SCHOOL OF NEUTRON SCATTERING
FRANCESCO PAOLO RICCI

NEUTRON SOURCES

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CNISM and NAST Center

University of Tor Vergata

Nanoscience
Nanotechnology
Innovative Instrumentation

Summary

- ✓ The neutron particle
- ✓ Neutron production mechanisms
- ✓ Neutron sources
- ✓ An overview on large scale neutron facilities
- ✓ Neutronics of spallation neutron sources

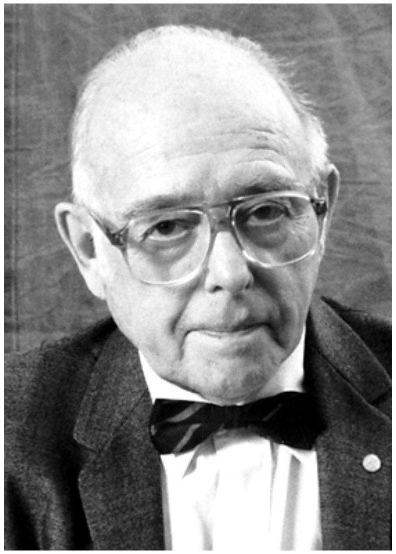
The neutron particle

1935

Discovery of the neutron
1932

James Chadwick

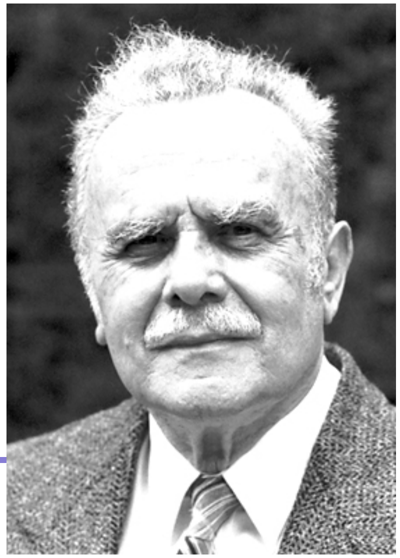
1994



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

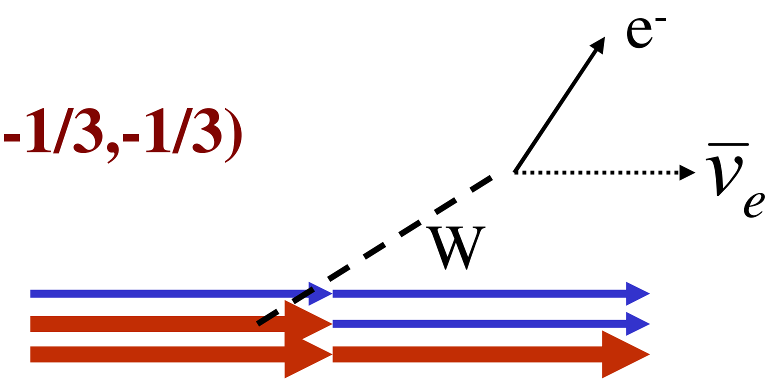
Interactions: Electroweak, strong, gravitational

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)

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



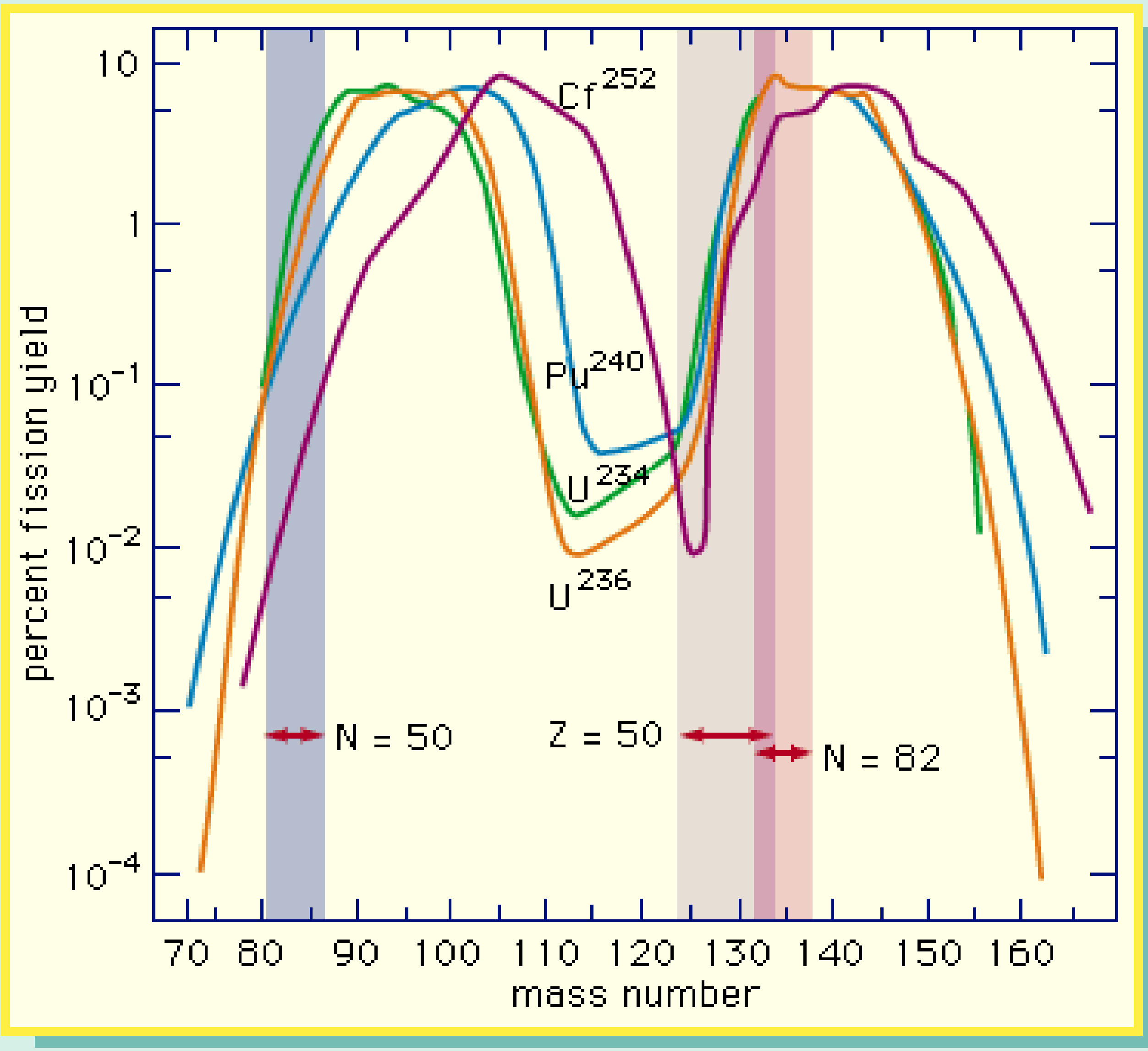
Magnetic moment: μ_m= - 0.966 236 40(23) x 10^{-26} JT^{-1}

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

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

A little of physics

The spontaneous fission



Distributions of mass numbers for different fissile nuclides:
^{252}Cf
^{240}Pu
^{234}U
^{236}U

Induced Fission

Nuclear fission can be induced by bombarding atoms with neutrons.

The nuclei of the atoms then split into 2 equal parts.

Induced fission decays are also accompanied by the release of neutrons.

The Fission Process

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

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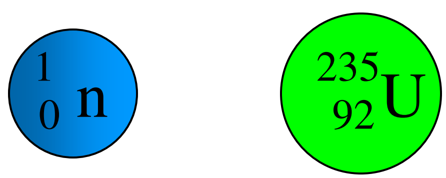

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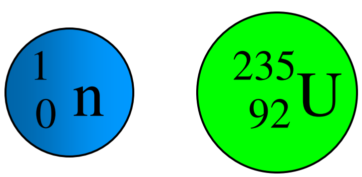
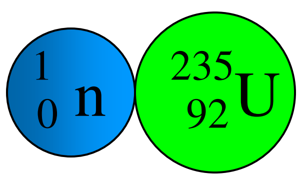


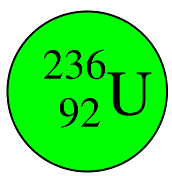
The Fission Process

The neutron strikes the nucleus which then captures the neutron.



The Fission Process

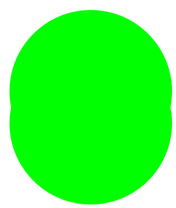
The nucleus changes from being uranium-235 to uranium-236 as it has captured a neutron.



