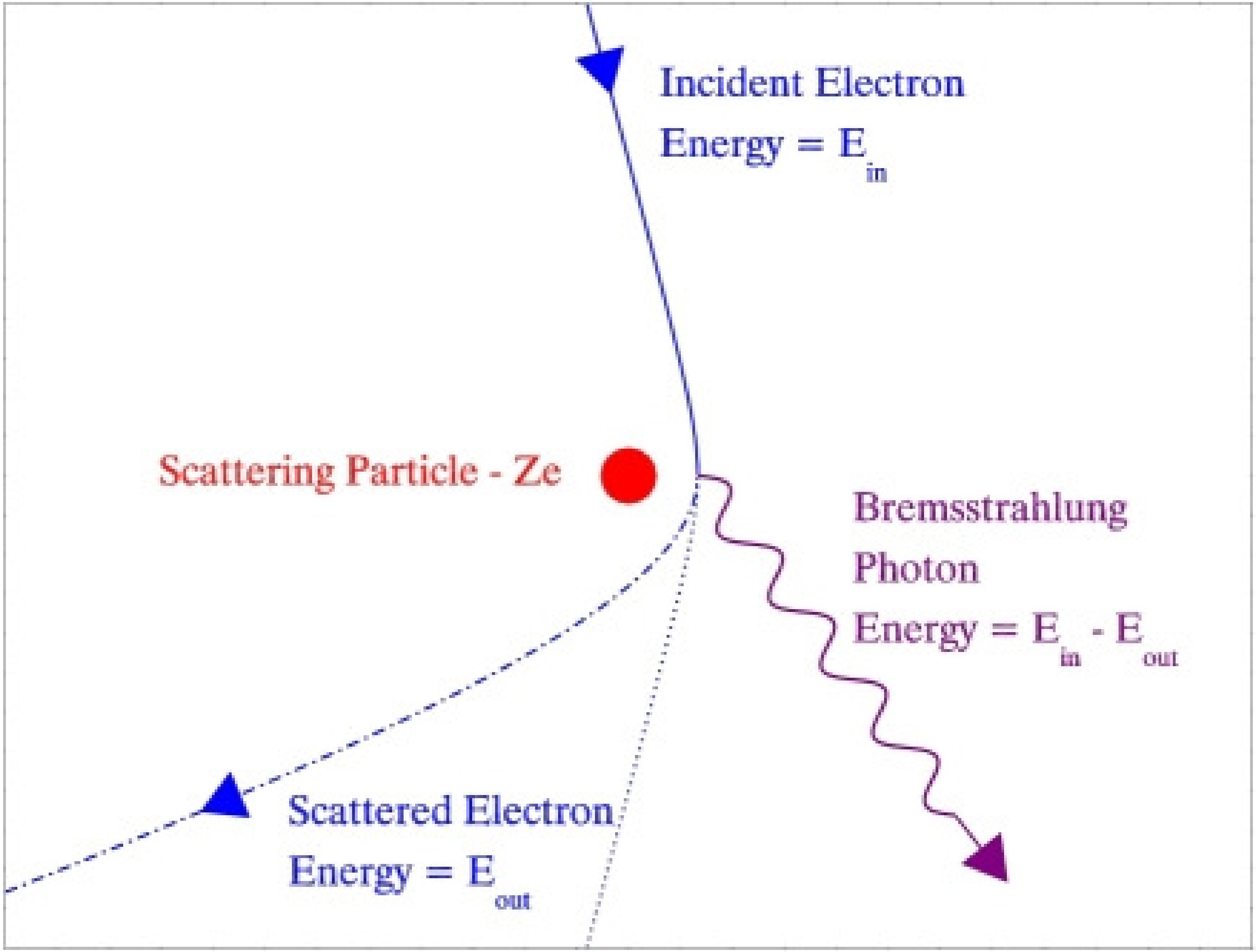
$^{1}_{0}n$

$^{4}_{2}He$

ENERGY

The Fusion Process




Incident Electron
Energy = E_{in}
Scattering Particle - Ze
Bremsstrahlung
Photon
Energy = E_{in} - E_{out}
Scattered Electron
Energy = E_{out}

e

e
e

The charge particle induced reactions

At low energies (let say below 100 MeV) interactions with formation of compound (not stable) nuclei that in turn decay with emission of neutrons is likely to occur

Examples of neutron sources

Radioisotopes

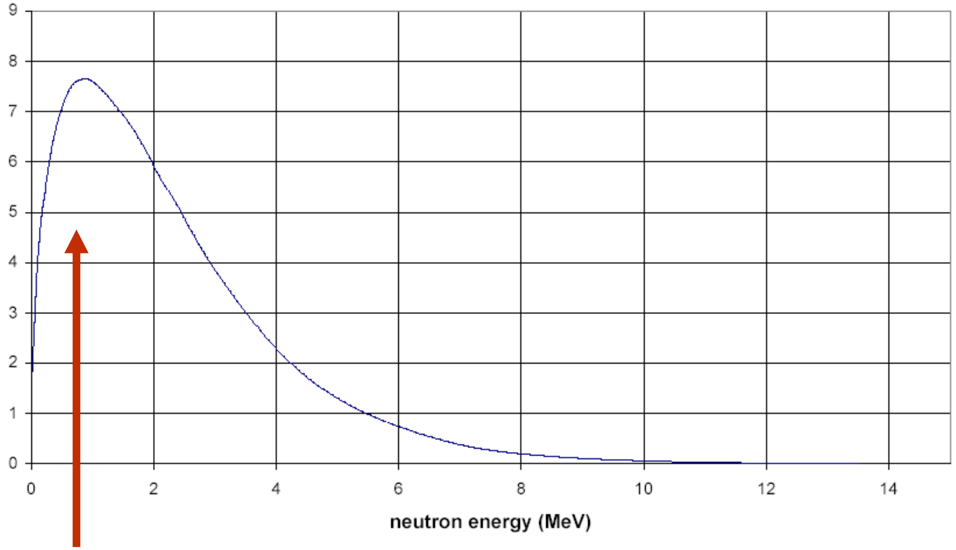


Figure 2: Neutron kinetic energy spectrum produced in the spontaneous fission of Californium nuclei.

^{252}Cf spontaneous fission:

spectrum well described by the relation:

$$\frac{dN}{dE} = E^{1/2} e^{-\frac{E}{T}} \qquad T \approx 1.3\ \text{MeV}$$

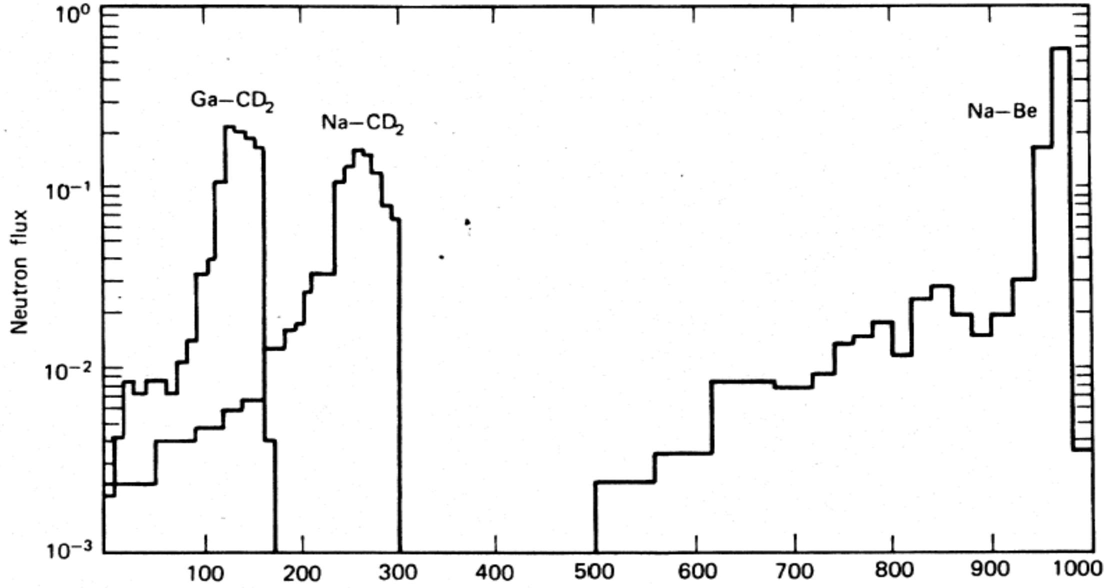
$I \approx 2.3\ 10^{6}$ n s^{-1} μgr^{-1}

3.8 n/fission + 9.7 γ (85% prompt $\tau <$ ns and high energy)

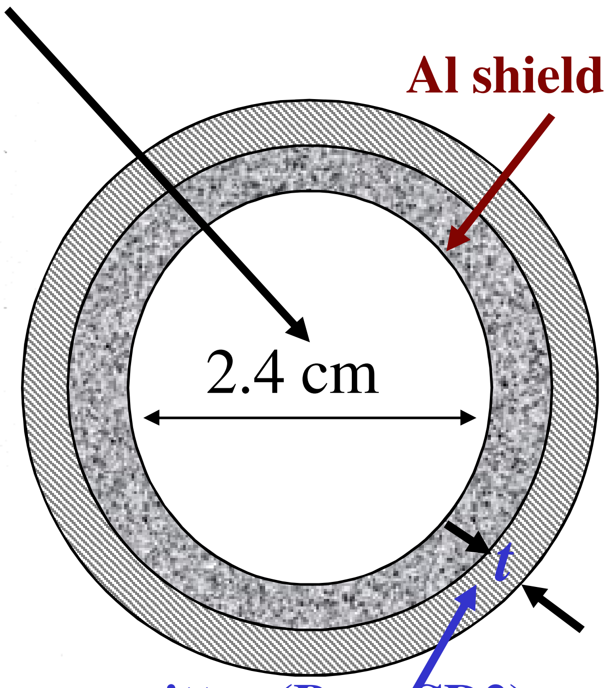
Photoproduction

$^{9}\mathrm{Be}_4 + h\nu \rightarrow {}^{8}\mathrm{Be}_4 + \mathrm{n}$ (-1.666 MeV)

$^{2}\mathrm{H}_1 + h\nu \rightarrow {}^{1}\mathrm{H}_1 + \mathrm{n}$ (-2.226 MeV)



Neutron spectra calculated for the source in the picture.
Typical γ sources are ^{72}Ga and ^{22}Na. The external shell may be made of Berillium or deuterated Poly(CD_2)



γ Source at the center

Al shield

2.4 cm

t

n emitter (Be o CD2)

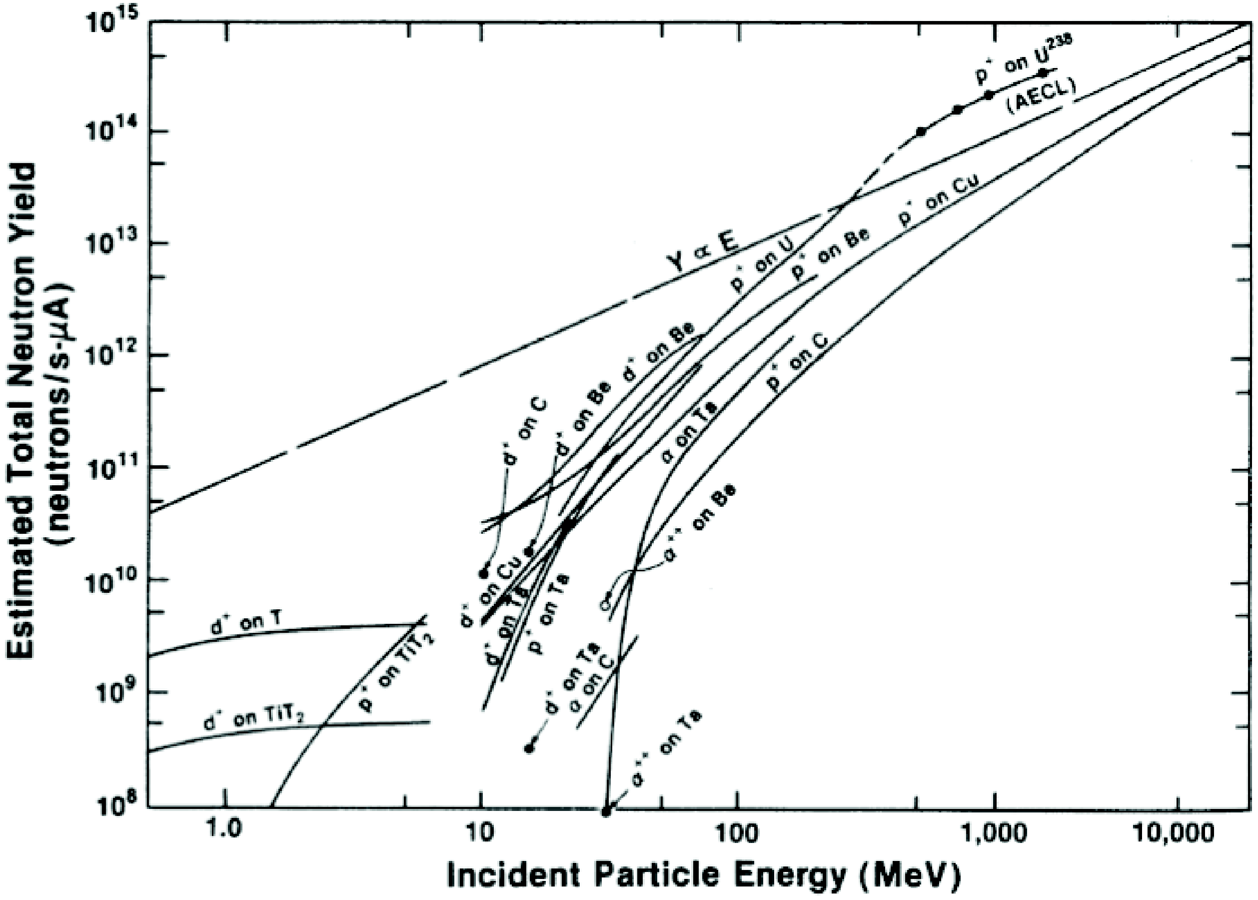
***t* ≈ 3.2 mm**

$$E_n(\vartheta)=\frac{M(E_\gamma+Q)}{m+M}+\frac{E_\gamma\left[(2mM)(m+M)(E_\gamma+Q)\right]^{1/2}}{(m+M)^2}\cos\vartheta$$

ϑ γ – n sngle
M recoiling nucleus mass
m neutron mass

Charged particle induced reactions

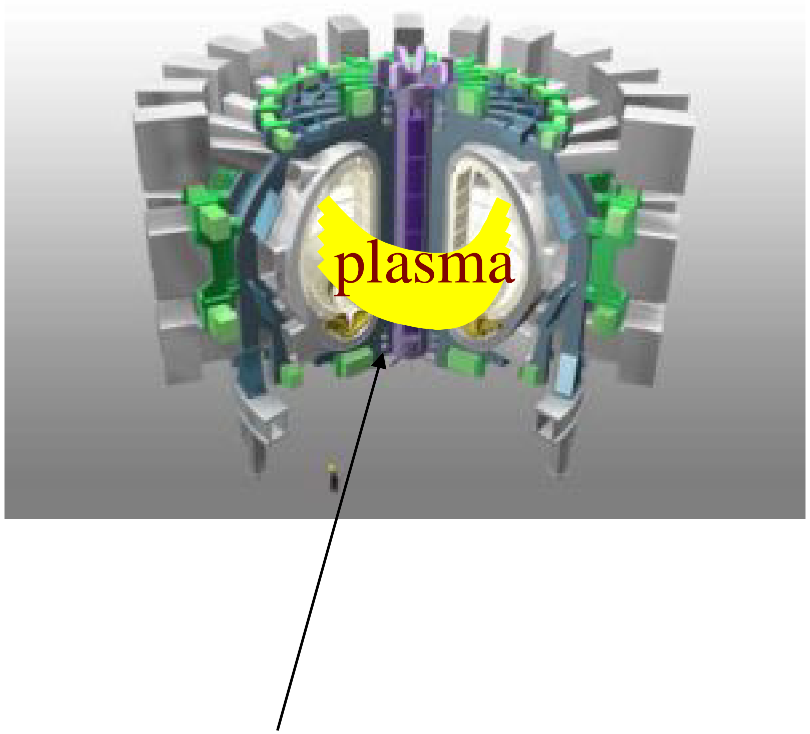
Two examples: (i) **^{9}Be + p → ^{9}B+n**, (ii) **^{2}H+^{3}H → ^{4}He + n**