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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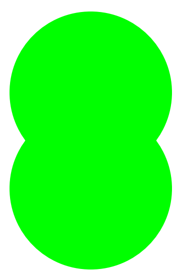

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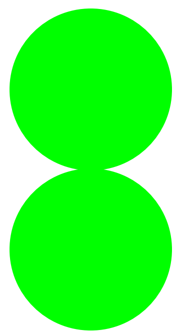
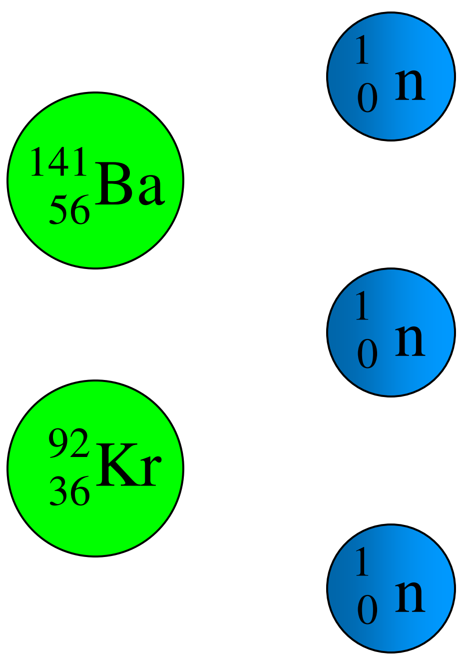


The Fission Process

It then splits into 2 fission fragments and releases neutrons.



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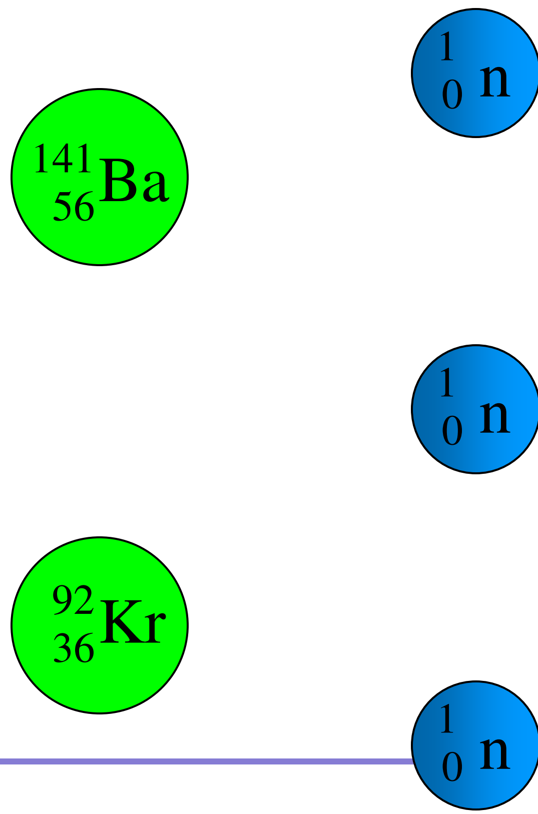

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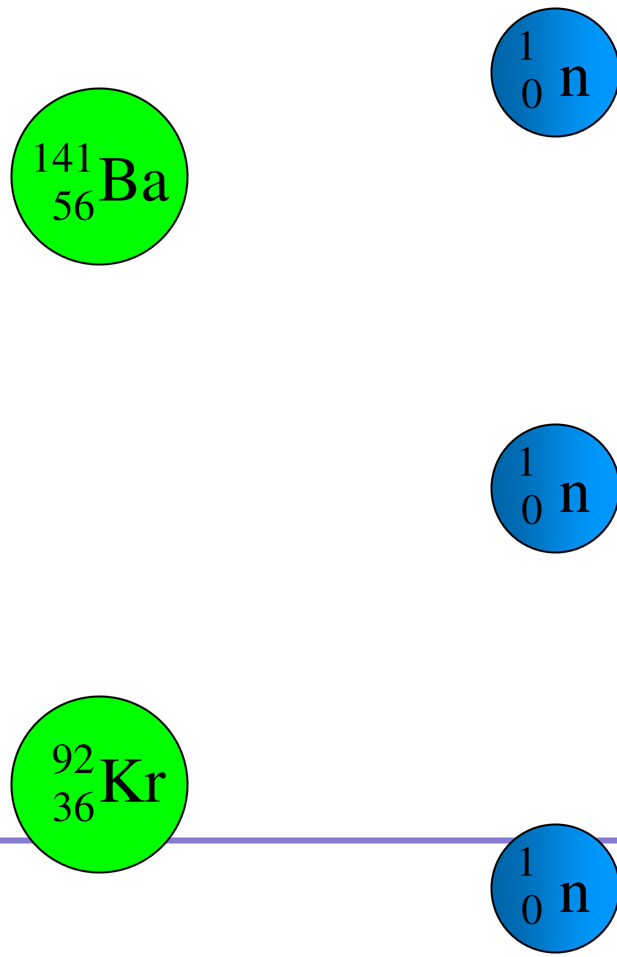

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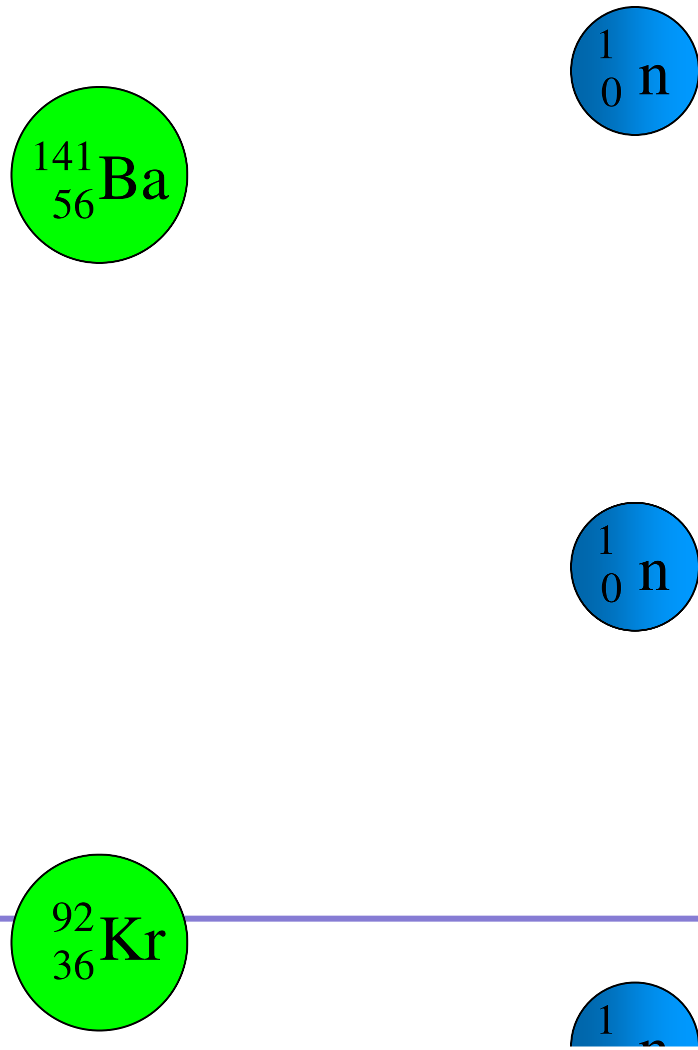


Delayed fission neutrons

- Neutrons generated by fission are prompt, while from the fission products, that in turn decay via a weak process, are emitted neutrons that are called "delayed neutrons".

$$(A,Z)^{**} \rightarrow (A,Z \pm 1)^{**} + e^{\pm}$$
$$(A,Z \pm 1)^{**} \rightarrow (A-1,Z \pm 1)^{**} + n$$

These delayed neutrons are almost monoenergetic as they proceed from the decay of a single nuclear excited state of the fission product

Nuclear Fusion

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

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

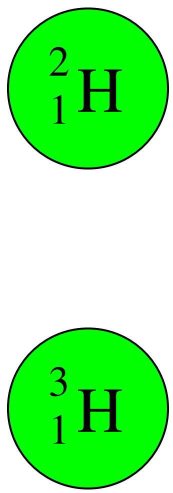
The Fusion Process

The Fusion Process

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

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

The Fusion Process



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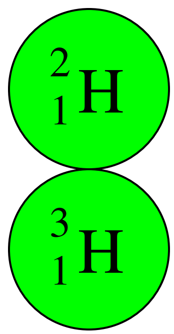

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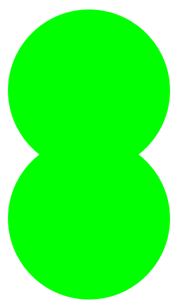

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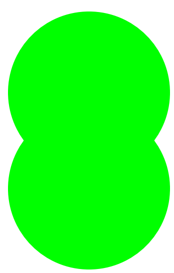

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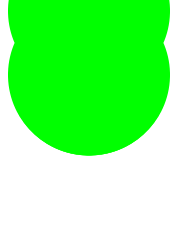

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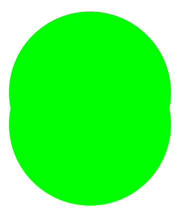

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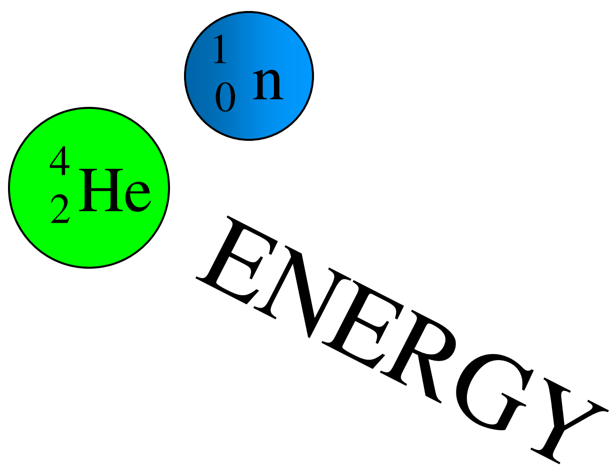