Neutron Yield for a series of charged particle induced reactions

Neutrons from fusion plasma
TOKAMAK

ITER



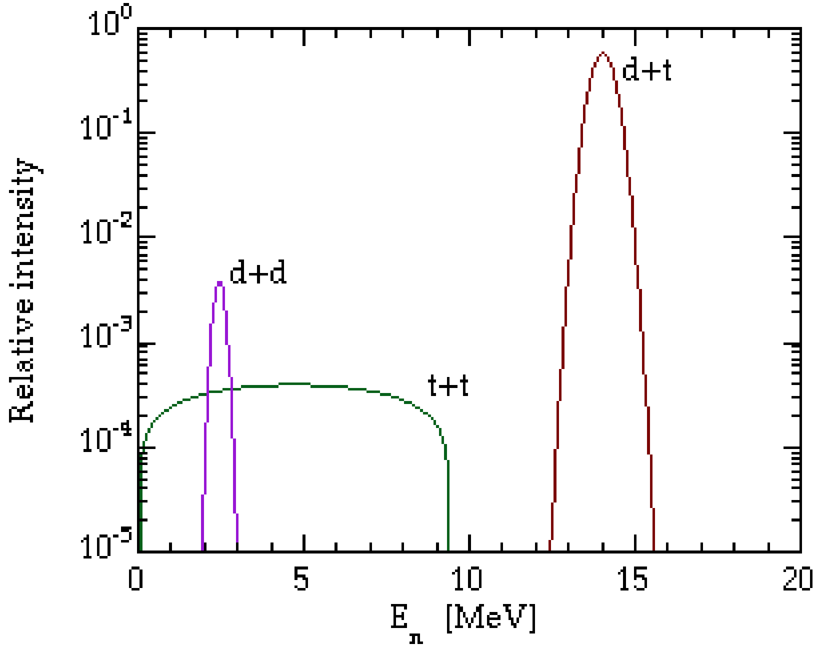
Toroidal vacuum chamber

D-D Reaction:

$^{2}H_{1} + {}^{2}H_{1} \rightarrow {}^{3}He_{2} + n \quad (+\ 3.26\ \mathrm{MeV})$

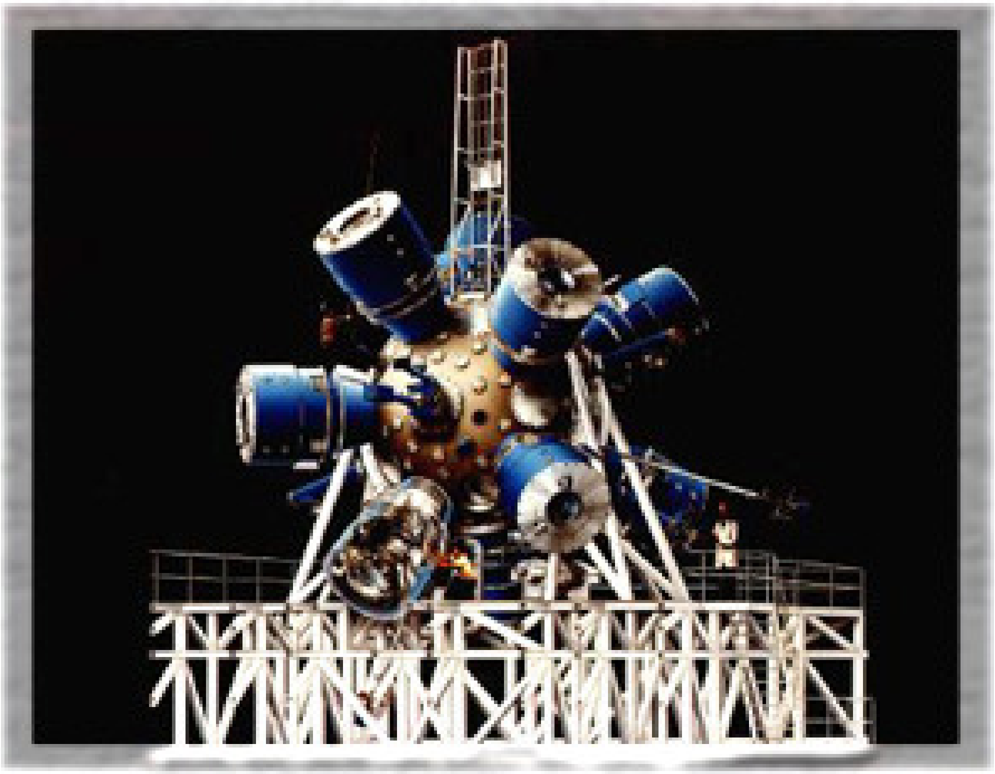
D-T Reaction

$^{2}H_{1} + {}^{3}H_{1} \rightarrow {}^{4}He_{2} + n \quad (+\ 17.6\ \mathrm{MeV})$

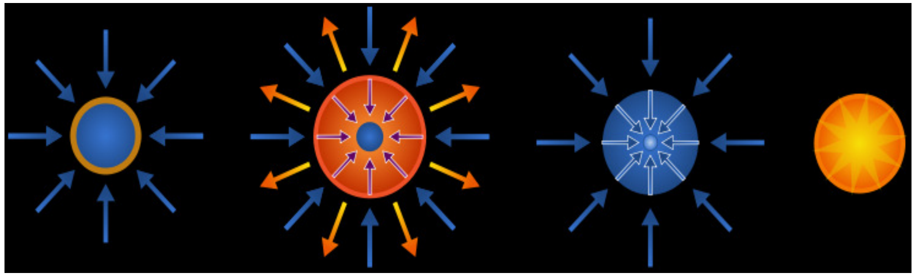


Inertial fusion

laser & heavy ions

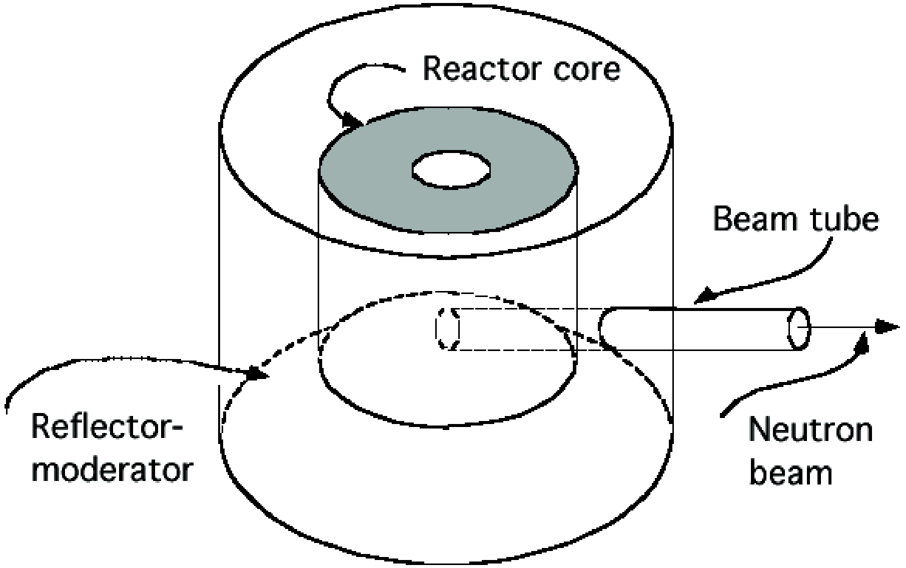


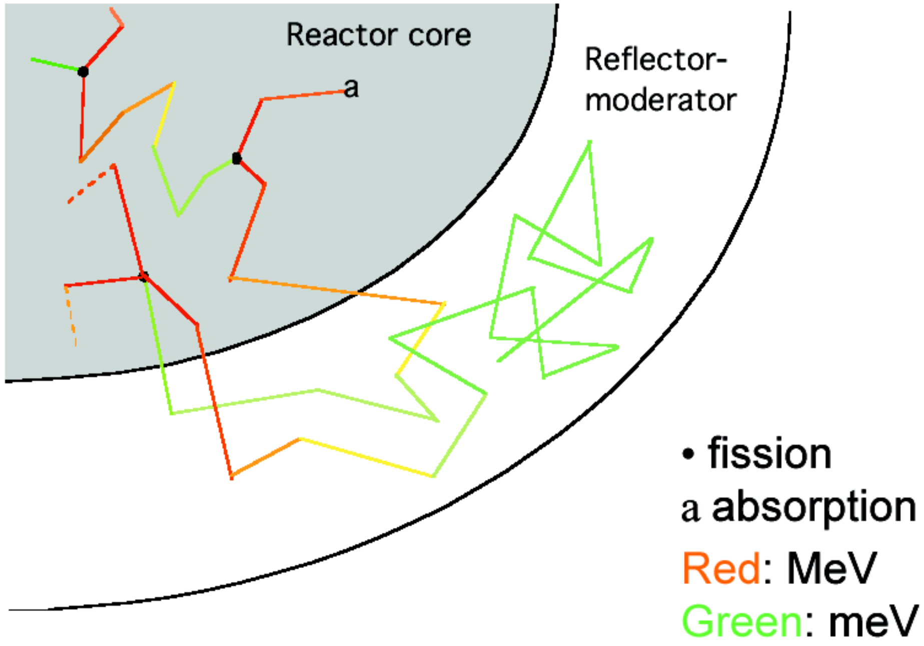
The NOVA reactor @ Lawrence Livermore labs (CA, US)



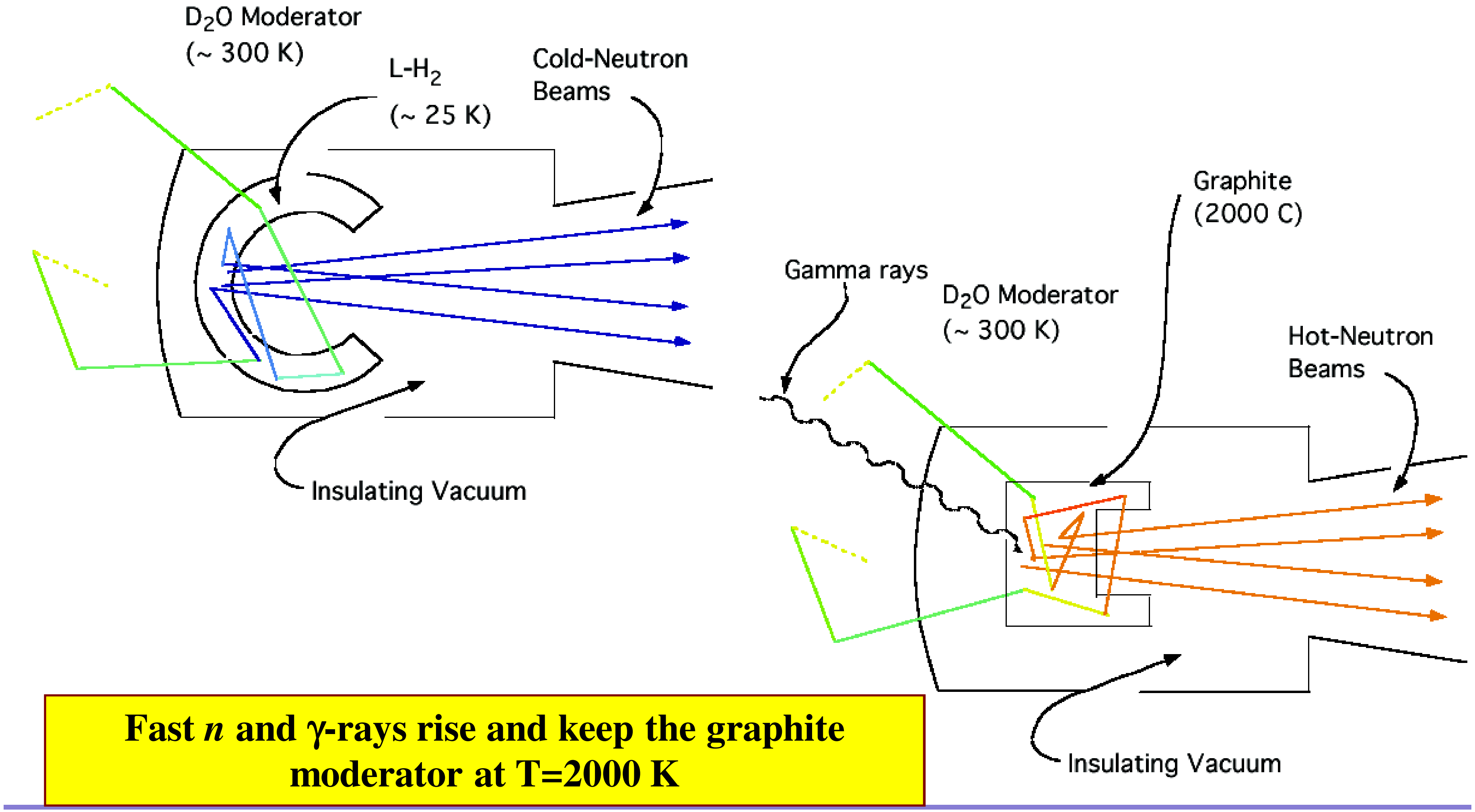
Sources at large scale facilities

Fission Reactors

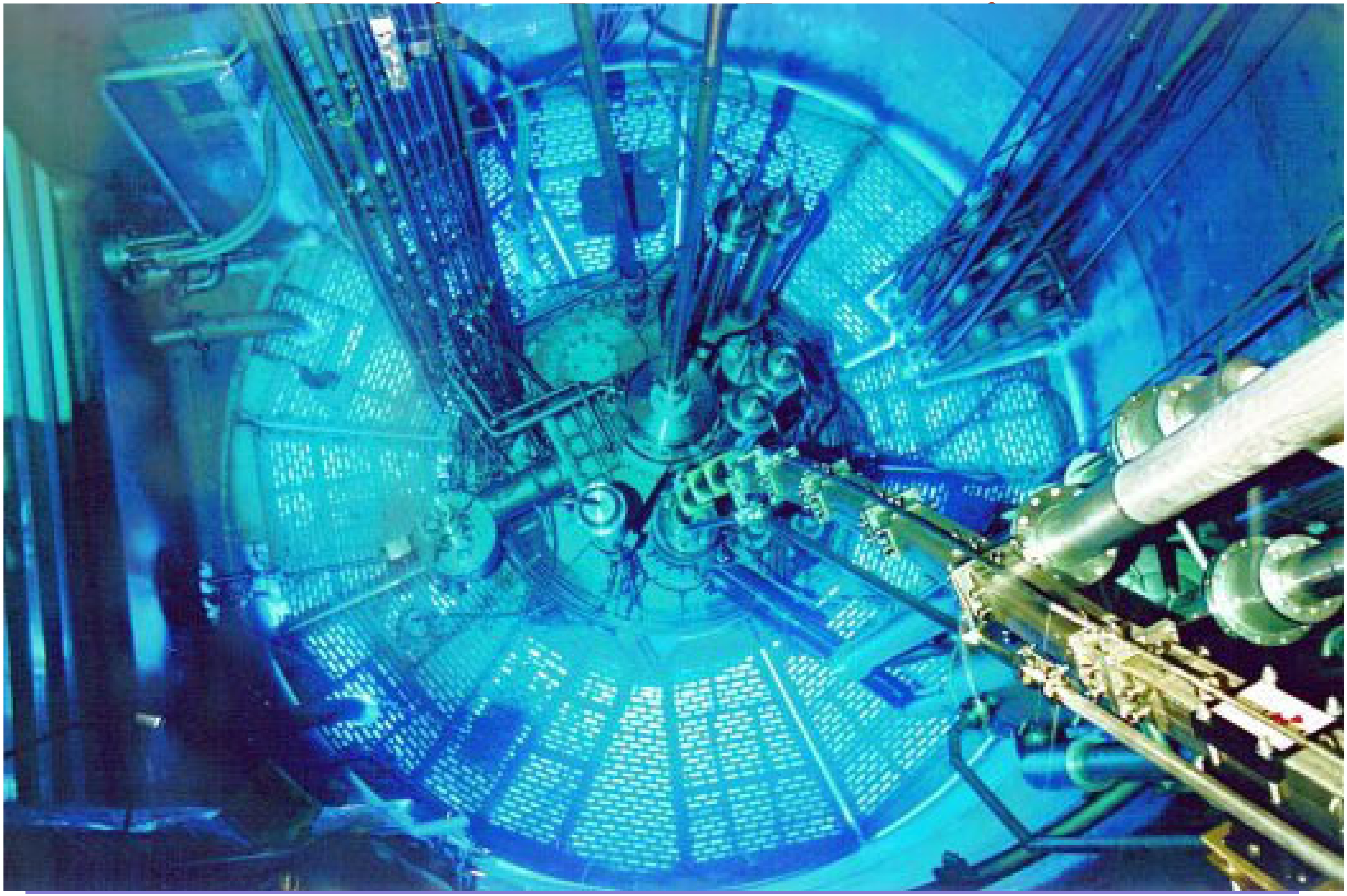




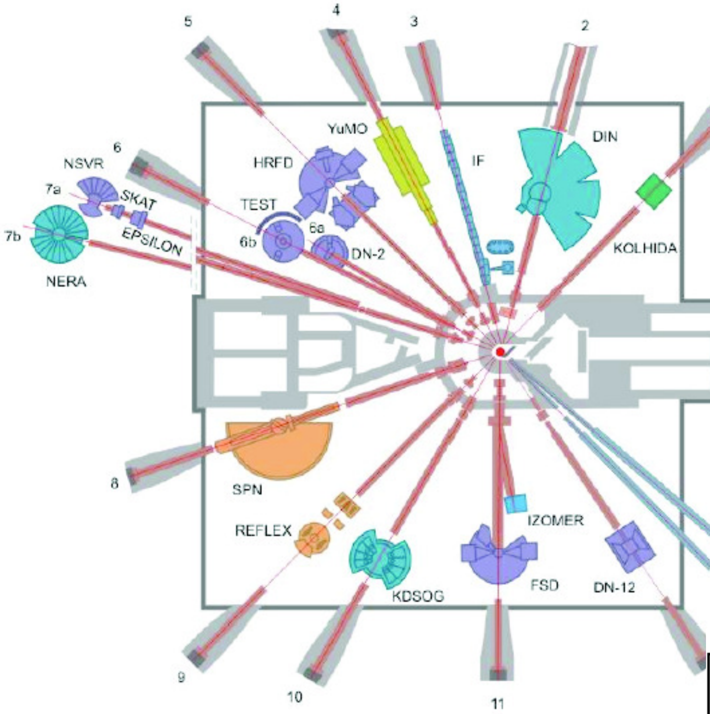
Cold and hot sources

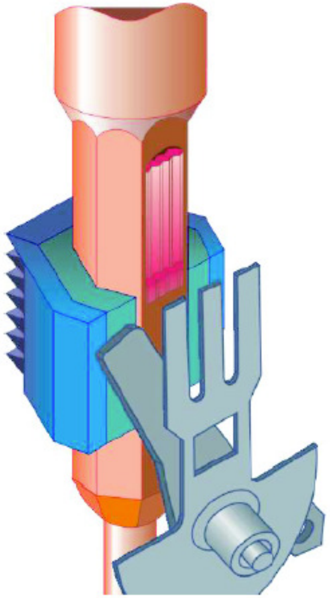


Fast *n* and γ-rays rise and keep the graphite moderator at T=2000 K



IBR-2 Reactor
Dubna





Reactor parameters

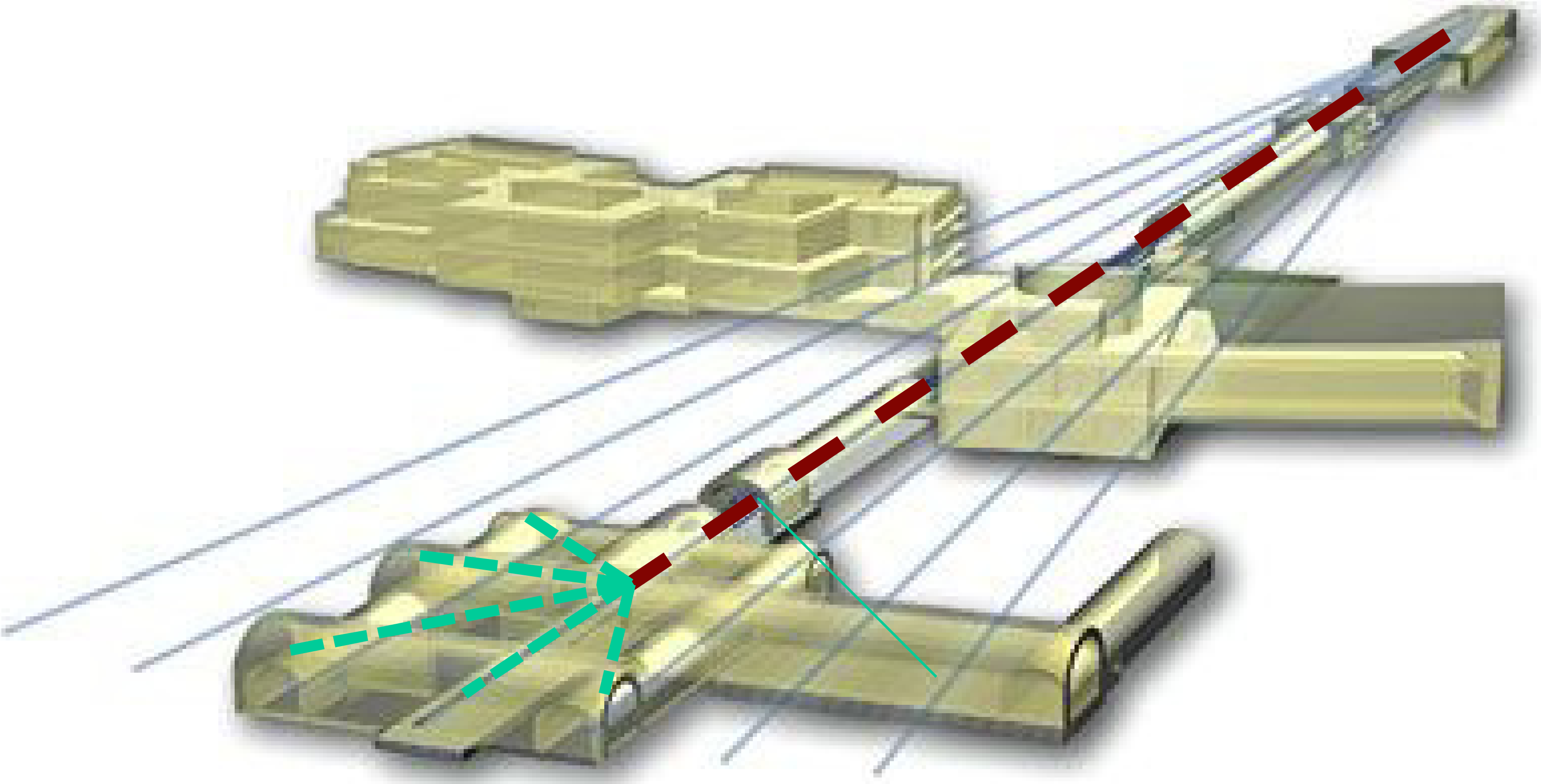
Average thermal power, MW	Peak Power in Pulse, MW	Pulse Repetition Rate, Hz	Thermal-Neutron Flux at Moderator surface, n/cm^2-sec (surface average)		Pulse FWHM, μsec	Status
			Time-Average	Peak		
2.0	1500.	5.	8×10^{12}	5×10^{15}	320.	Operating Upgrade pending

Worlwide reactors

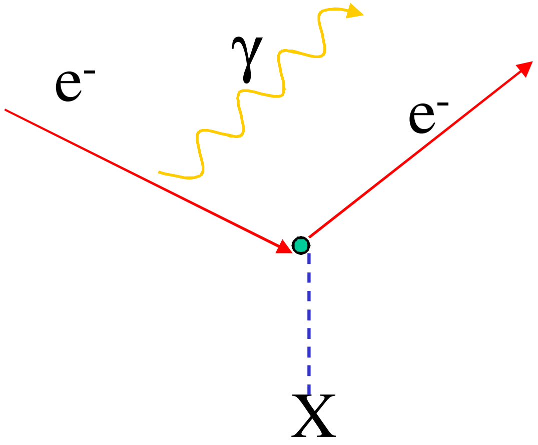
Reactor	Location	First Operation	Power, MW	Flux, n/cm^2-sec	Cold and Hot Sources
OPAL[a]	Lucas Heights, Australia	2007	20.	4.0 x 10^{14}	1 Cold
~~NRU[a]~~	~~Chalk River, Canada~~	~~1957~~	~~120~~	~~3.0 x 10^{14}~~	
CNF	Chalk River, Canada	~2012	40.	4.0 x 10^{14}	1 Cold
CARR[b]	Beijing, china	2006	60.	8.0 x 10^{14}	1 Cold 1 hot (?)
ILL-HFR[a]	Grenoble, France	1972	58.	1.2 x 10^{15}	2 Cold, 1 Hot
Orphée[a]	Saclay, France	1980	14.	3.0 x 10^{14}	2 Cold, 1 Hot
BER-2[a]	Berlin, Germany	1973	10.	2.0 x 10^{14}	1 Cold
FRM-2[a]	Munich, Germany	2004	20.	7.0 x 10^{14}	1 Cold, 1 Hot
BNC[a]	Budapest, Hungary	1959	10.	1.6 x 10^{14}	1 Cold
Dhruva[b]	Trombay, India	1985	100.	1.8 x 10^{14}	
JRR-3M[a]	Tokai, Japan	1962	20.	2.0 x 10^{14}	1 Cold
Hanaro[a]	Taejon, Korea	1996	30.	2.8 x 10^{14}	—
PIK[a]	St. Petersburg, Russia	?	100.	1.2 x 10^{15}	1 Cold, 1 Hot
HFIR[a]	Oak Ridge, United States	1966	85.	1.2 x 10^{15}	1 Cold
NBSR[a]	Gaithersburg, United States	1969	20.	4.0 x 10^{14}	1 Cold

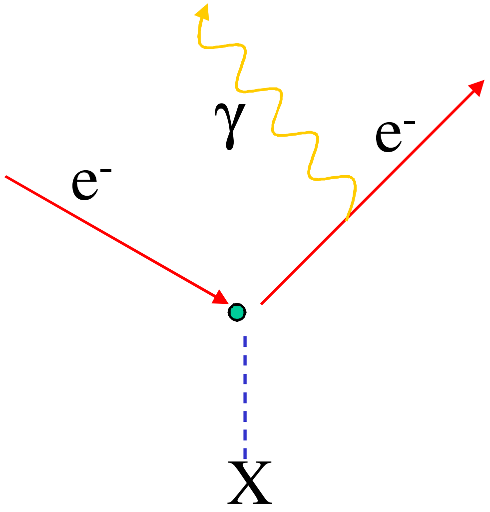
Accelerator-driven pulsed neutron sources

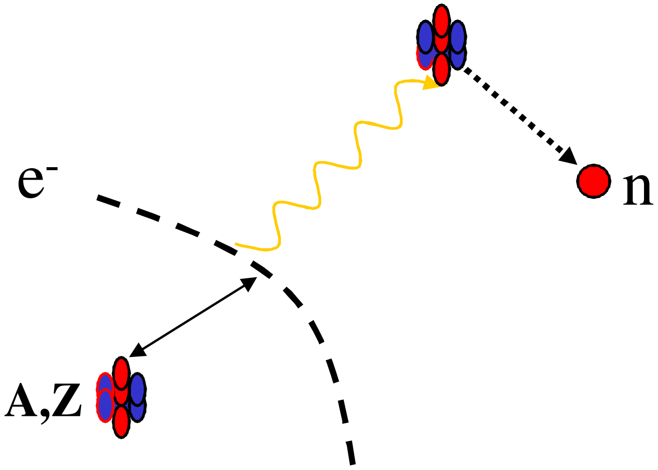
LINAC sources



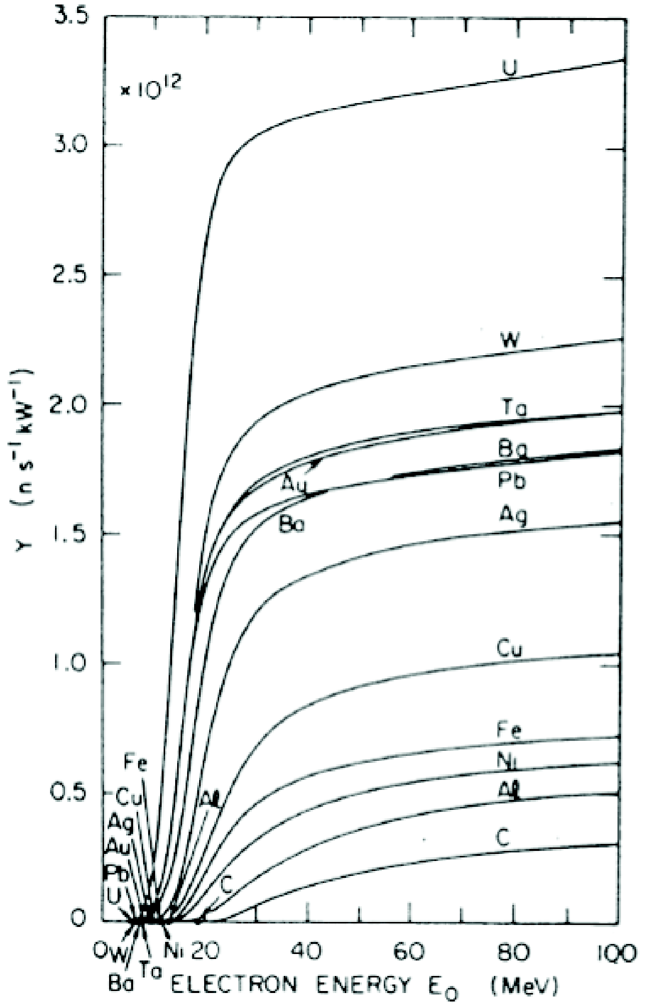
Electrons-induced neutron production
Bremsstrahlung







Some examples

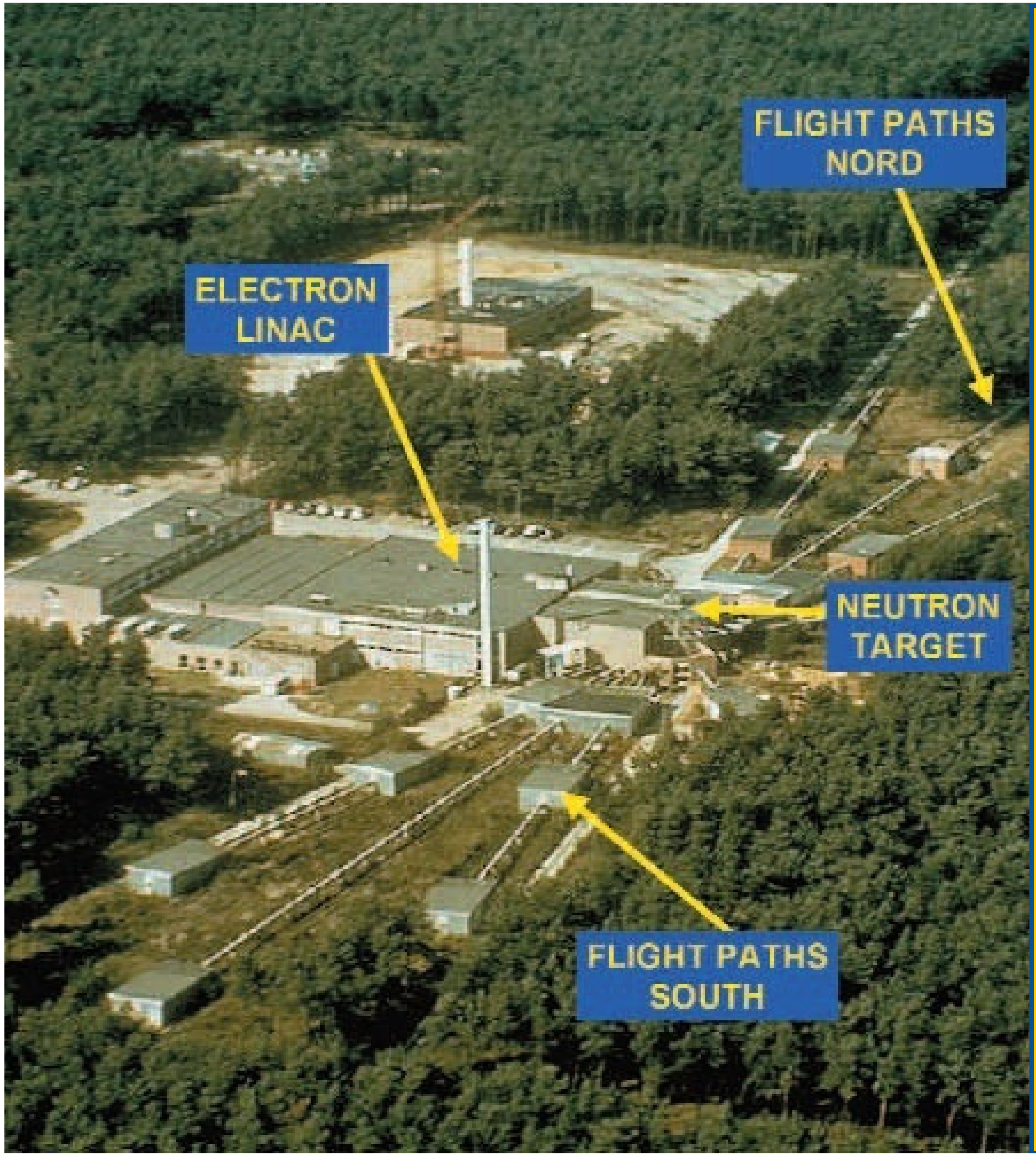


$$-\left(\frac{dE}{dx}\right)=\frac{NEZ(Z+1)e^2}{137m_0^2c^4}\left(4\ln\frac{2E}{m_0c^2}-\frac{4}{3}\right)$$

$$\frac{(dE/dx)_{Brems}}{(dE/dx)_{Bethe}}=\frac{E(MeV)Z}{700}$$

At the typical electron energies (**E≈ 50 MeV**) and for the typical values of Z of the target (e.g.**Z = 92** for U) , the erngy loss due to Bremsstrahlung is more intense by a factor of about **6**