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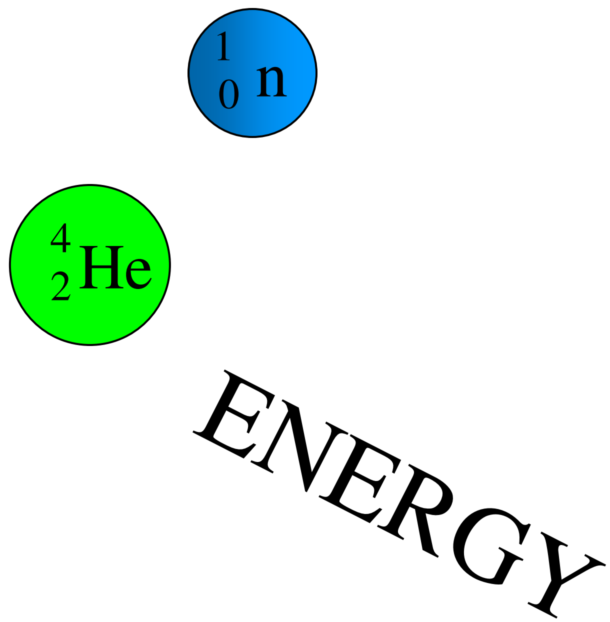

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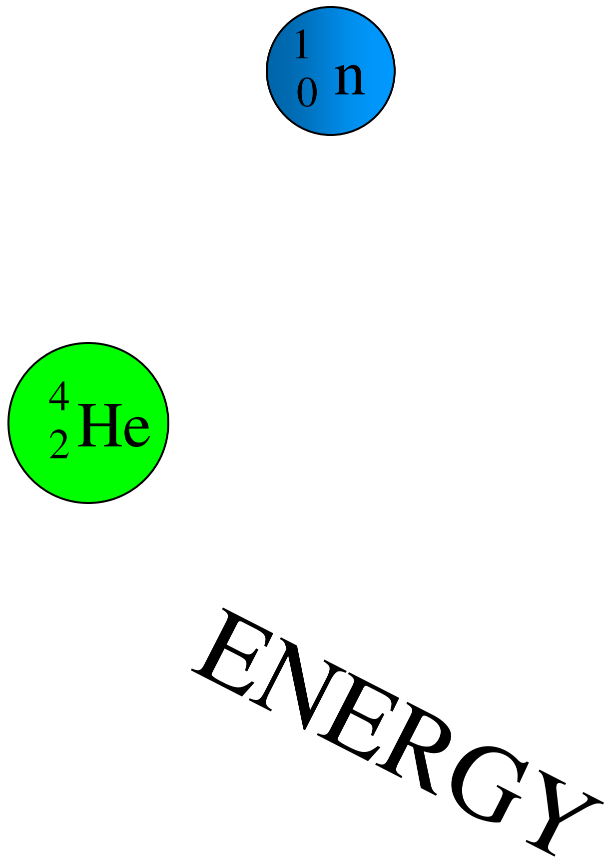

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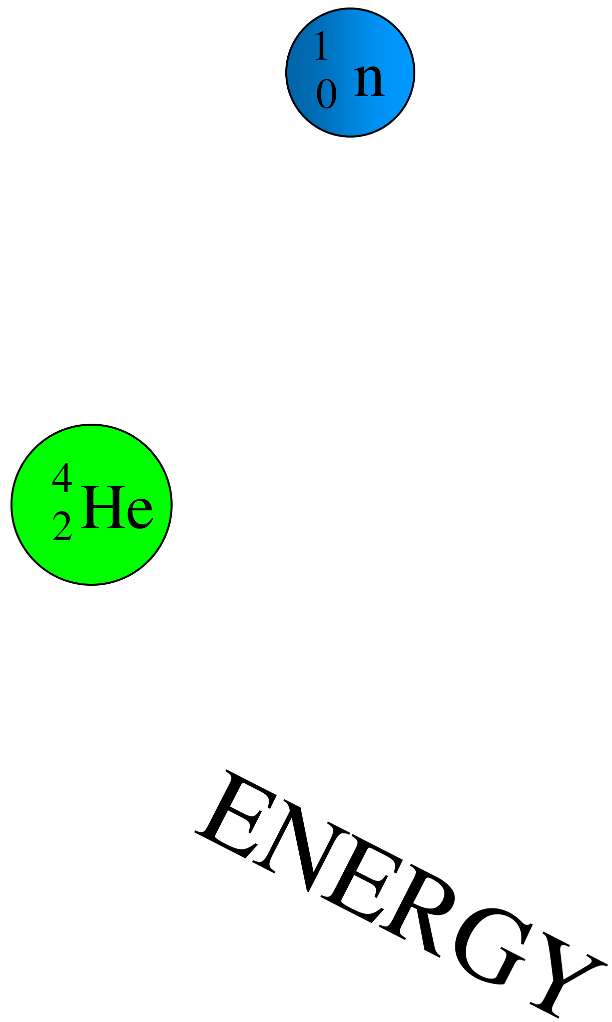
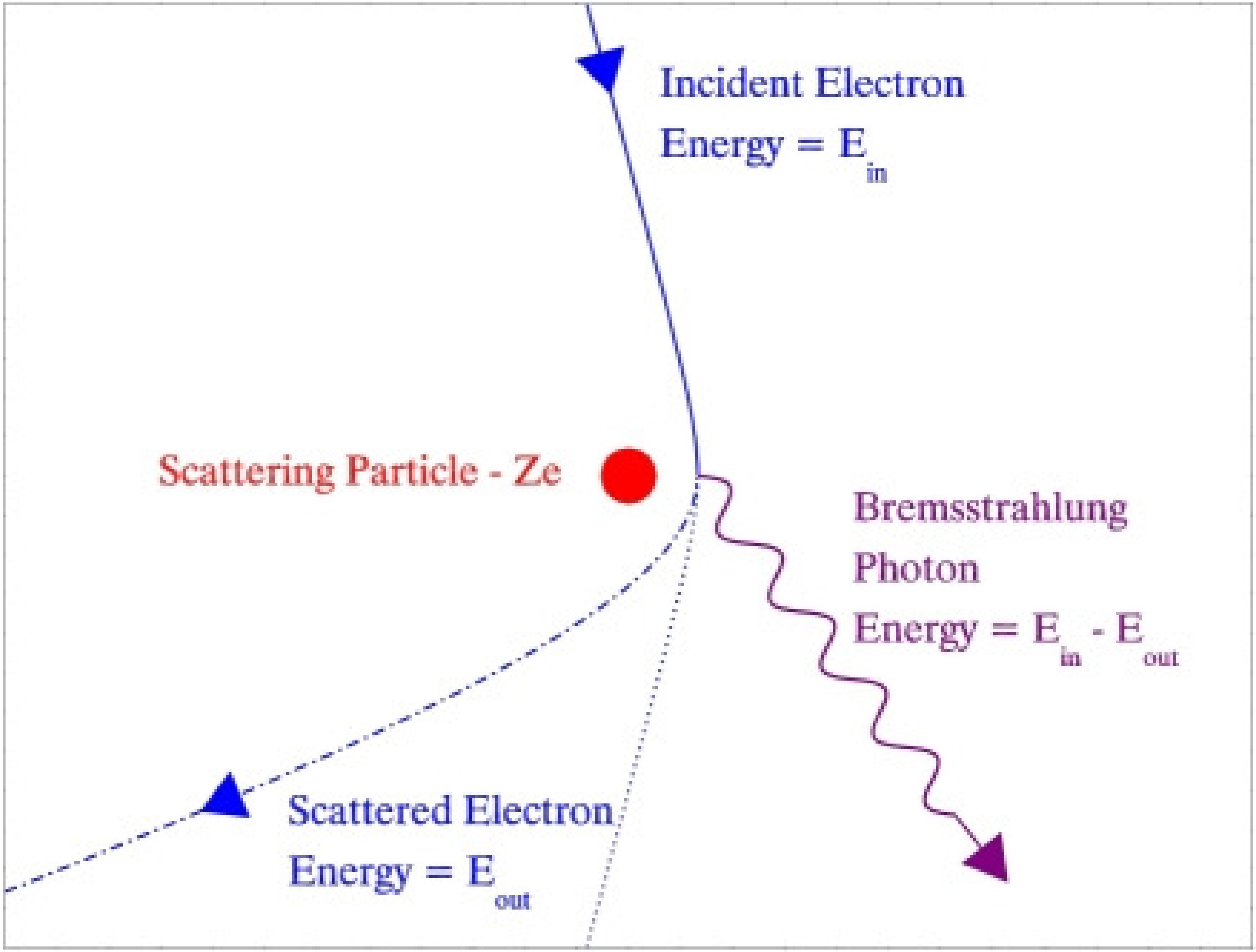



Incident Electron
Energy = E_{in}
Scattering Particle - Ze
Bremsstrahlung
Photon
Energy = E_{in} - E_{out}
Scattered Electron
Energy = E_{out}

n

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

A few examples:

$$\alpha + T \rightarrow \begin{cases} {}^{3}He + n + X \\ {}^{3}H + p + X \\ d + d + X \\ d + n + p + X \\ n + n + p + p + X \end{cases}$$