GELINA Facility @ Geel (Belgio)



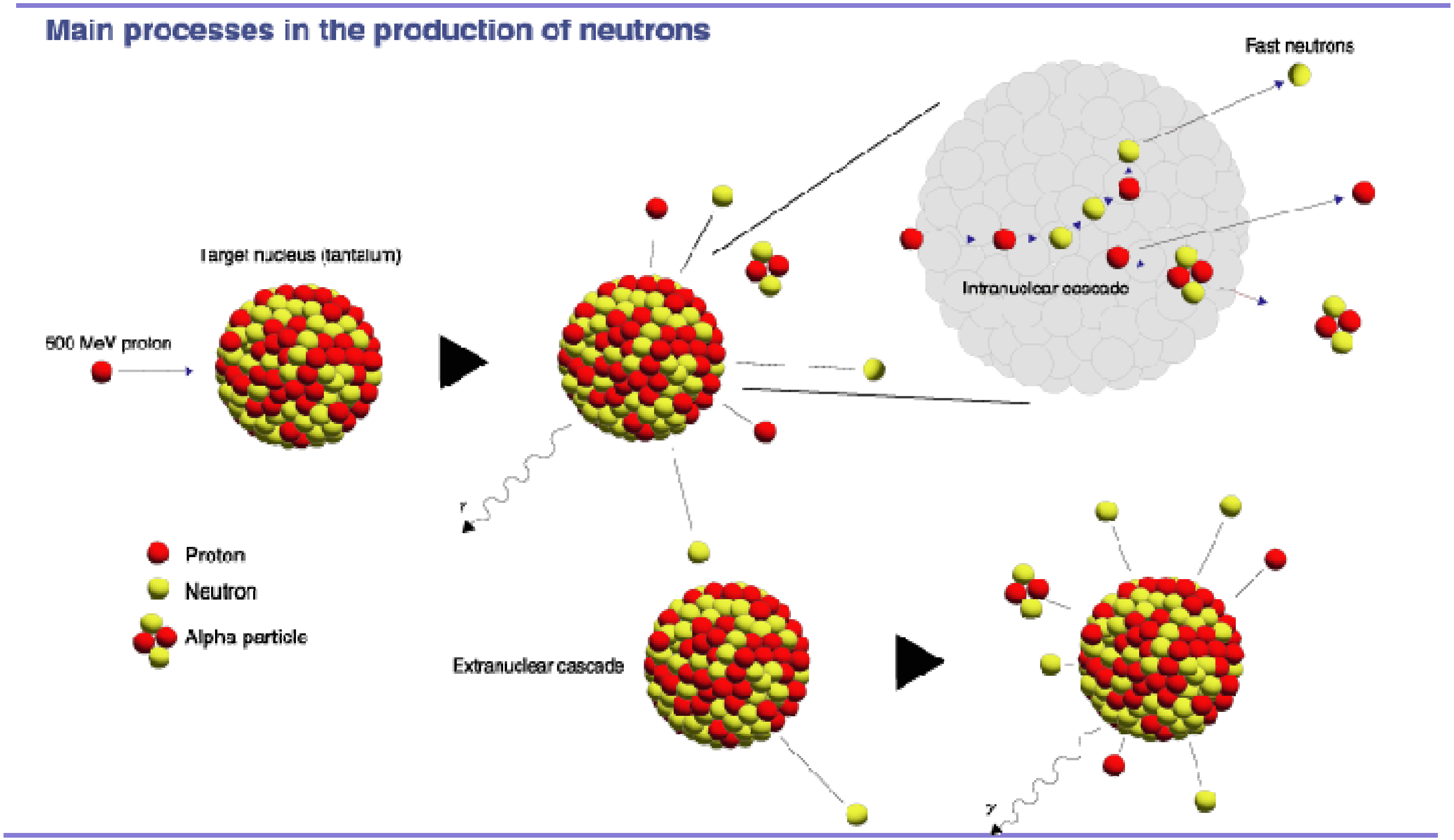
Neutron energy range:
1 meV-20 MeV

Neutrons bunches duration:
< 1 ns

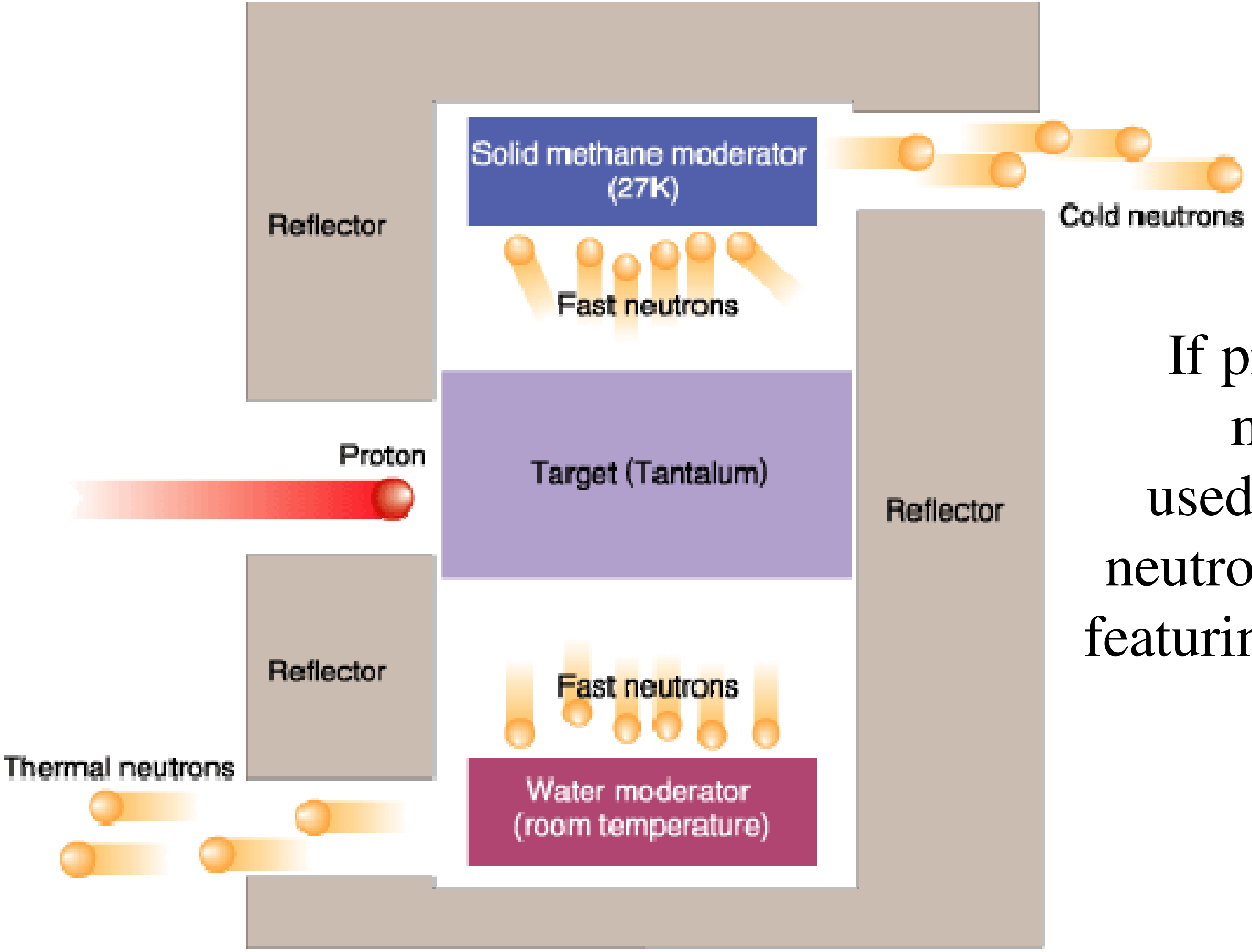
repetition rates:
up to 800 Hz

Total neutron flux of the target:
3.4 x 10^{13} neutrons/s

Spallation production



Projectiles, targets and moderator



If properly designed
moderators are
used, undermoderated
neutrons can be produced
featuring an 1/E epithermal
tail

Deposited energy into the target

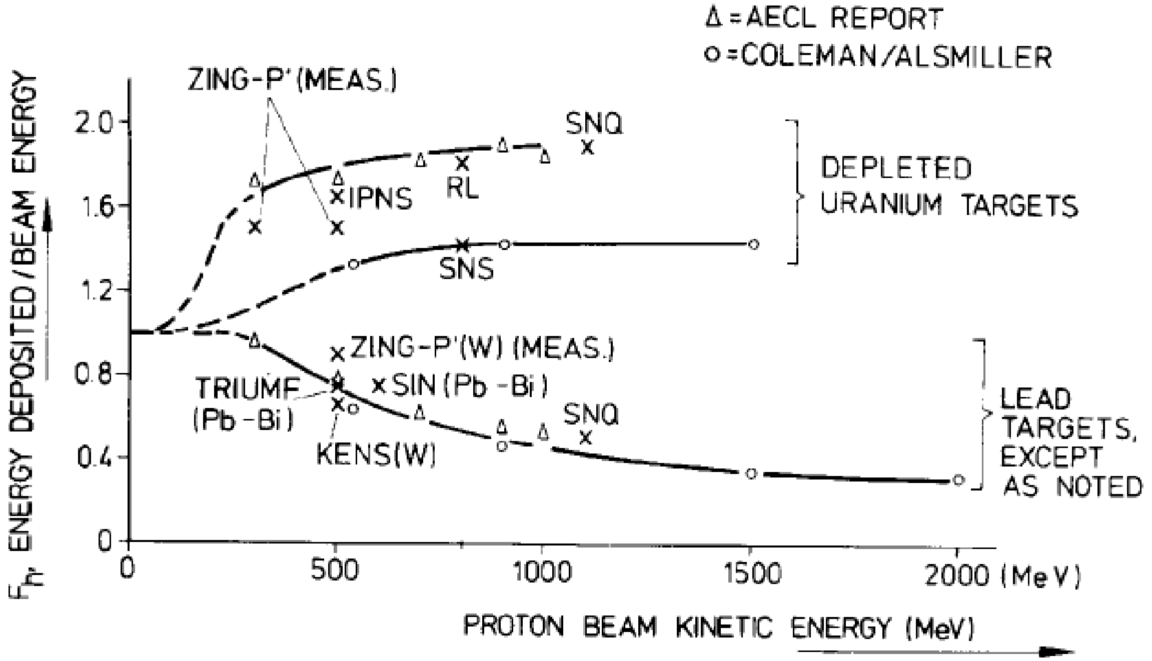
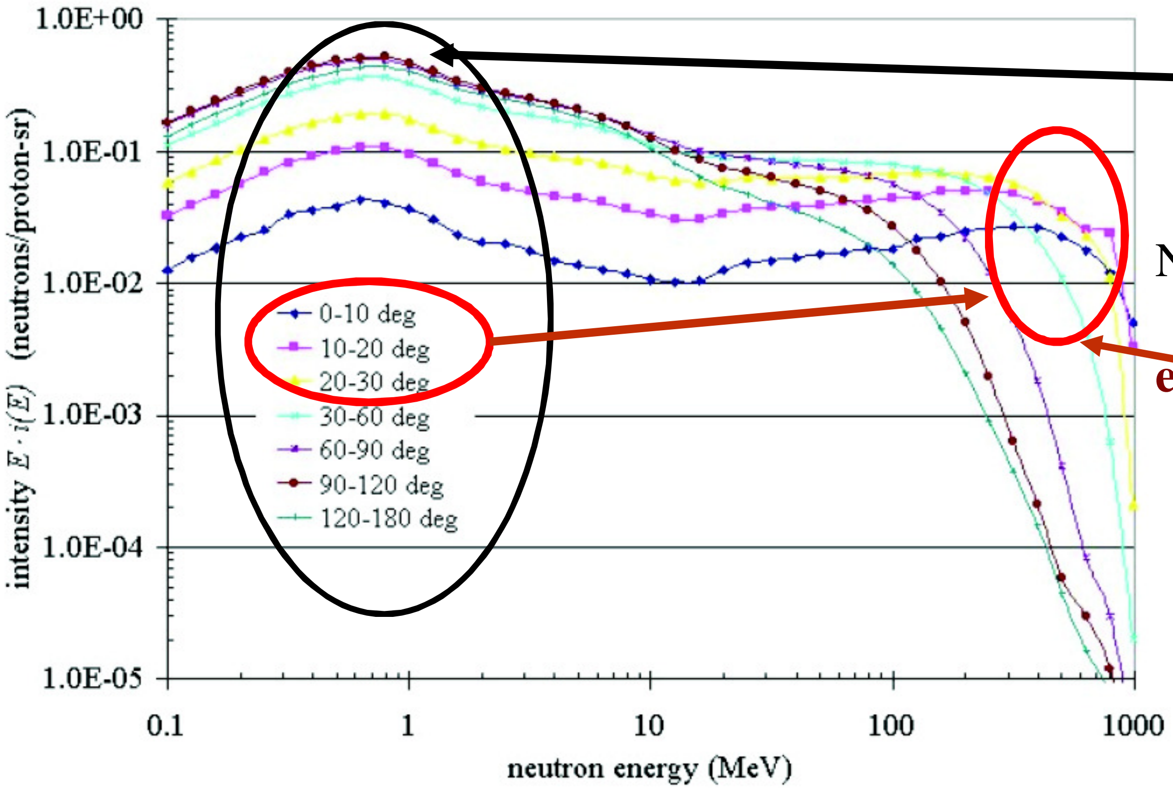


Figure 8. Calculated values of fractional energy deposition in the target to the proton-beam energy, F_h, as a function of proton kinetic energy (E_p). SNS and SIN mean the present ISIS and SINQ, respectively. Data labelled 'MEAS' are measured values.

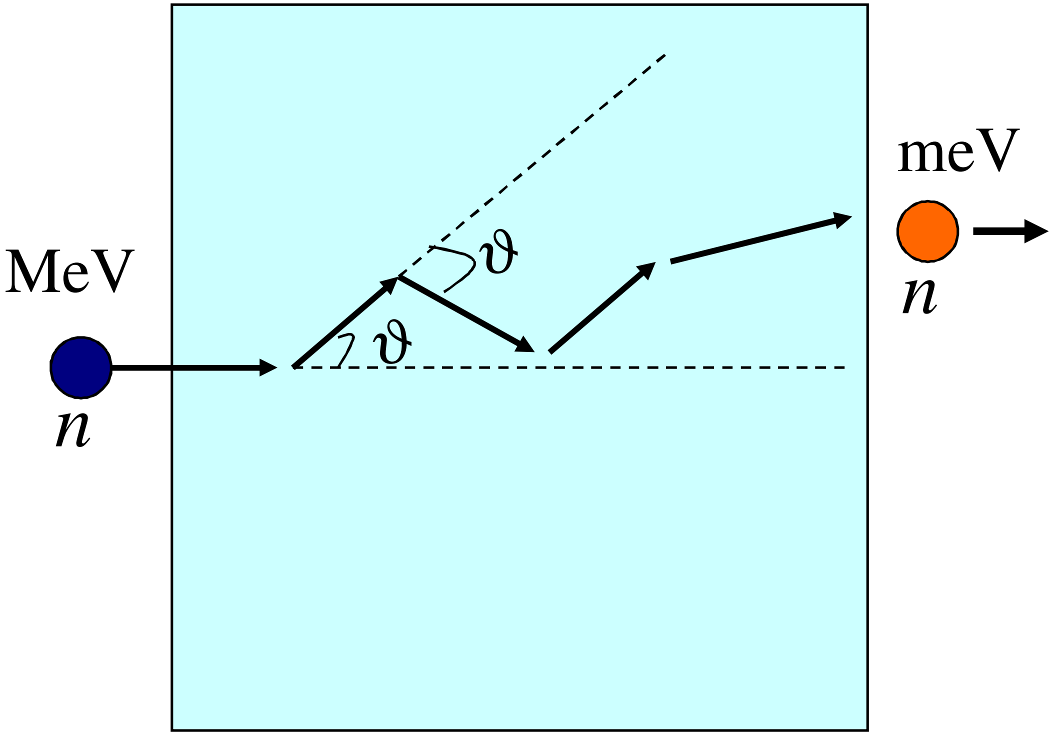
Angular distribution of the neutrons prodeuced by **p + W (E_p = 1 GeV)** reactions.
Angles are measured with respect to the incident direction of the protons.



Neutrons from the evaporation phase (**low energy**) are mostly isotropically distributed

Neutrons from direct interaction of the protons with the target (**high energy**) have a distribution peaked at low angles (***Lorentz boost***).

Letargy



To slow down fast neutrons the inelastic scattering off hydrogenous materials is exploited.

ξ: **$\langle \ln E_0/E \rangle_{d\Omega}$** lethargy variation for each collision with a ϑ scattering angle

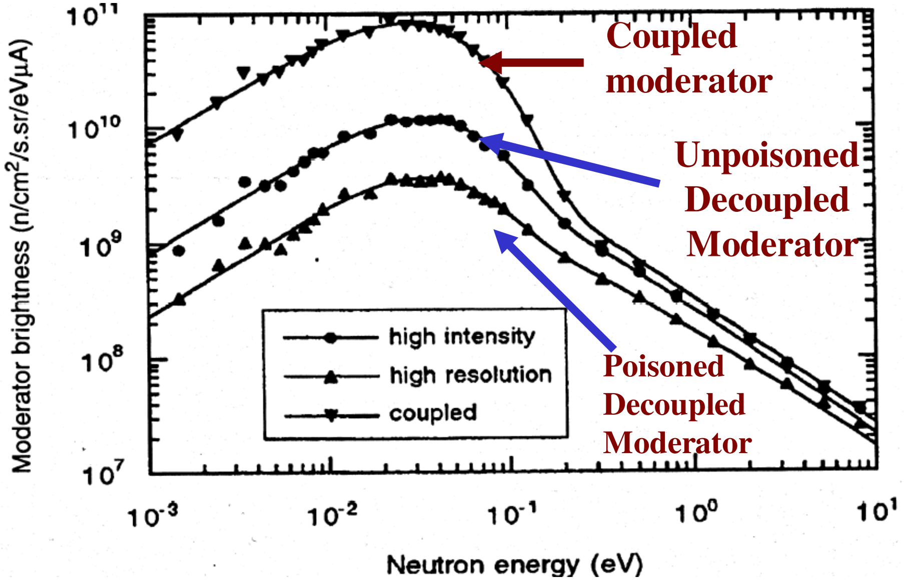
$$\xi = 1 + \frac{(A-1)^2}{2A} \ln \frac{A-1}{A+1}$$

$$n = \frac{1}{\xi} \ln \frac{E_0}{E_f}$$

By moderating, the peak of the energy distribution shifts at lower energy

Energy Spectra

H_2O Moderator



Coupled moderator

Unpoisoned Decoupled Moderator

Poisoned Decoupled Moderator

H_2 Moderator

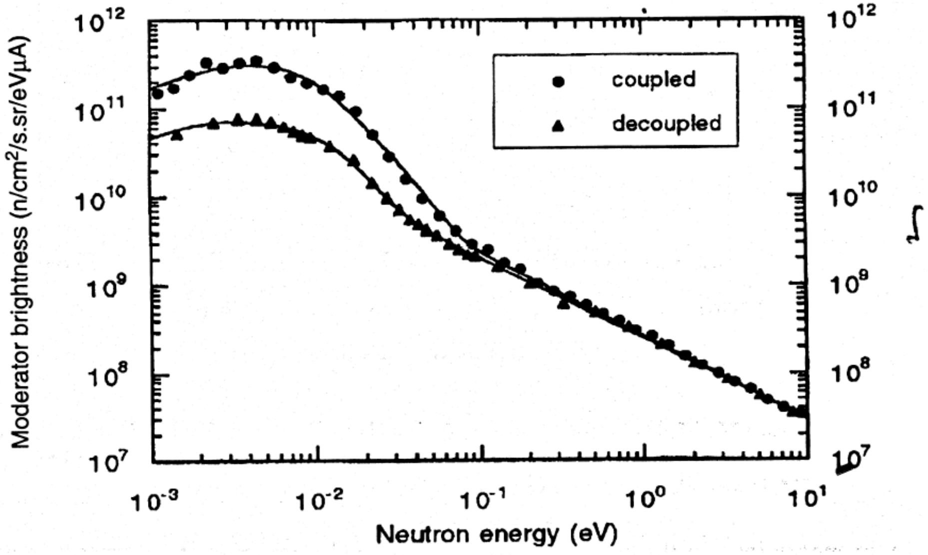


Figure 19. Measured energy spectra from three H_2O moderators with fits by equation (5.1) (upper) and those from two H_2 moderators with fits (lower). For the definition of coupled and decoupled moderators, see section 5.2: 'high intensity' and 'high-resolution' mean decoupled unpoisoned and poisoned moderators, respectively.

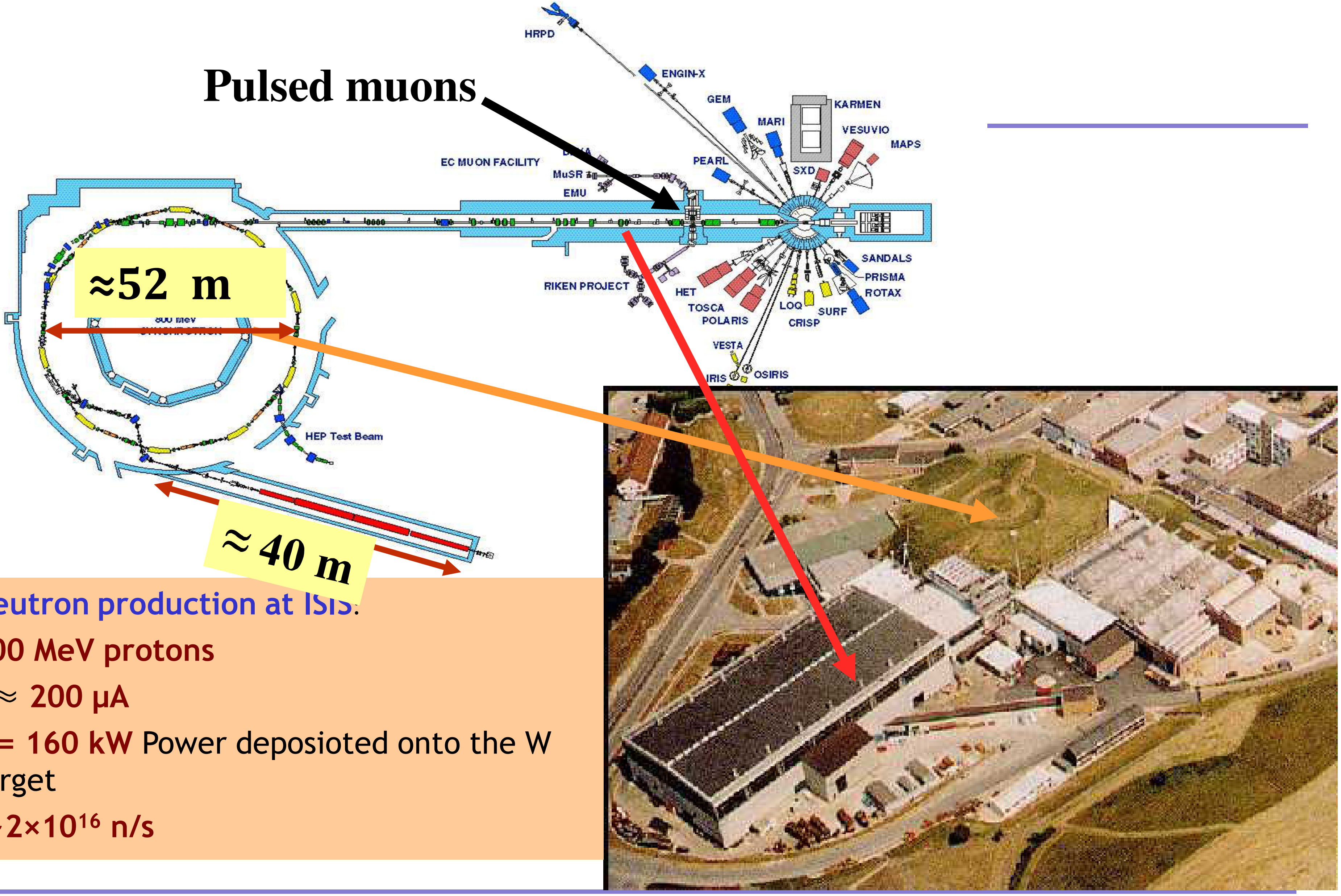
$$\tau_p = \frac{1.2}{\sqrt{E(eV)}}\,\mu\mathrm{s}$$

FWHM of the neutorn pulse at the energy *E* in the "slowing down" region

What energy has to be used ?

	Electrons (bersaglio U)	Protons (bersaglio U)	Reactors (U)
Reaction	Bremsstrahlung	Spallation	Nuclear fission
Typical incident particle energy	100 MeV	800 MeV	-
Neutron Yield	5×10^{-2} n/e^{-}	30 n/p	1 n/fissione
Deposited energy	2 GeV	55 MeV	180 MeV

ISIS pulsed neutron source



Neutron production at ISIS:

800 MeV protons

I ≈ 200 μA

P = 160 kW Power deposioted onto the W target

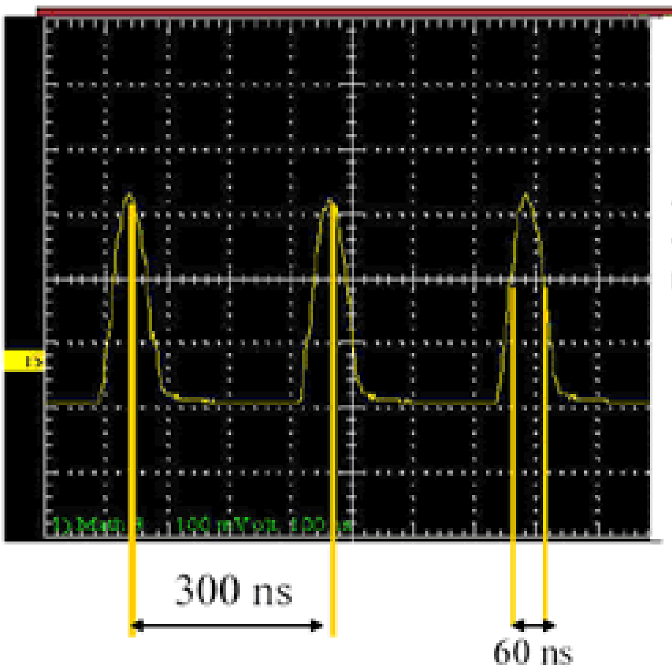
ϕ~2×10^{16} n/s

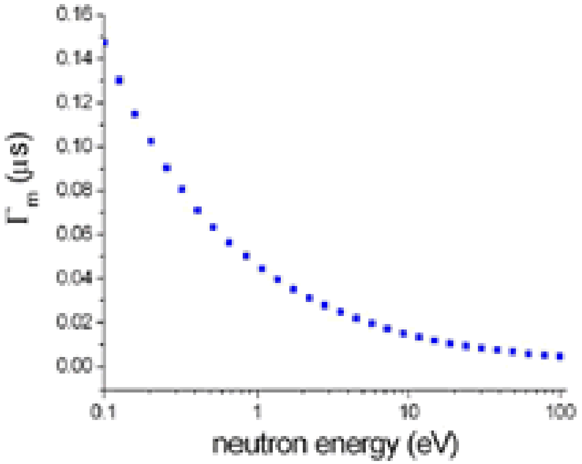
All beam in synchrotron extracted in one turn

β = v/c = 0.84, 163 m circumference → revolution time = 0.65 μs

4 μC ÷ 0.65 μs → 6 A circulating current

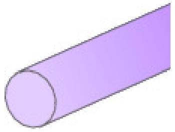
Extracted pulse ~0.3 μs long (double peak proton pulse)

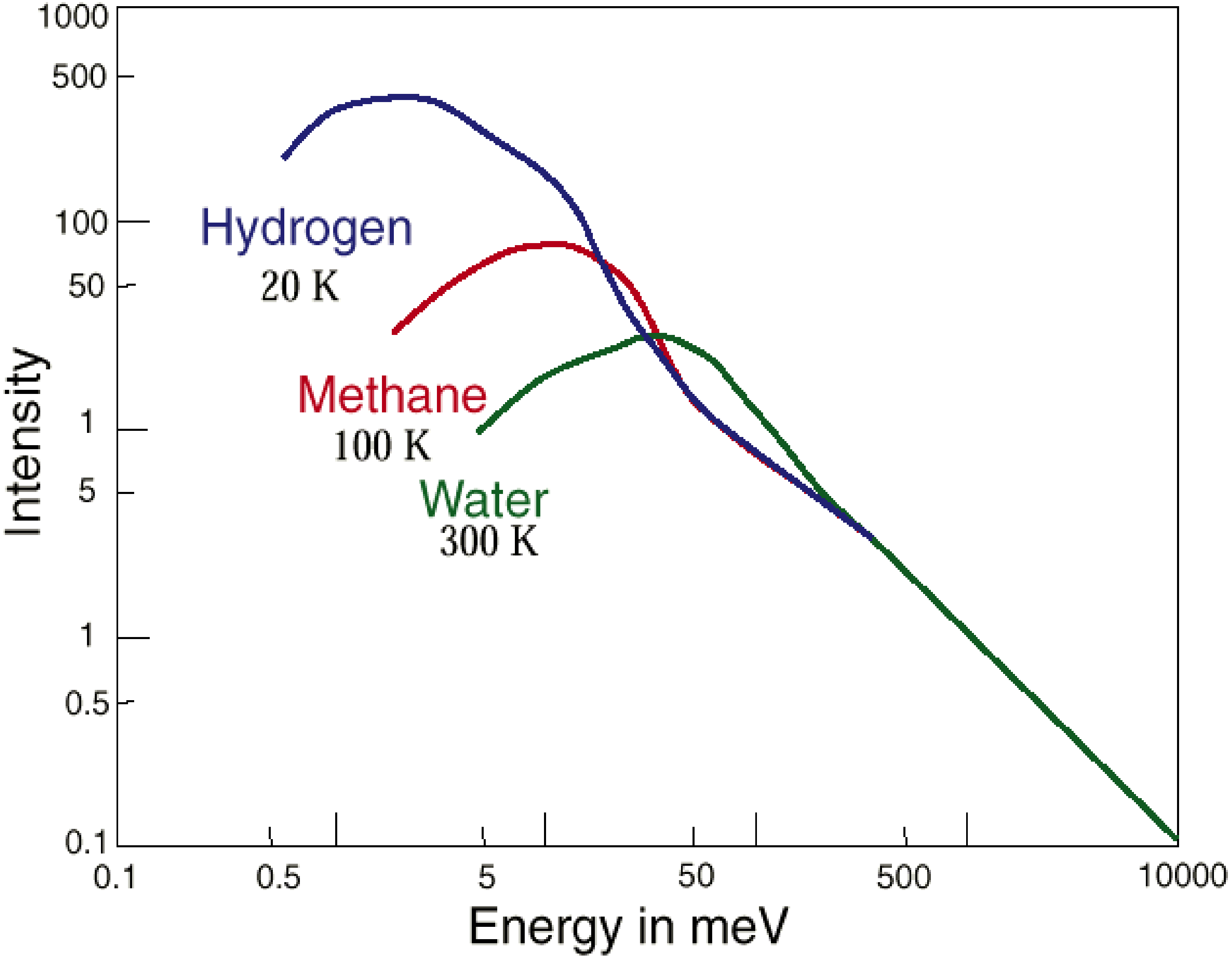


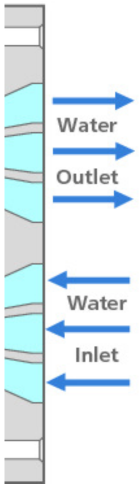


$$\Delta t = \sqrt{\Gamma_m^2 + \Gamma_{acc}^2}$$

ators
ors)