T being the Target and X represents the final state of the Target

These reactions where fragmentation of the projectile (α particle) occurs are important at **very high energies** (e.g. in the cosmic rays, 10-12% of the cosmic rays flux are α) as π exchange is a likely mechanism

Examples of neutron sources

Radioisotopes

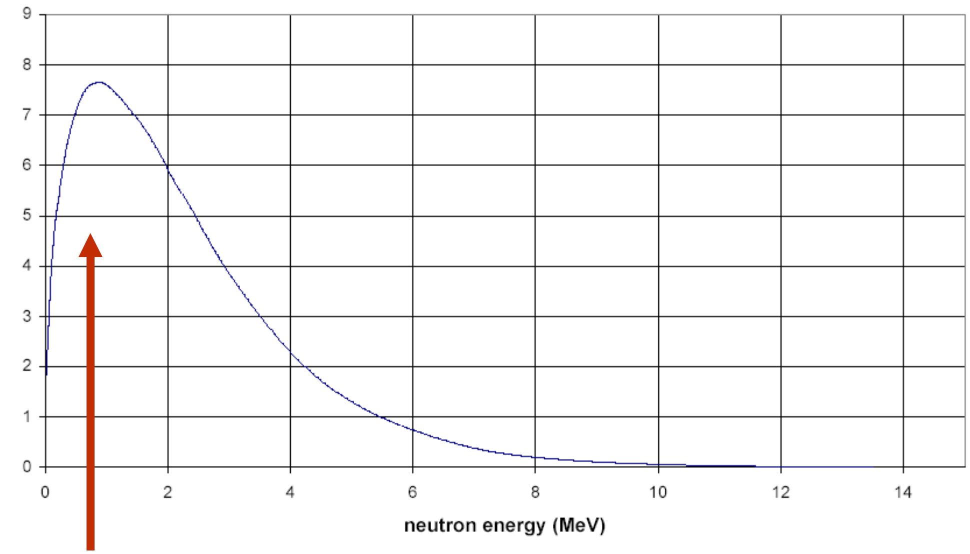


Figure 2: Neutron kinetic energy spectrum produced in the spontaneous fission of Californium nuclei.

^{252}Cf spontaneous fission:

spectrum well described by the relation:

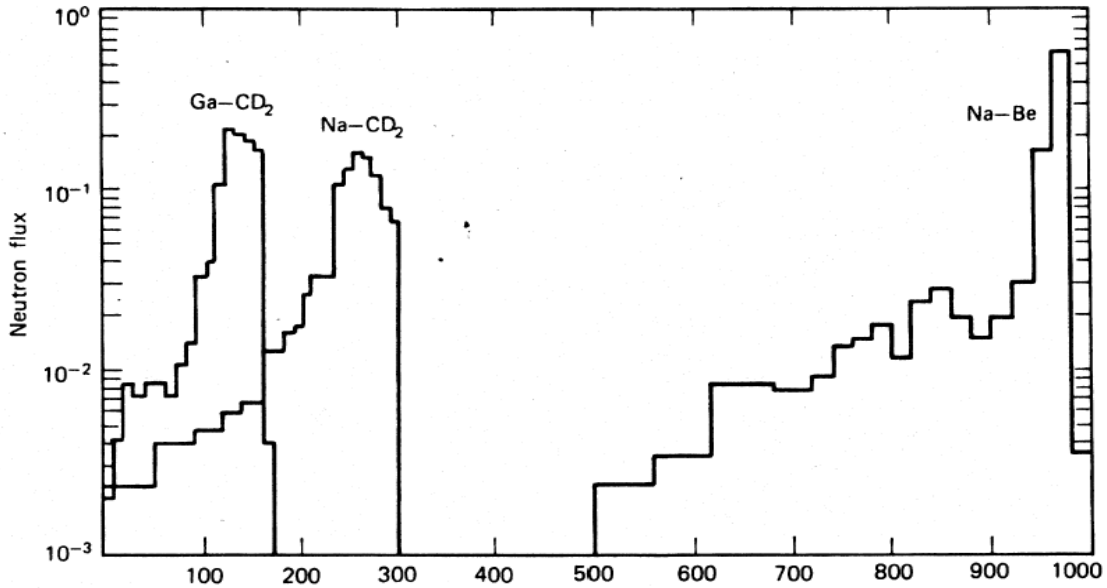
$$\frac{dN}{dE} = E^{1/2} e^{-\frac{E}{T}} \qquad T \approx 1.3 \text{ MeV}$$

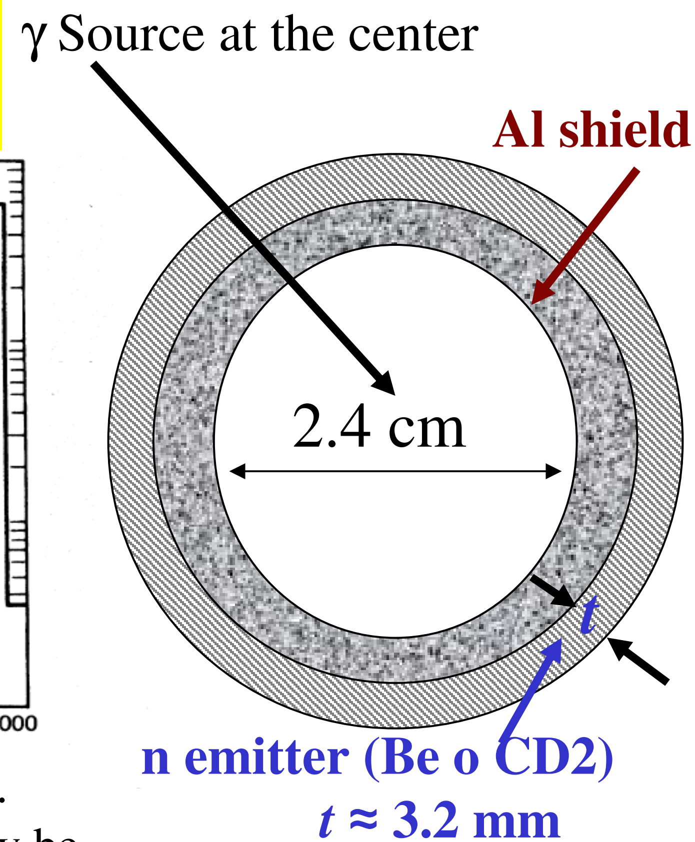
I ≈ 2.3 10^6 n s^{-1} μgr^{-1}

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

Photoproduction

$$^{9}Be_{4} + h\nu \rightarrow {}^{8}Be_{4} + n \quad (-1.666\ \text{MeV})$$
$$^{2}H_{1} + h\nu \rightarrow {}^{1}H_{1} + n \quad (-2.226\ \text{MeV})$$





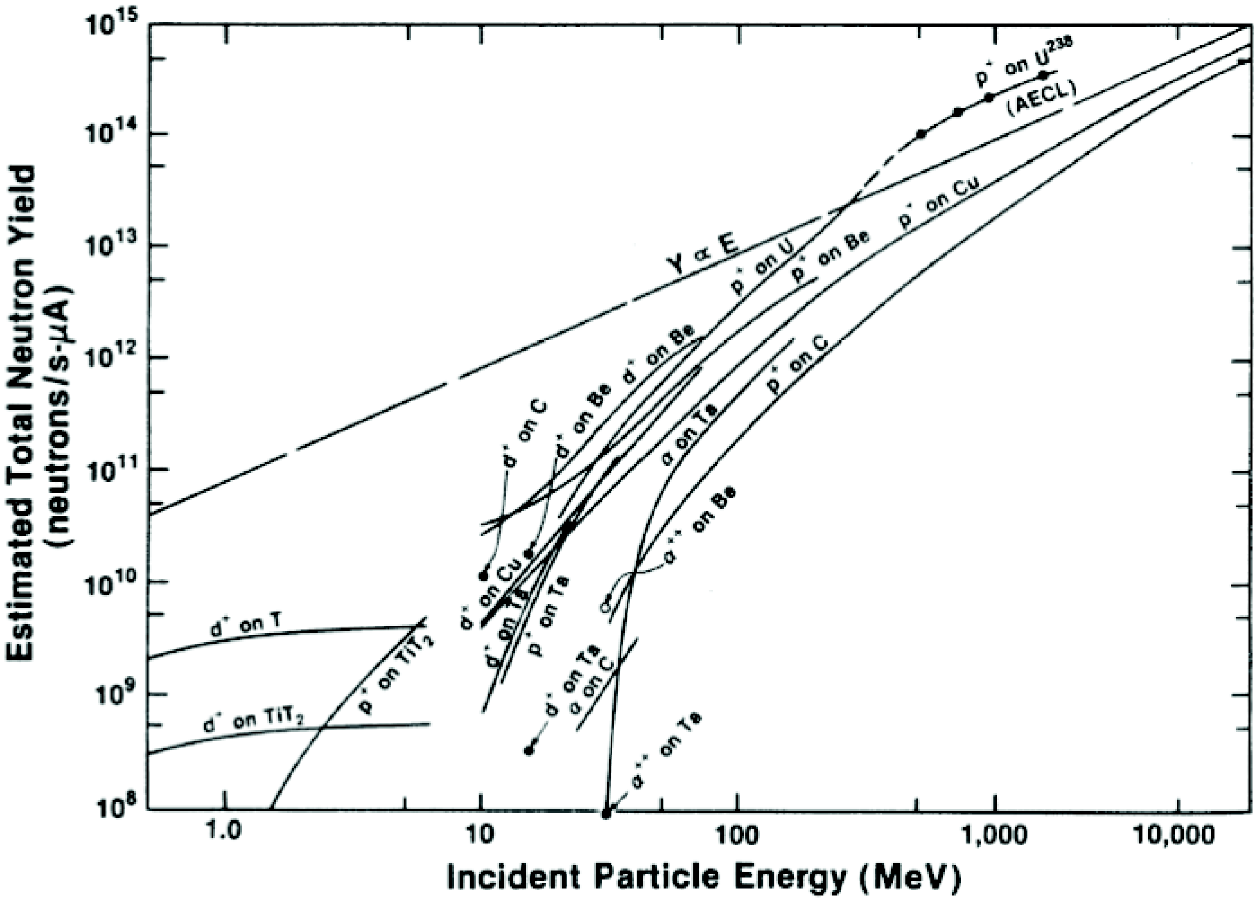
Neutron spectra calculated for the source in the picture. Typical γ sources are ^{72}Ga and ^{22}Na. The external shell may be made of Berillium or deuterated Poly(CD$_2$)