The E
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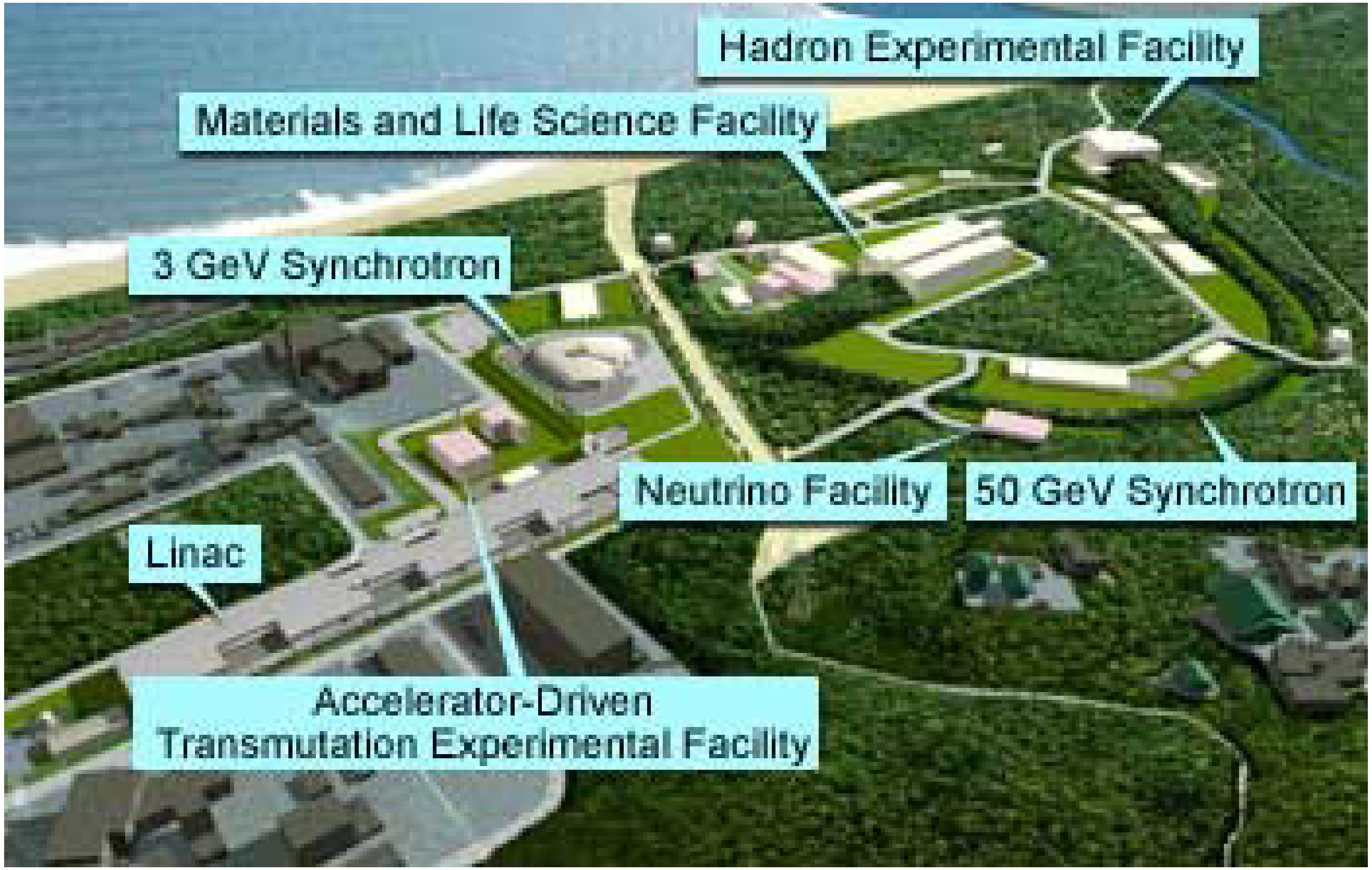
Spallation sources worldwide

………present and future

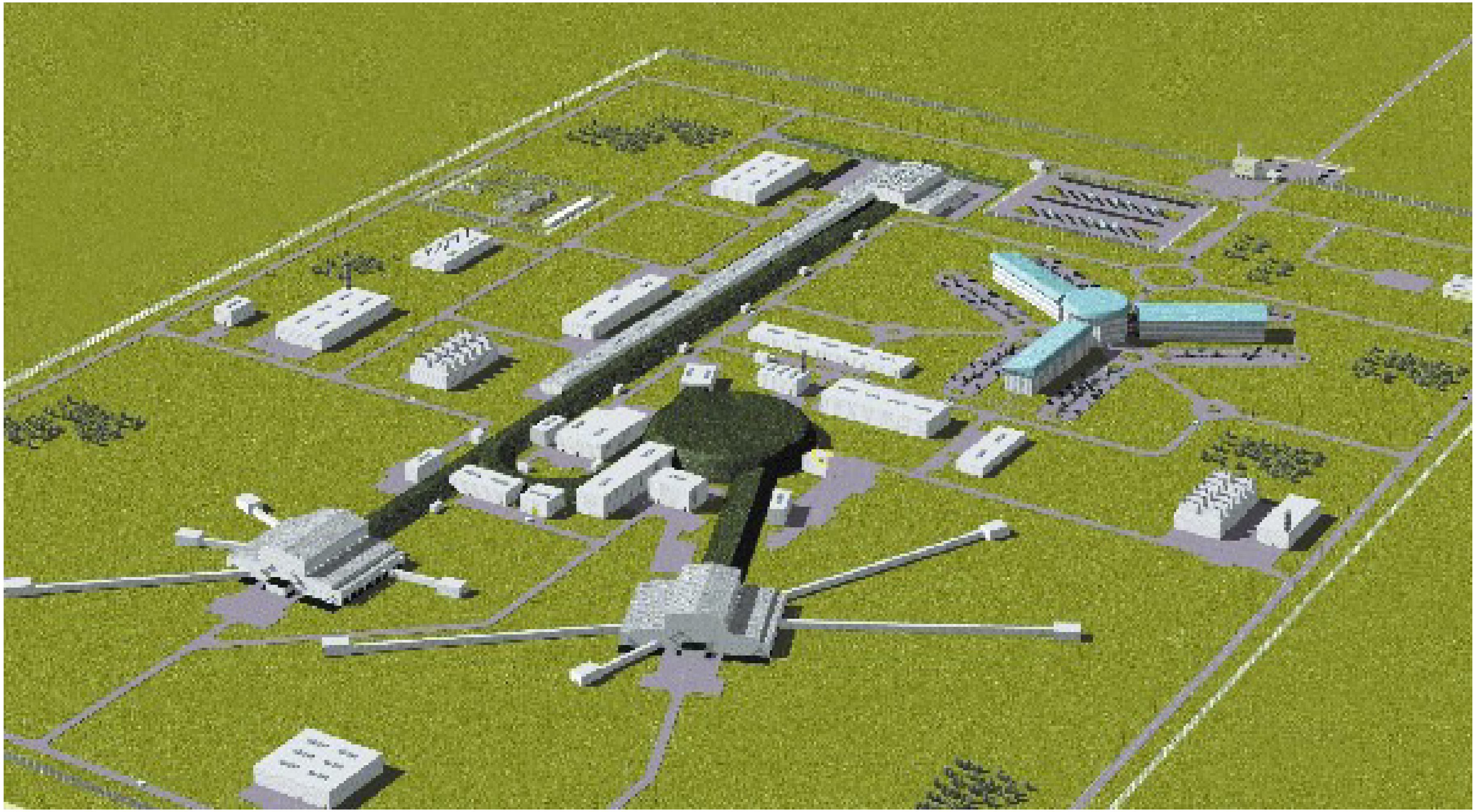
STFC-ISIS
United Kingdom

Spallation Neutron Source (SNS) United States of America

J-PARC
Japan

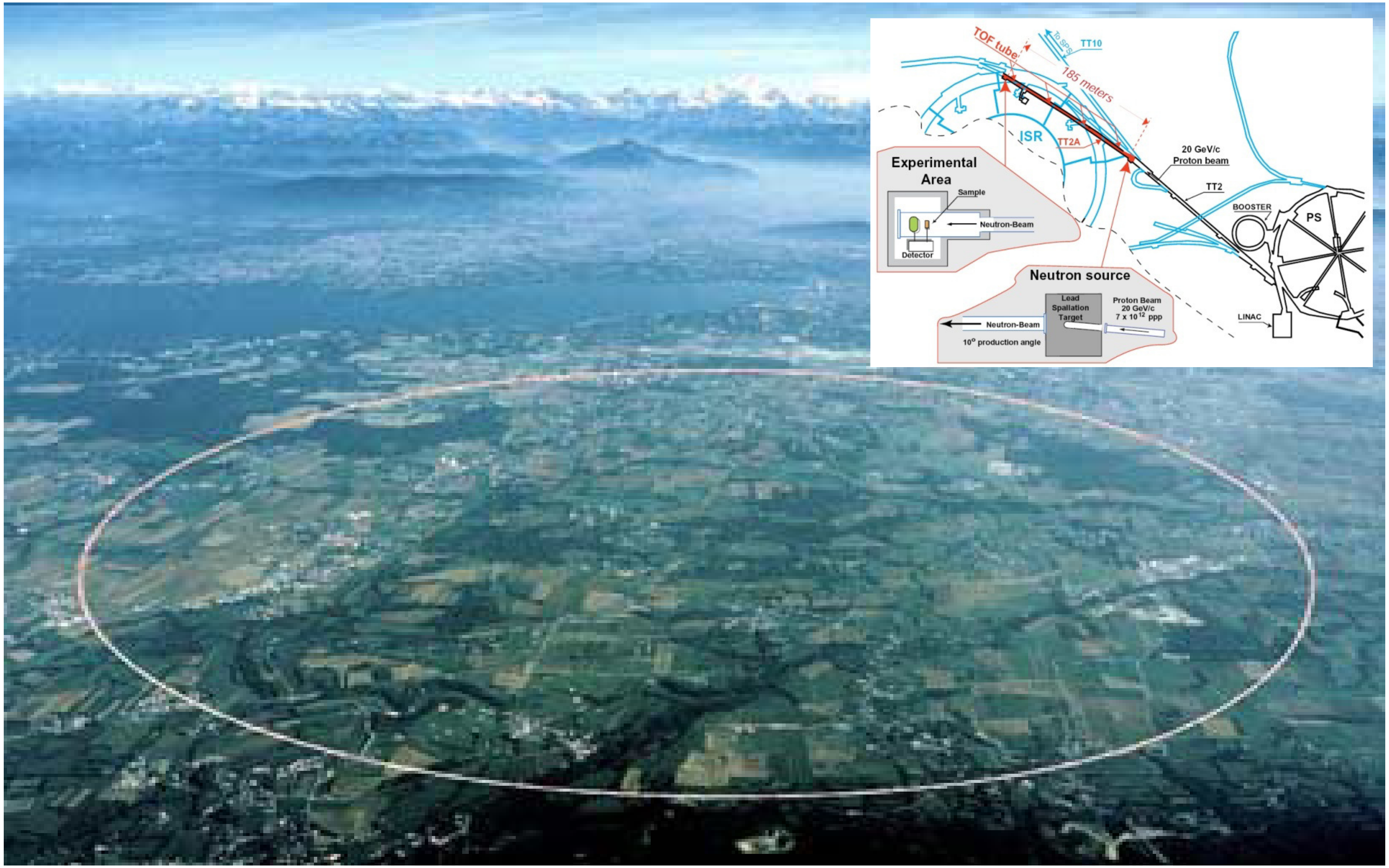

Hadron Experimental Facility
Materials and Life Science Facility
3 GeV Synchrotron
Neutrino Facility
50 GeV Synchrotron
Linac
Accelerator-Driven
Transmutation Experimental Facility

European Spallation Source (ESS)
Sweden



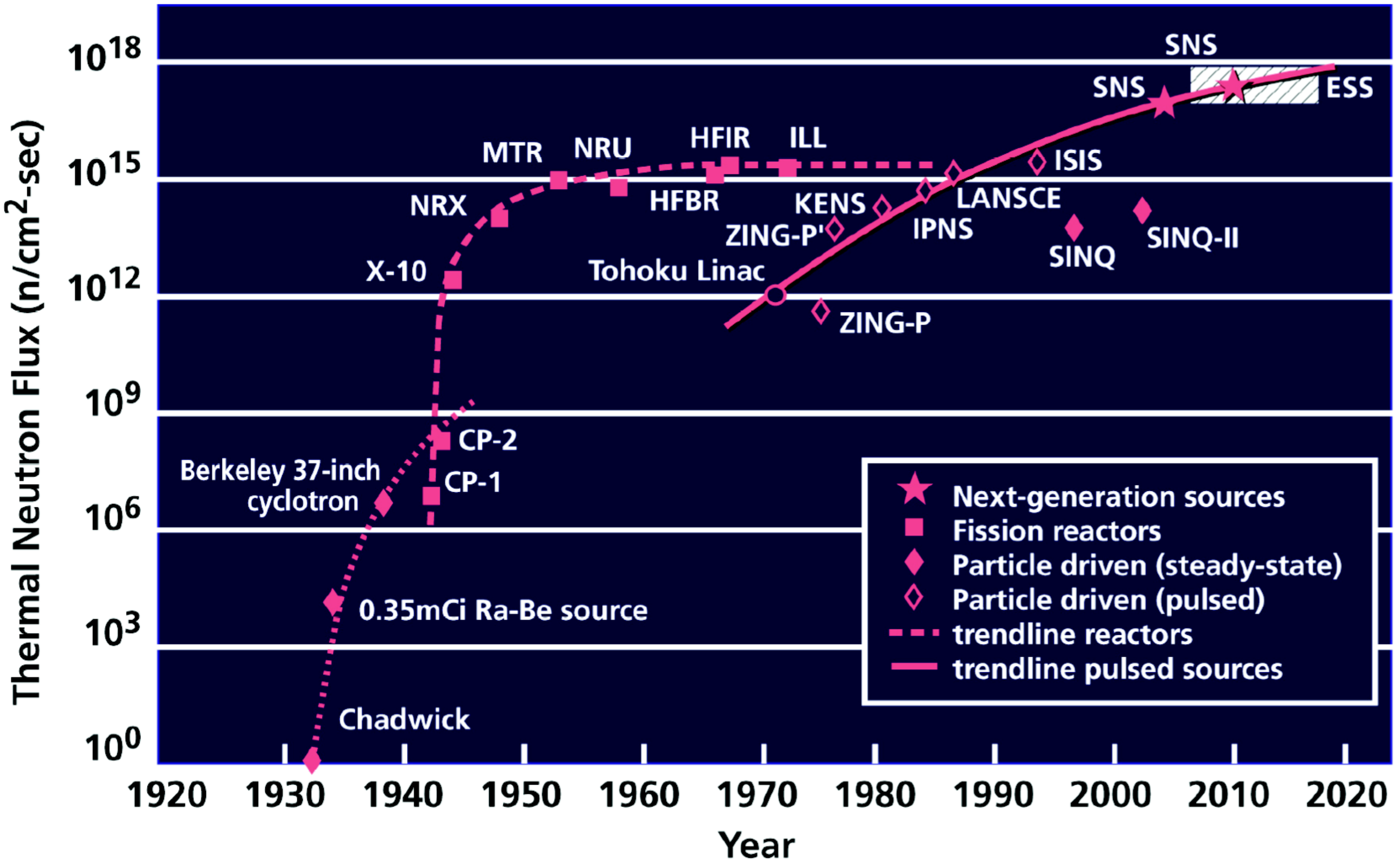
Paul Sherrer Institute (PSI) Switzerland

nTOF @ CERN
Switzerland



China Spallation Neutron Source (CSNS)
China

Development of spallation sources



Sorgenti DD e DT

Overview

☐ The Frascati Neutron Generator (FNG)

- What it is
- Main purposes
- FNG in the D-T mode
- FNG in the D-D mode

☐ FNG activities

☐ The FNG instrumentation

☐ Future perspectives

The Frascati Neutron Generator

- FNG is a compact accelerator driven neutron source
- Designed and built in ENEA that operates the source at its own expenses.
- First operation in November 1992

FNG main purposes

- ☐ Neutronics experiments (mock-up, benchmarks)
- ☐ Data base & code improvement
- ☐ Development of (new) experimental techniques and detectors.