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

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

Charged particle induced reactions

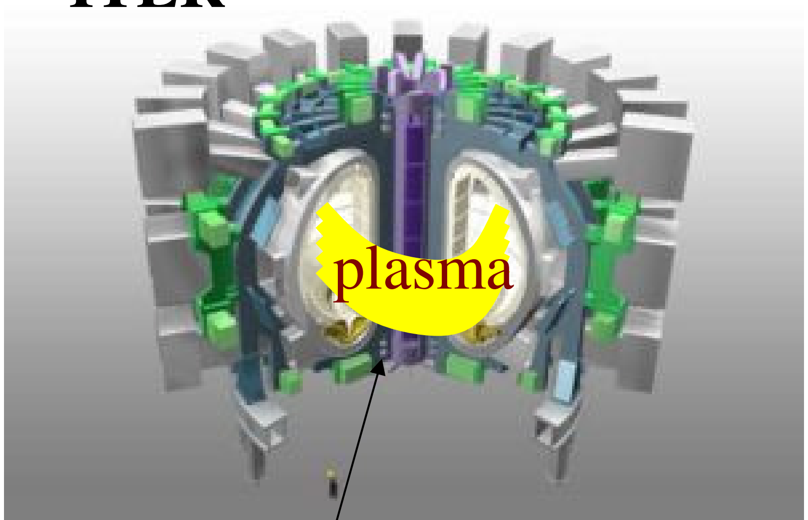
Two examples: (i) ^{9}**Be + p → ^{9}B+n**, (ii) **^{2}H+^{3}H → ^{4}He + n**



Neutron Yield for a series of charged particle induced reactions

Neutrons from fusion plasma
TOKAMAK

ITER



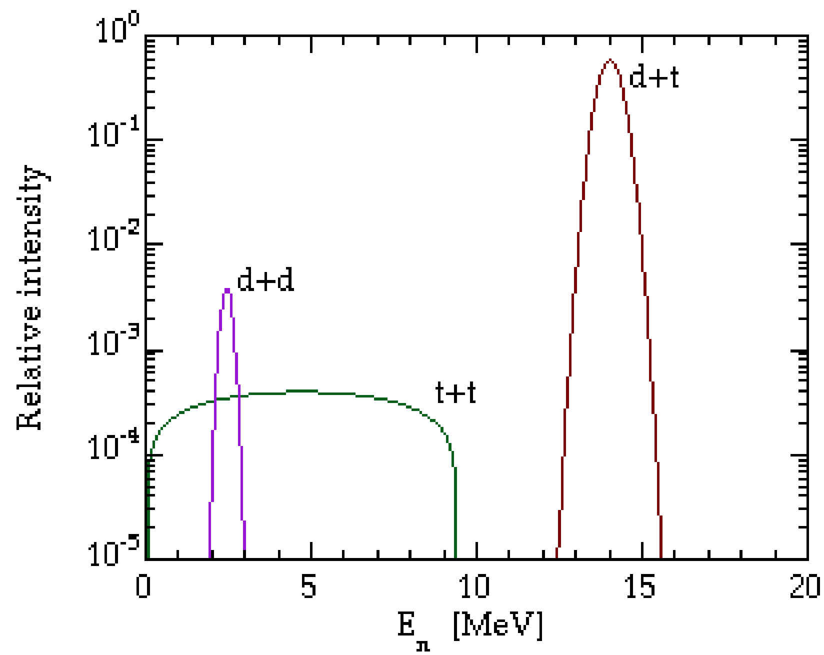
Toroidal vacuum chamber

D-D Reaction:

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

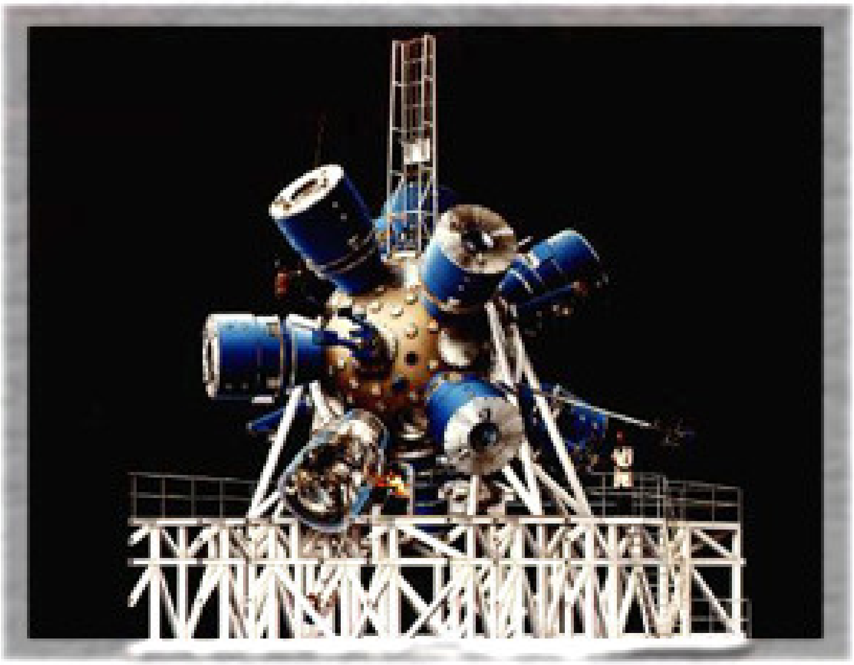
D-T Reaction

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

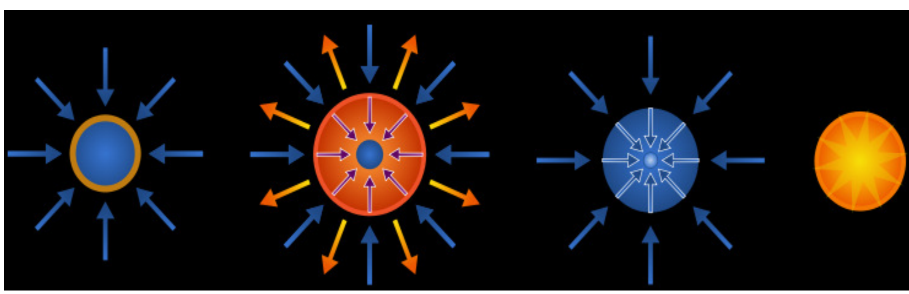


Inertial fusion

laser & heavy ions



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

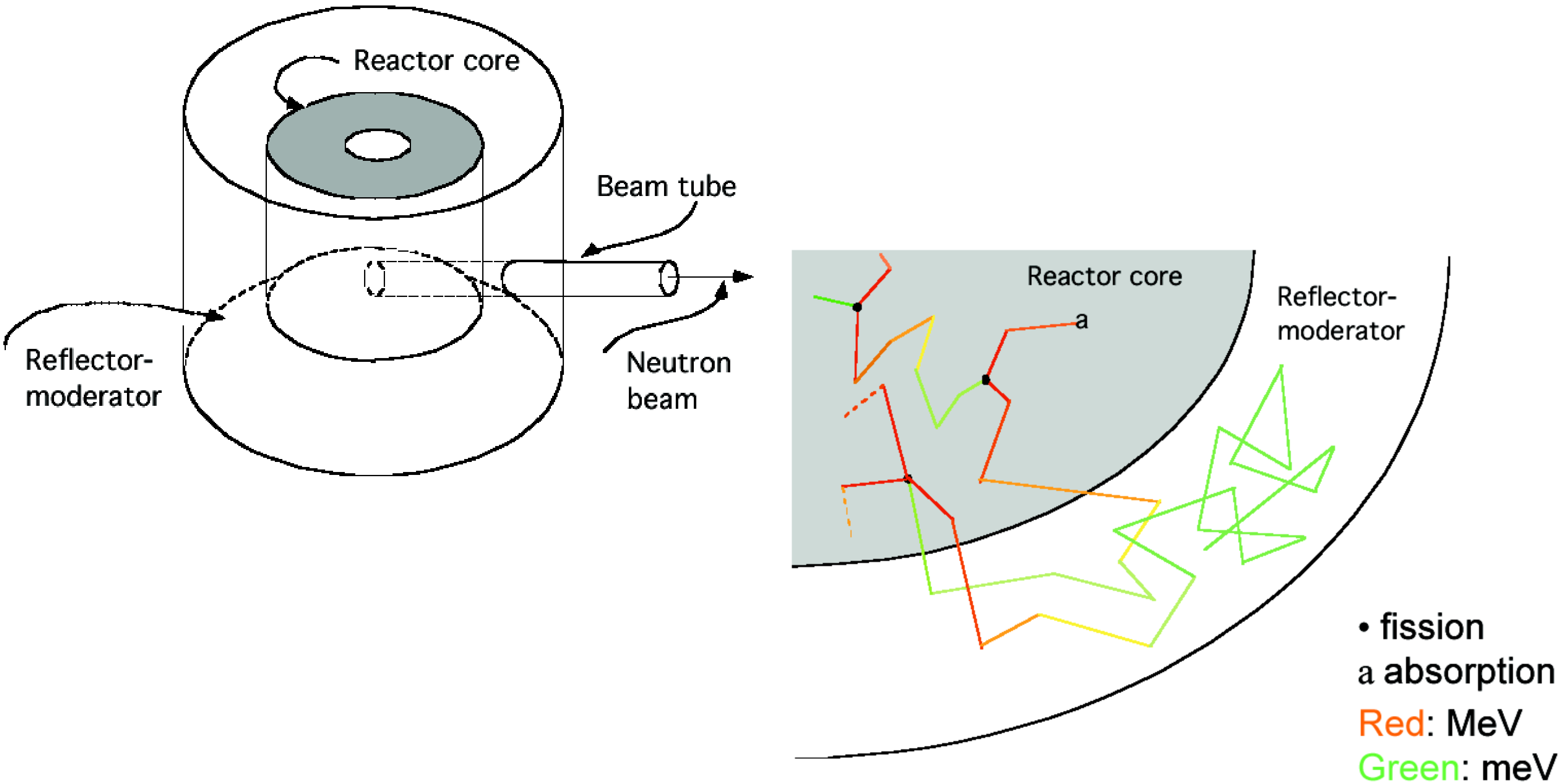


Inertial confinement is the other direction or research towards plasma confinement. This technique involves imploding a small fuel pellet (most likely a 50/50 mixture of deuterium and tritium). If it is compressed quickly and hard enough, temperature and density rise, allowing the reaction to reach or exceed the Lawson criterion. It is the inertia of the imploding pellet that keeps it confined momentarily. Because it is confined only by its own inertia, the plasma lasts for about one nanosecond.

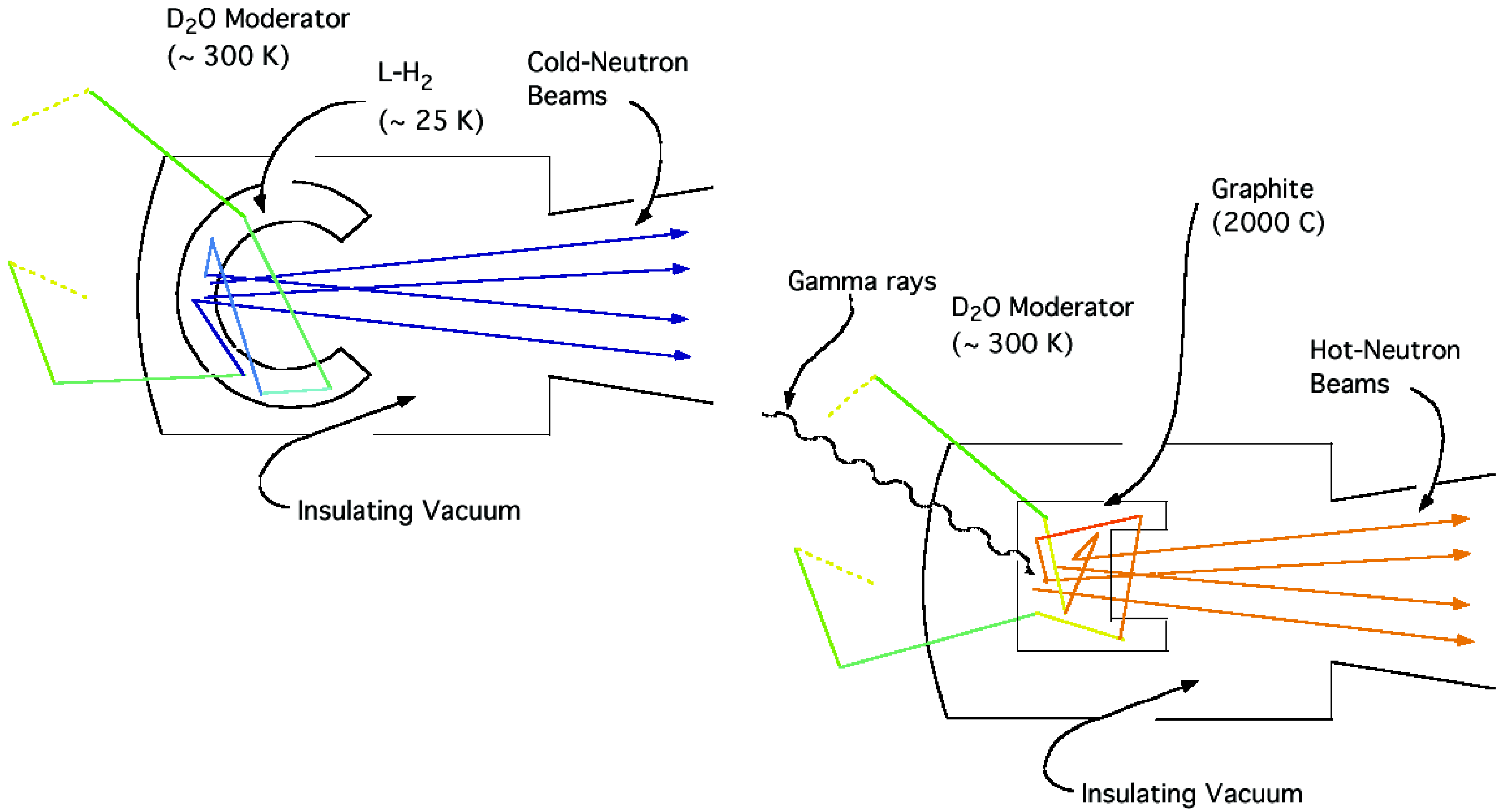
Therefore, to achieve breakeven point, a very large density is needed, usually around 1024 particles/cm3, which is many times more than lead. The fuel pellet, or target, is compressed and heated with what are called energy drivers. These high-powered sources of energy are usually either high-powered laser or ion beams, which bombard the target from all sides symmetrically. The outer layer of the pellet vaporizes and moves away from the pellet like a rocket. This projection creates shock waves which go on to compress and heat the core. The compressed fuel then burns, releasing much energy, and expands. This is partially offset by the shock waves, which tend to continue compressing the material. This behavior is known as inertia. The result is an inertial confinement fusion reaction.

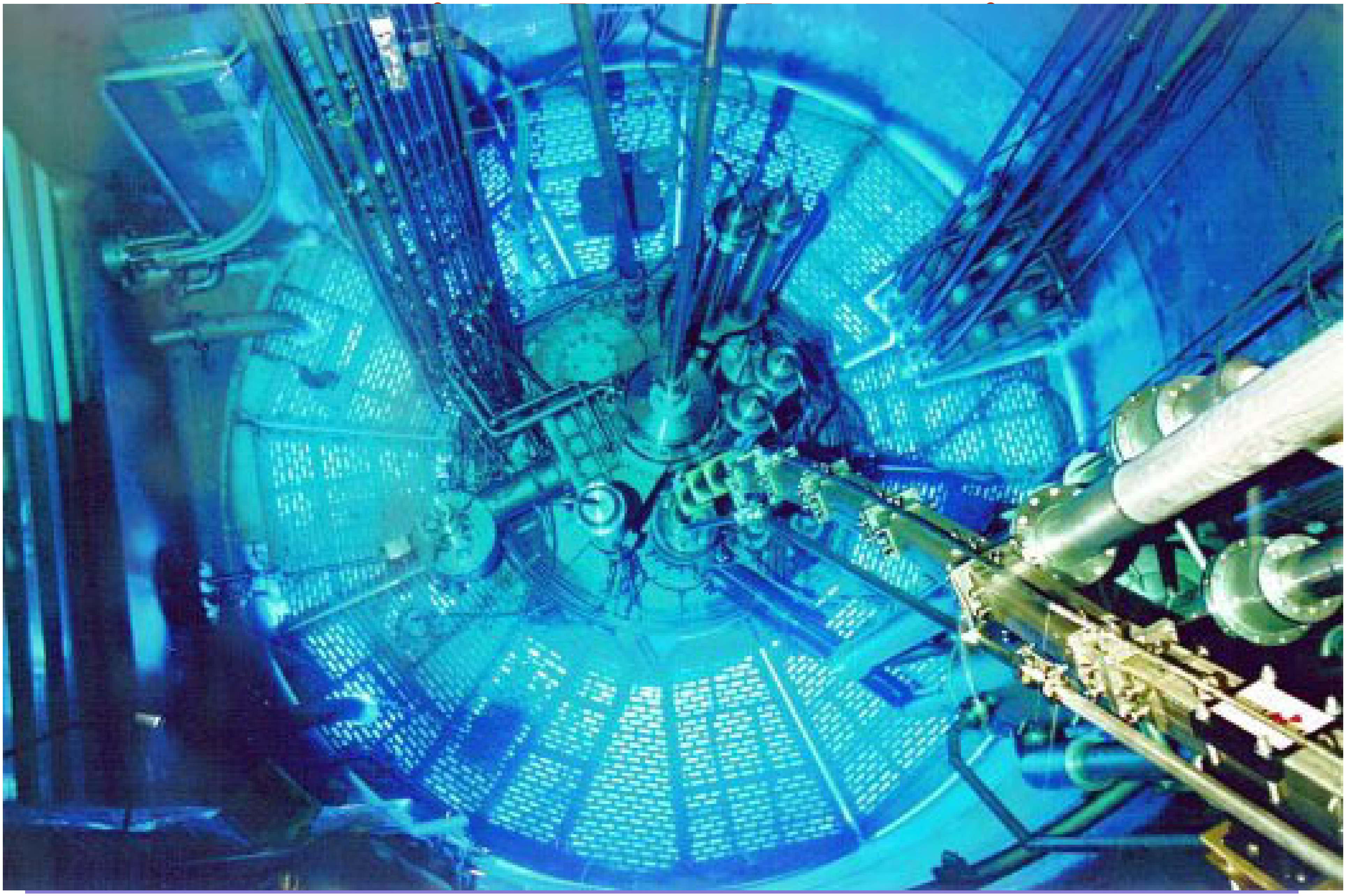
Sources at large scale facilities

Fission Reactors

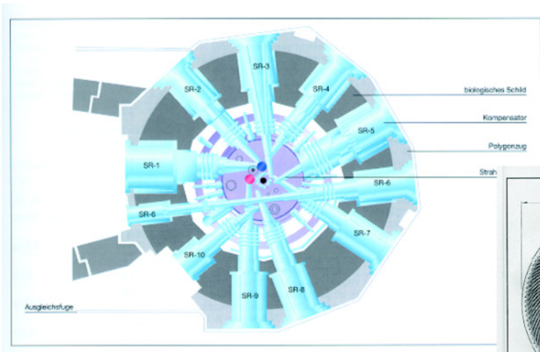


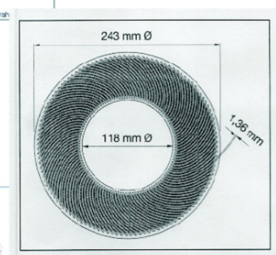
Cold and hot sources

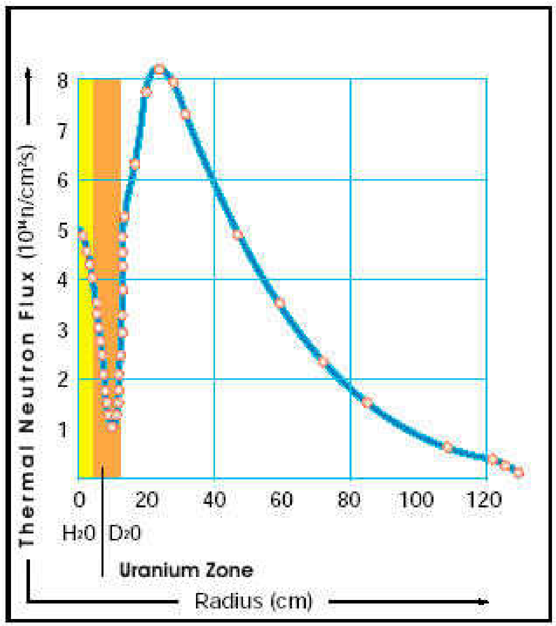




Heinz Maier Leibnitz Reactor
FRM-II (Munich, Germany)



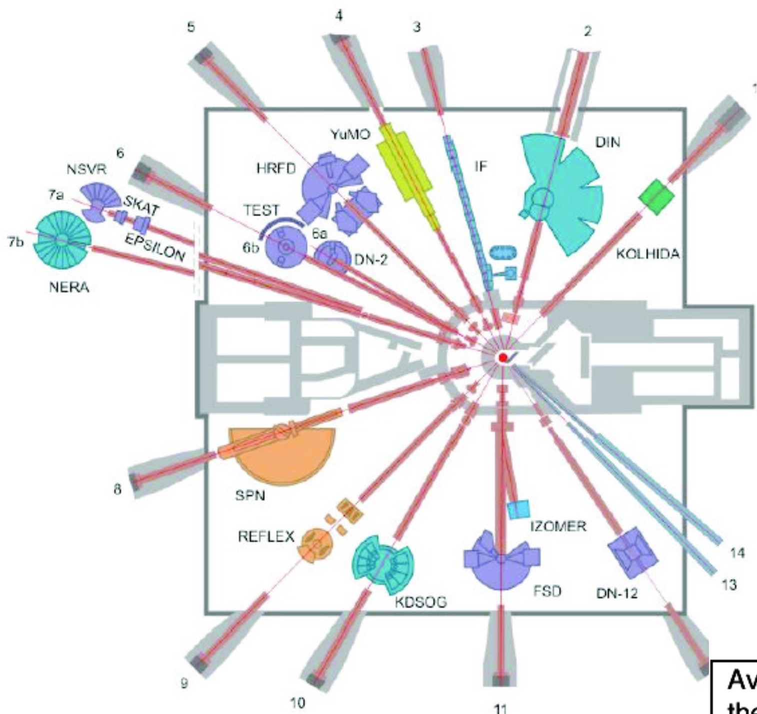


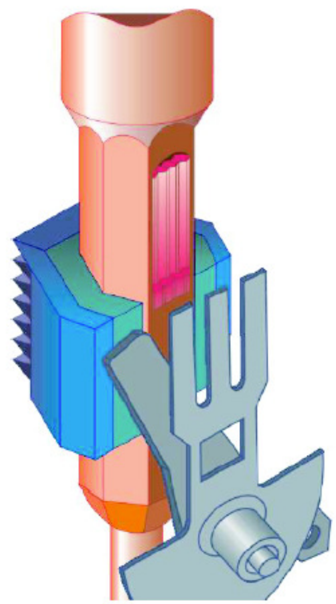


Characteristic Data

Reactor Type:	• compact reactor core in the centre of a D_2O-Moderator tank 2,5m in diameter and 2,5m high
Nominal Thermal Power:	• 20MW
Reactor Core:	• single, cylindrical fuel element (inside 118mm, outside 243mm, approx. 700mm height) • 113 involuted, curved fuel plates • uranium silicide-aluminium dispersion • graded uranium densities (1,5gcm^{-3} und 3,0gcm^{-3}) • enrichment factor 93% ^{235}U • approx. 8kg uranium in total • duration of cycle approx. 52 days • 5 cycles per year
Shut-down Systems:	• central control rod (hafnium) with beryllium follower • five shutdown rods in moderator tank (hafnium)
Cooling:	• primary system: pool water (H_2O), throughput 1000m^{3}h^{-1}, temperature 37/52°C • secondary system: closed circuit (H_2O) • tertiary system: wet cooling units (H_2O), heat dissipation to atmosphere
Pool:	• approx. 700m^3 deionised water • isolating gate between decay pool and reator pool
Reactor Pool Wall:	• heavy concrete, density 4,5gcm^{-3}, thickness 1,5m
Building:	• reactor building 42m x 42m, 30m high • neutron guide hall: experimental area approx. 50m long, 24m wide
Neutron Flux Density:	• 8x10^{14}cm^{-2}s^{-1} maximum (thermal, undisturbed)