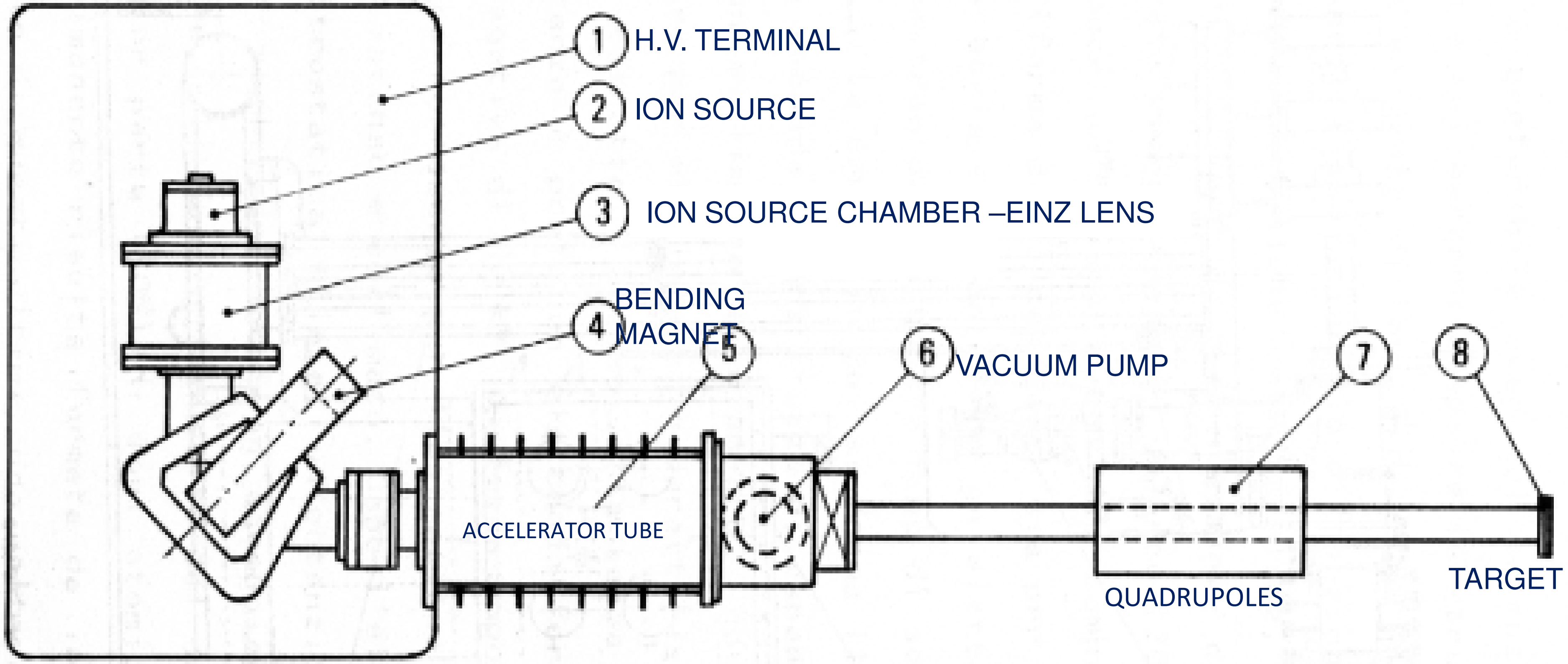
… but also

A number of activities in different fields within a series of collaborations are carried out at FNG so far

The Frascati Neutron Generator

FNG is a linear electrostatic accelerator-driven neutron source

Accelerated particles: **Deuterons (D^+)**
Energy: $E_D = 300$ keV
Current: $I_D = 1$ mA
Target: **Titanium layer (3 μm thickness) loaded with tritium/deuterium**



1 H.V. TERMINAL
2 ION SOURCE
3 ION SOURCE CHAMBER –EINZ LENS
4 BENDING MAGNET
5 ACCELERATOR TUBE
6 VACUUM PUMP
7 QUADRUPOLES
8 TARGET

The Frascati Neutron Generator

FNG is housed in a large shielded hall (11.5 x 12 m^2 and 9 m high) and the target is more than 4 m far from walls, floor and ceiling. The large hall reduces to very low level the neutron background due to neutron reflection from the walls rendering measurement at 14 MeV very “clean”.

Furthermore the target holder has a very light design to reduce the contamination of the spectrum due to neutron scattering produced by the target structure.

FNG in D-T mode

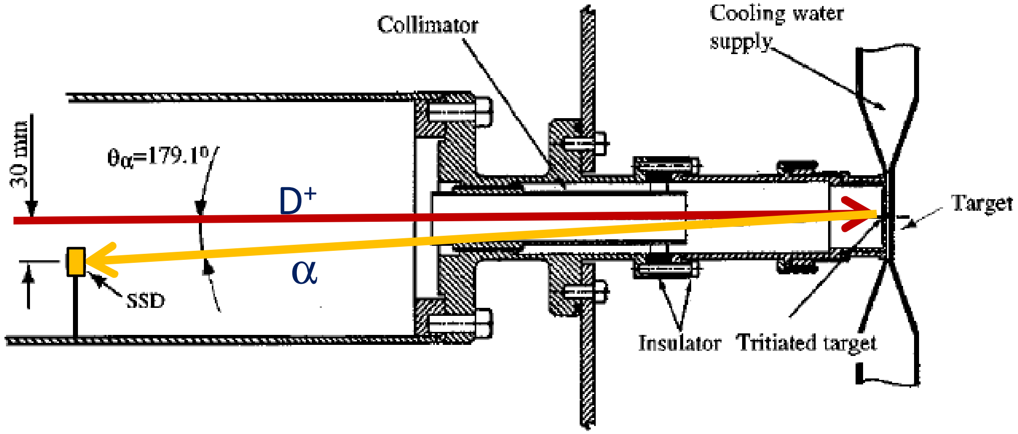
$D+T \rightarrow \alpha+n$ (Q=17.6 MeV)

Neutron Energy: E_n= 14.1 MeV

Source neutron emission rate: Y= 10^{11} s^{-1} continuous mode

Y is absolutely calibrated at ±3%: Associated Particle Method

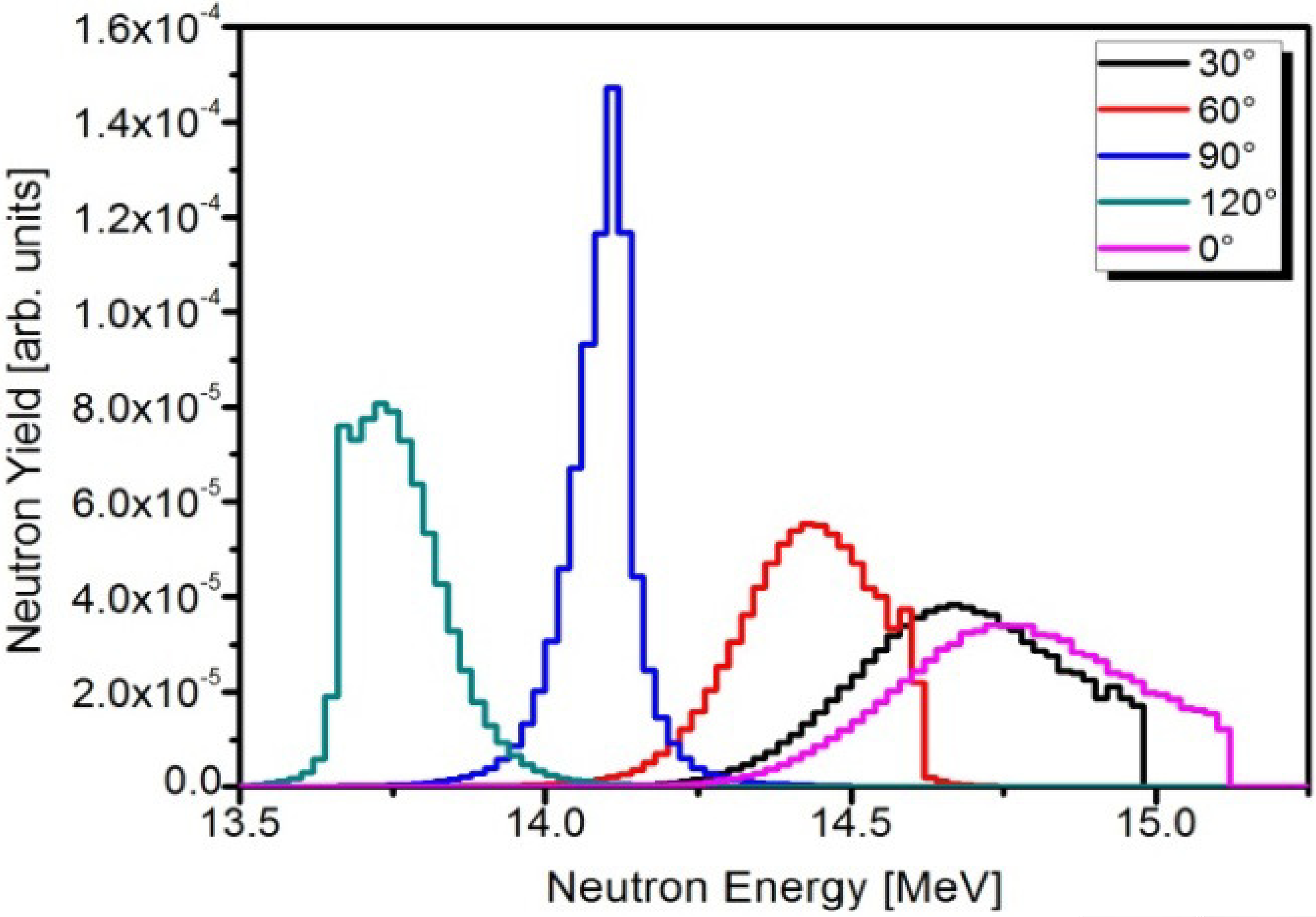
Half Yield Time: $T_{Y/2}$ ~ 25 h @ I_D = 1 mA



Neutron yield is monitored measuring the alpha particles from the **T(d,n)**α with a Silicon Detector.

FNG in D-T mode

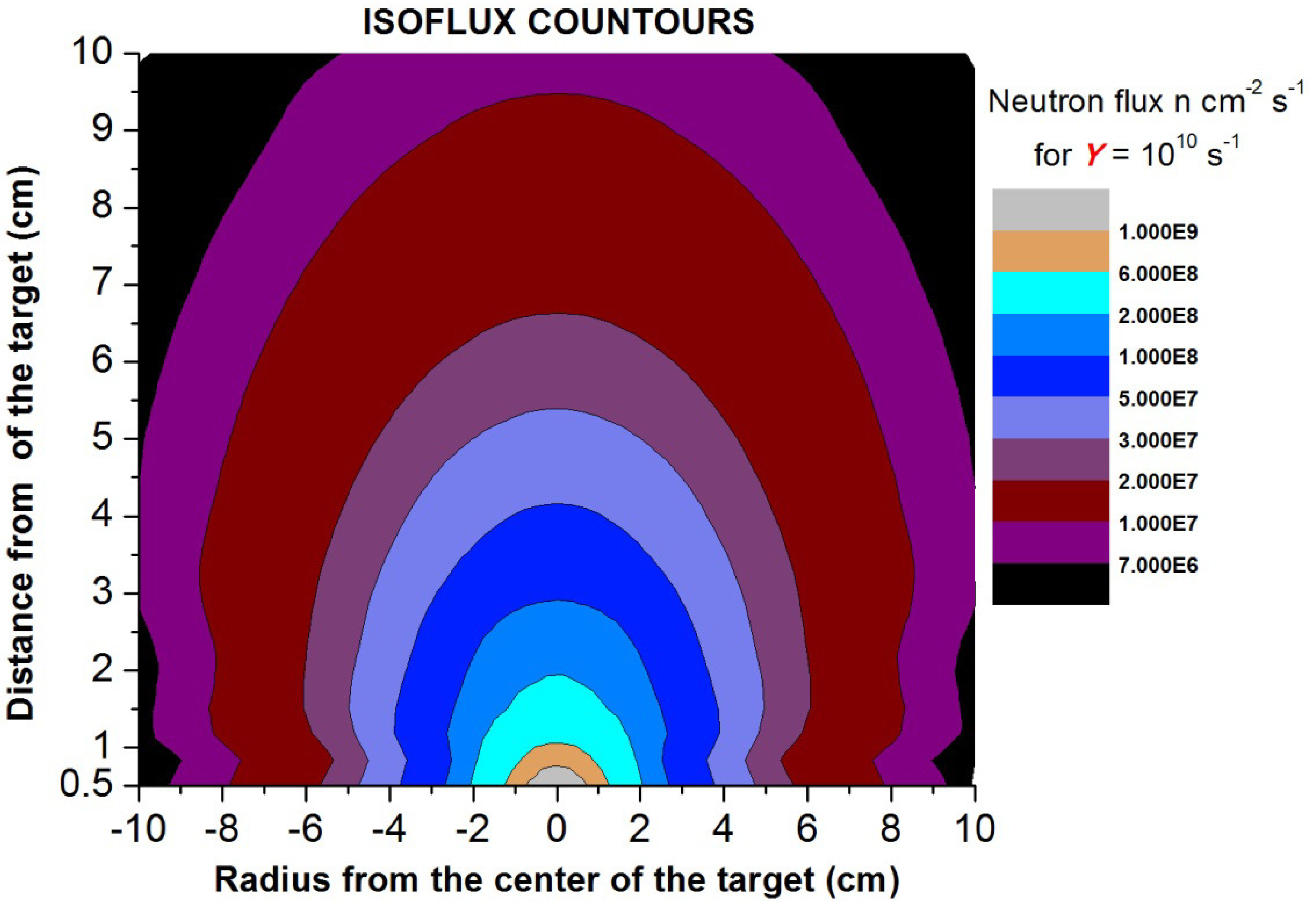
source spectrum simulation



FNG in D-T mode

source spectrum simulation

AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE



FNG in D-D mode

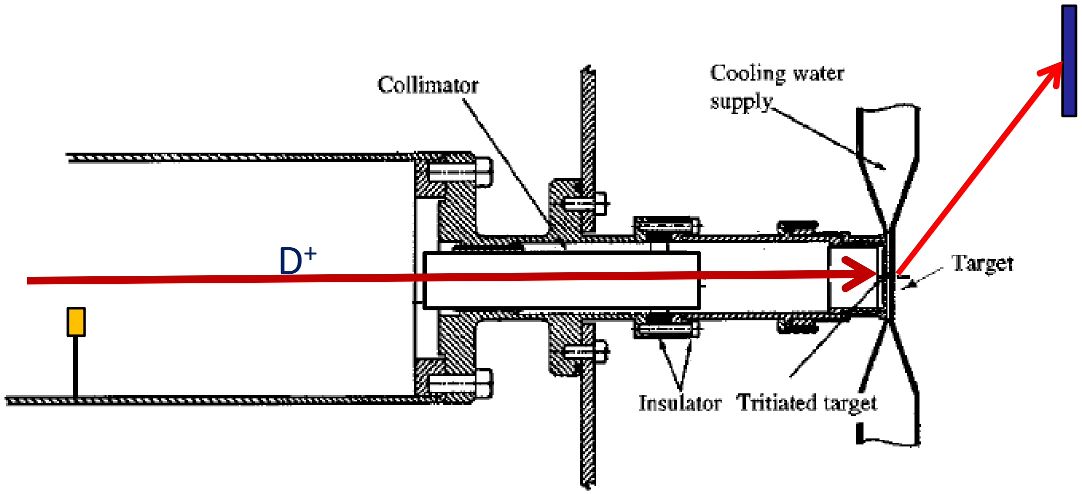
$D+D \rightarrow {}^{3}He+n$ (Q=3.27 MeV)

Neutron Energy: E_n= 2.5 MeV

Source neutron emission rate Y= 10^9 s^{-1} continuous mode

Y absolutely measured 7% uncertainty: activation technique $^{115}In(n,n')^{115}In^m$.

Half Yield Time: $T_{Y/2}$ “infinite” as D is continuously implanted by the D^+ beam



$^{115}In(n,n')^{115}In^m$

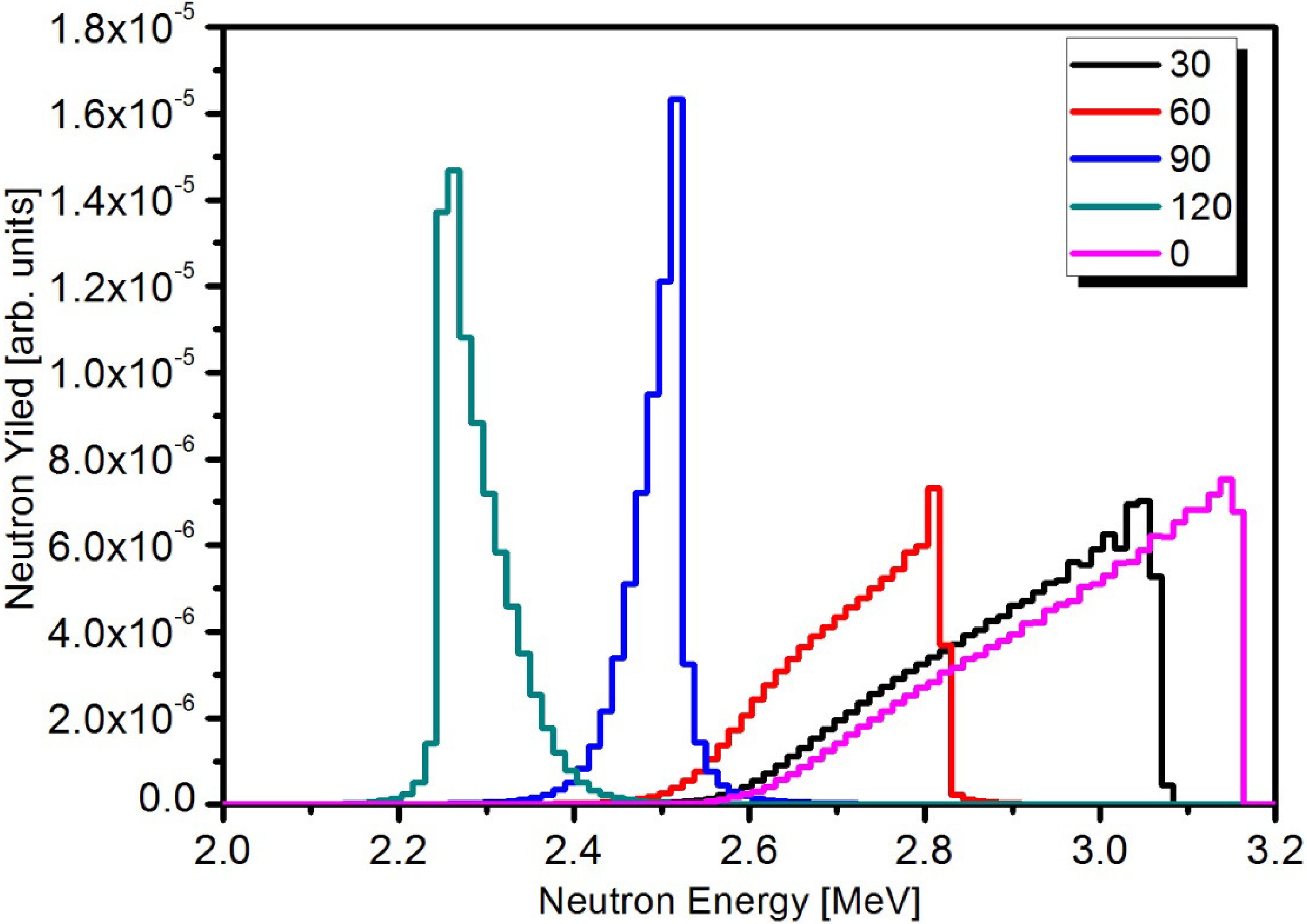
$\tau_{1/2}$=4.486 h; E_γ=336.24 keV

Gamma activity measured by means of a calibrated HpGe

FNG in D-D mode

source spectrum

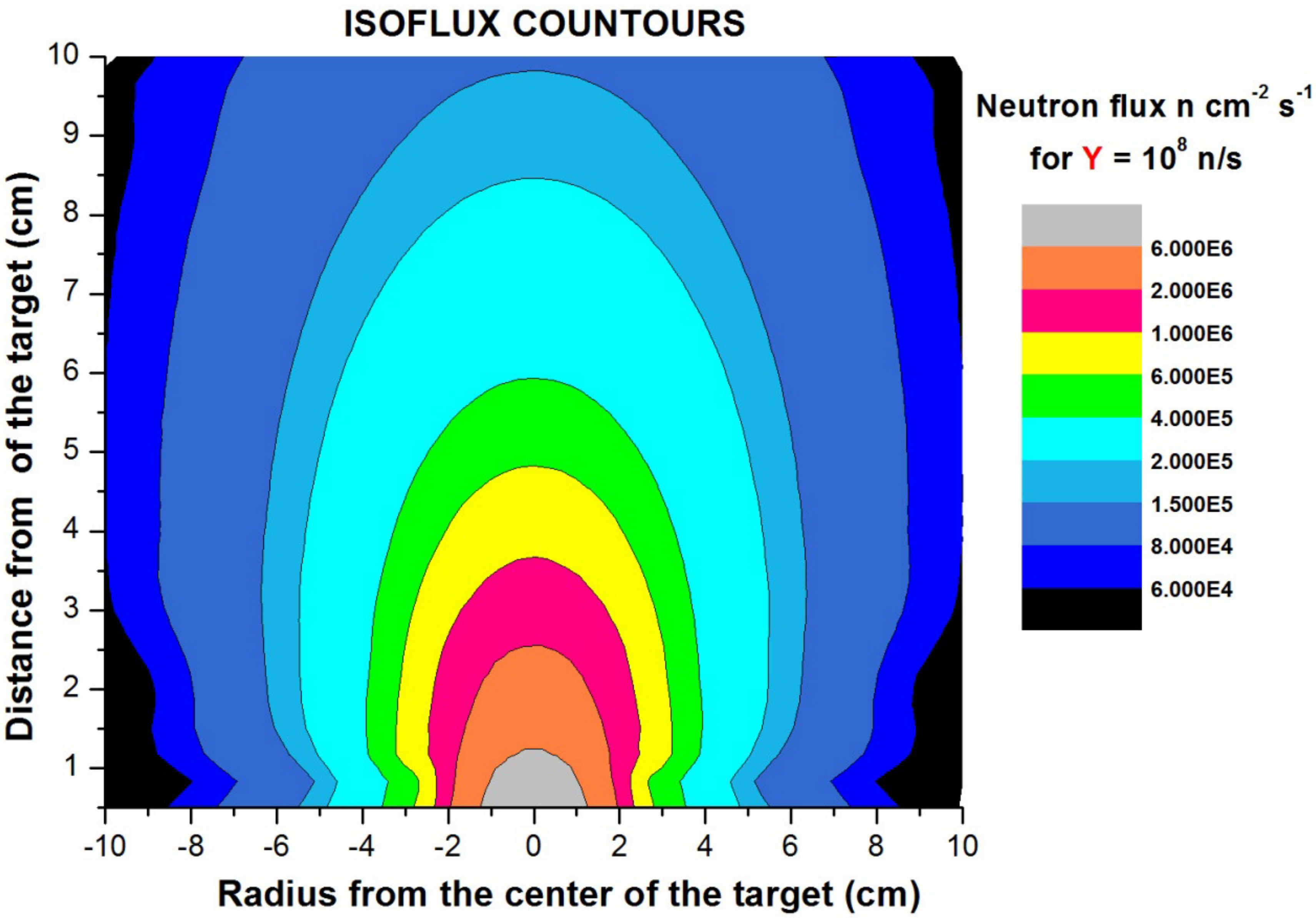
simulation



FNG in D-D mode

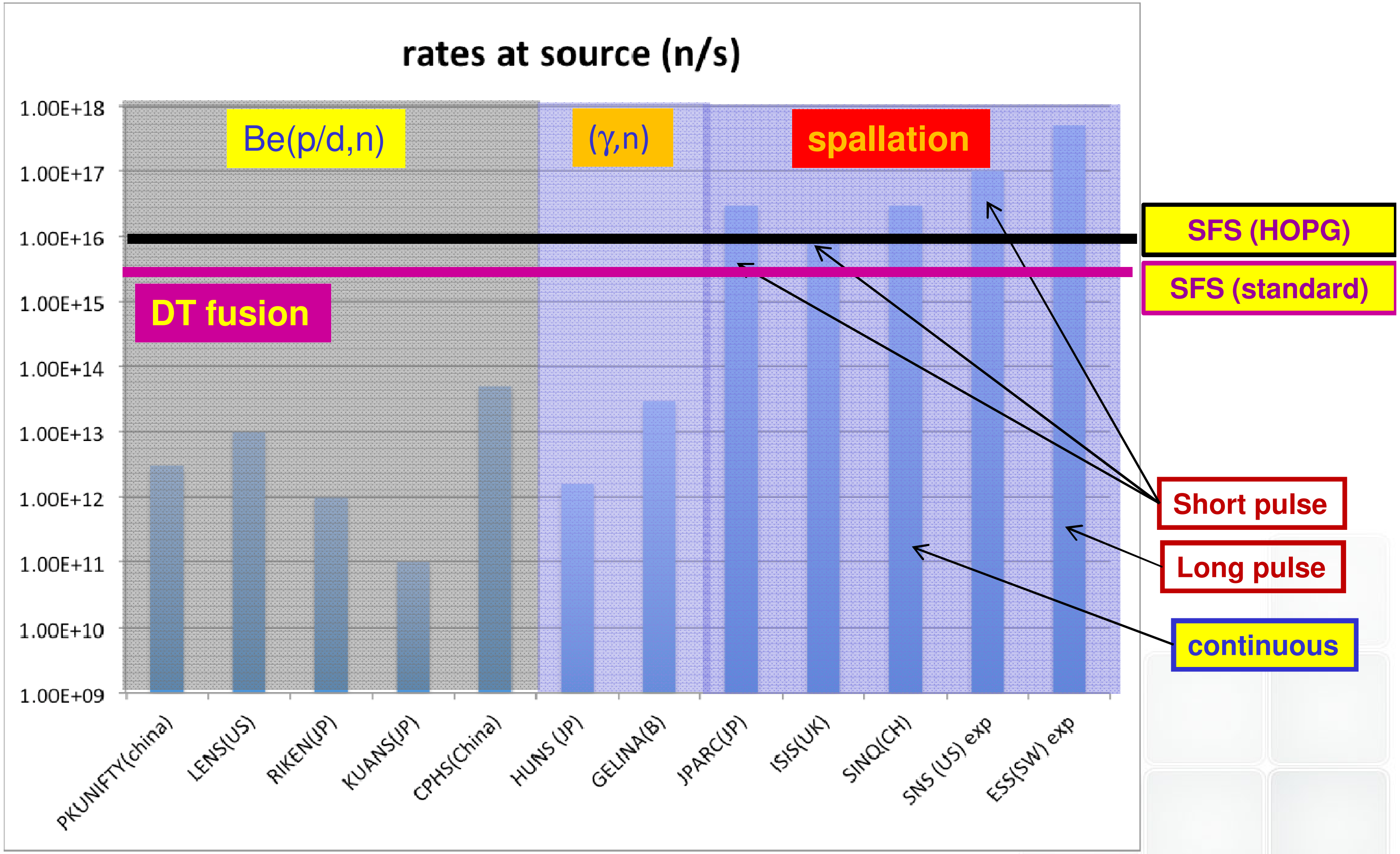
source spectrum

simulation

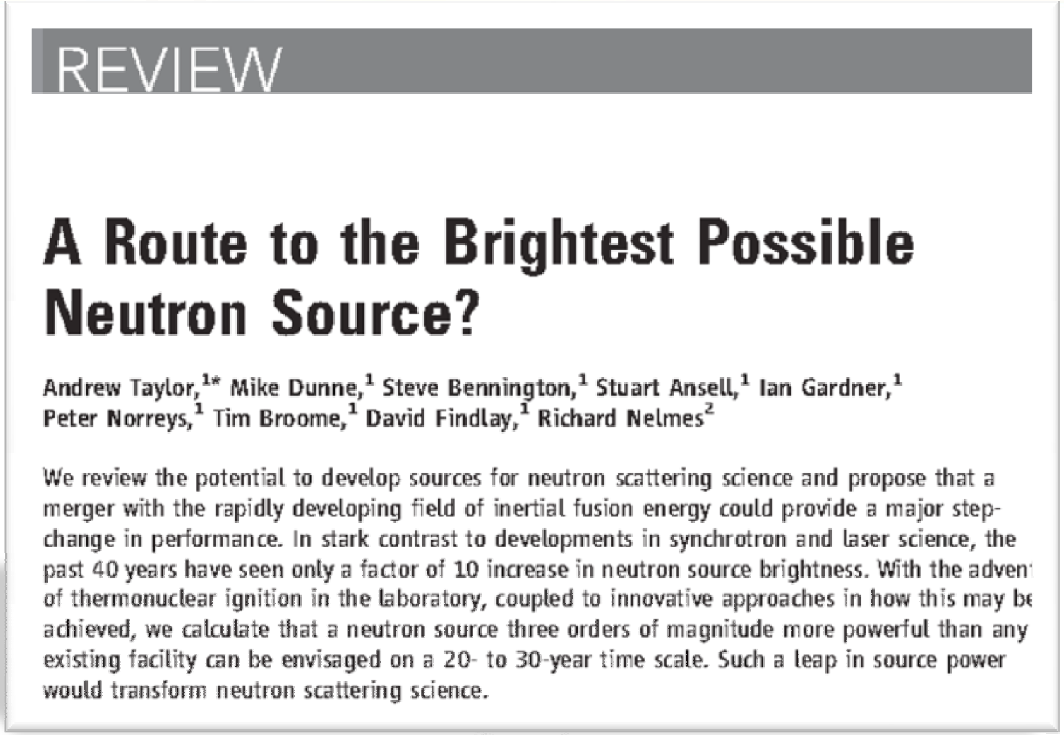


Sorgentina compared with other sources

Sorgentina is unique: produces a monochromatic neutron beam



....Do more...

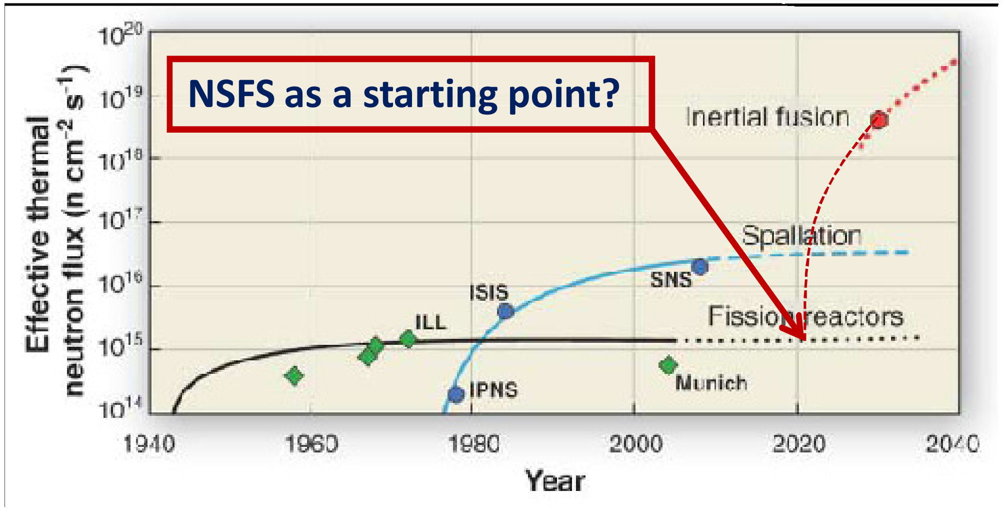


REVIEW

A Route to the Brightest Possible Neutron Source?

Andrew Taylor,[1*] Mike Dunne,[1] Steve Bennington,[1] Stuart Ansell,[1] Ian Gardner,[1]
Peter Norreys,[1] Tim Broome,[1] David Findlay,[1] Richard Nelmes[2]

We review the potential to develop sources for neutron scattering science and propose that a merger with the rapidly developing field of inertial fusion energy could provide a major step-change in performance. In stark contrast to developments in synchrotron and laser science, the past 40 years have seen only a factor of 10 increase in neutron source brightness. With the advent of thermonuclear ignition in the laboratory, coupled to innovative approaches in how this may be achieved, we calculate that a neutron source three orders of magnitude more powerful than any existing facility can be envisaged on a 20- to 30-year time scale. Such a leap in source power would transform neutron scattering science.



NSFS as a starting point?