Reattore IBR-2
Dubna





Reactor parameters

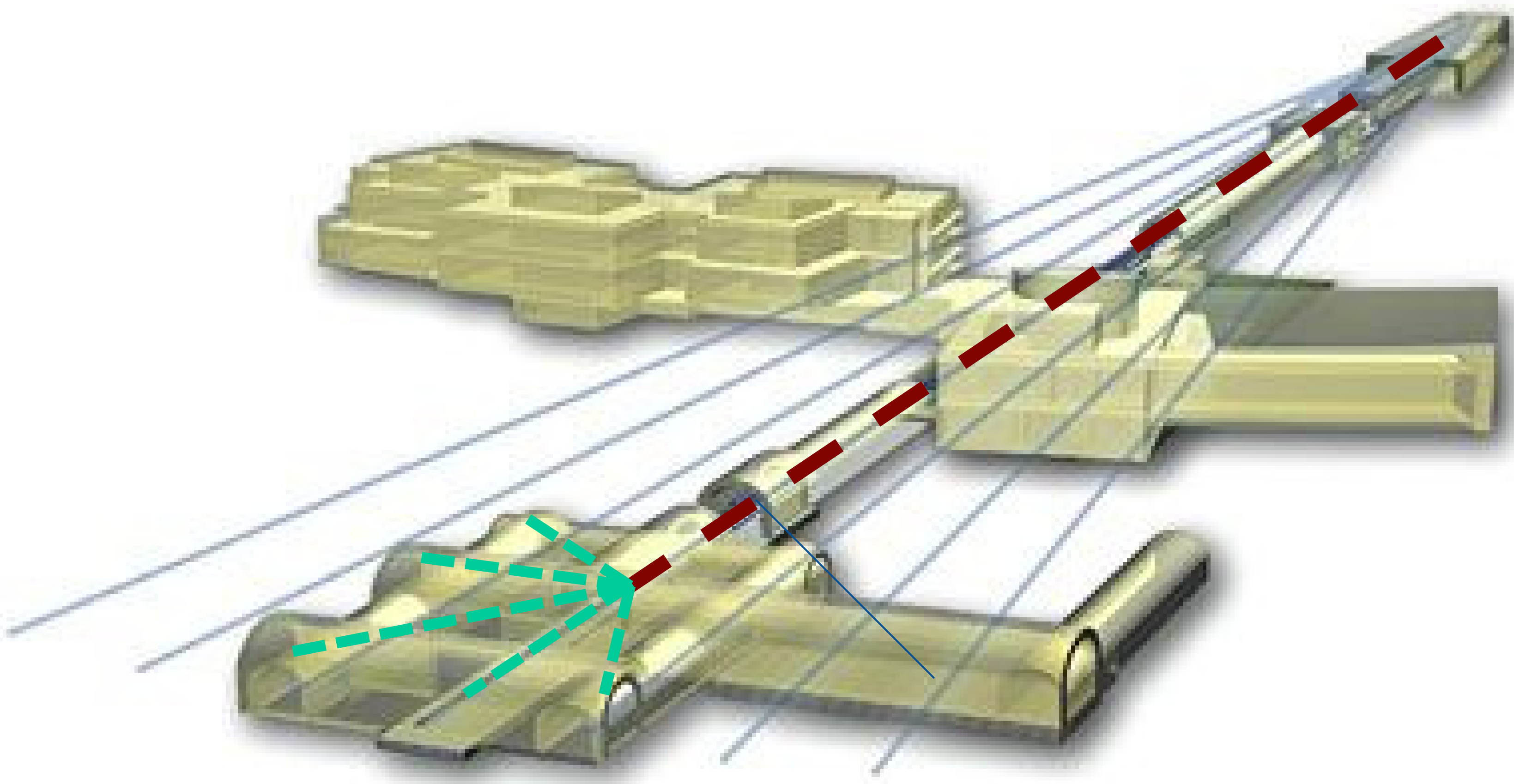
Average thermal power, MW	Peak Power in Pulse, MW	Pulse Repetition Rate, Hz	Thermal-Neutron Flux at Moderator surface, n/cm^2-sec (surface average)		Pulse FWHM, μsec	Status
			Time-Average	Peak		
2.0	1500.	5.	8 x 10^{12}	5 x 10^{15}	320.	Operating Upgrade pending

Worlwide reactors

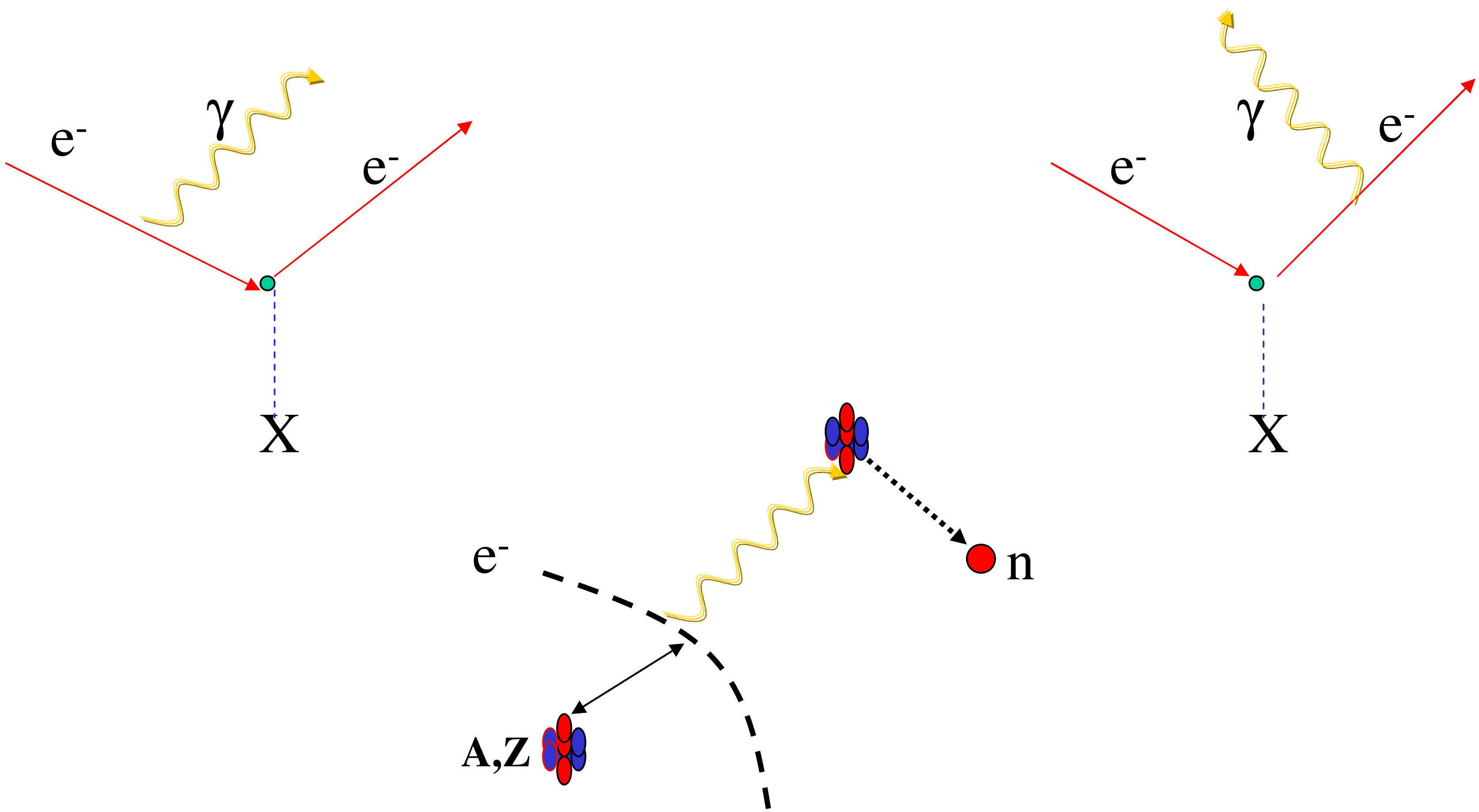
Reactor	Location	First Operation	Power, MW	Flux, n/cm^2-sec	Cold and Hot Sources
OPAL [a]	Lucas Heights, Australia	2007	20.	4.0×10^{14}	1 Cold
NRU [a]	Chalk River, Canada	1957	120.	3.0×10^{14}	—
CNF	Chalk River, Canada	~2012	40.	4.0×10^{14}	1 Cold
CARR [b]	Beijing, china	2006	60.	8.0×10^{14}	1 Cold 1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

Accelerator-driven pulsed neutron sources

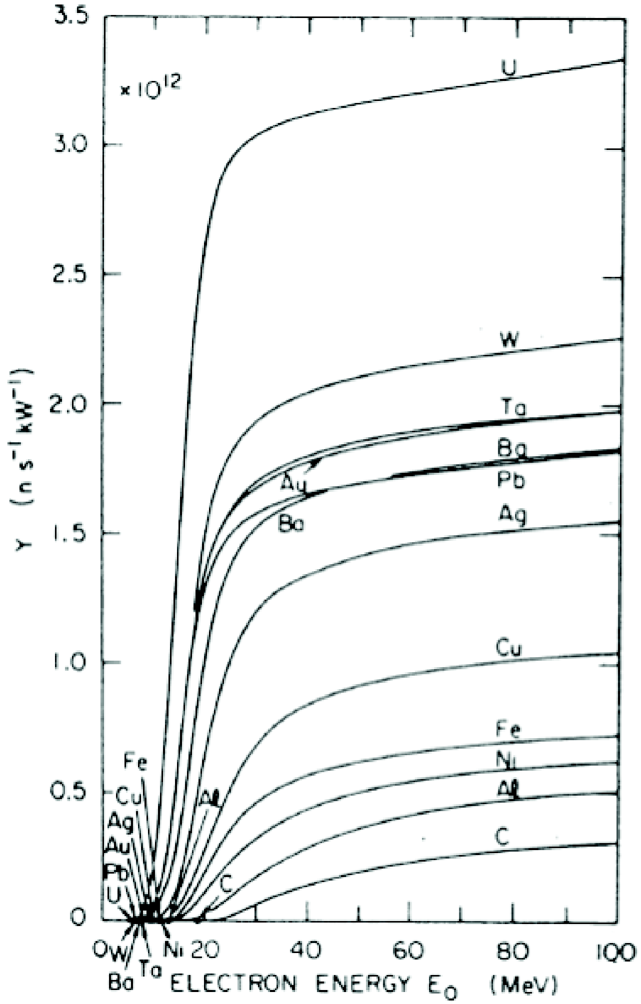
LINAC sources



Electrons-induced neutron production
Bremsstrahlung



Some examples

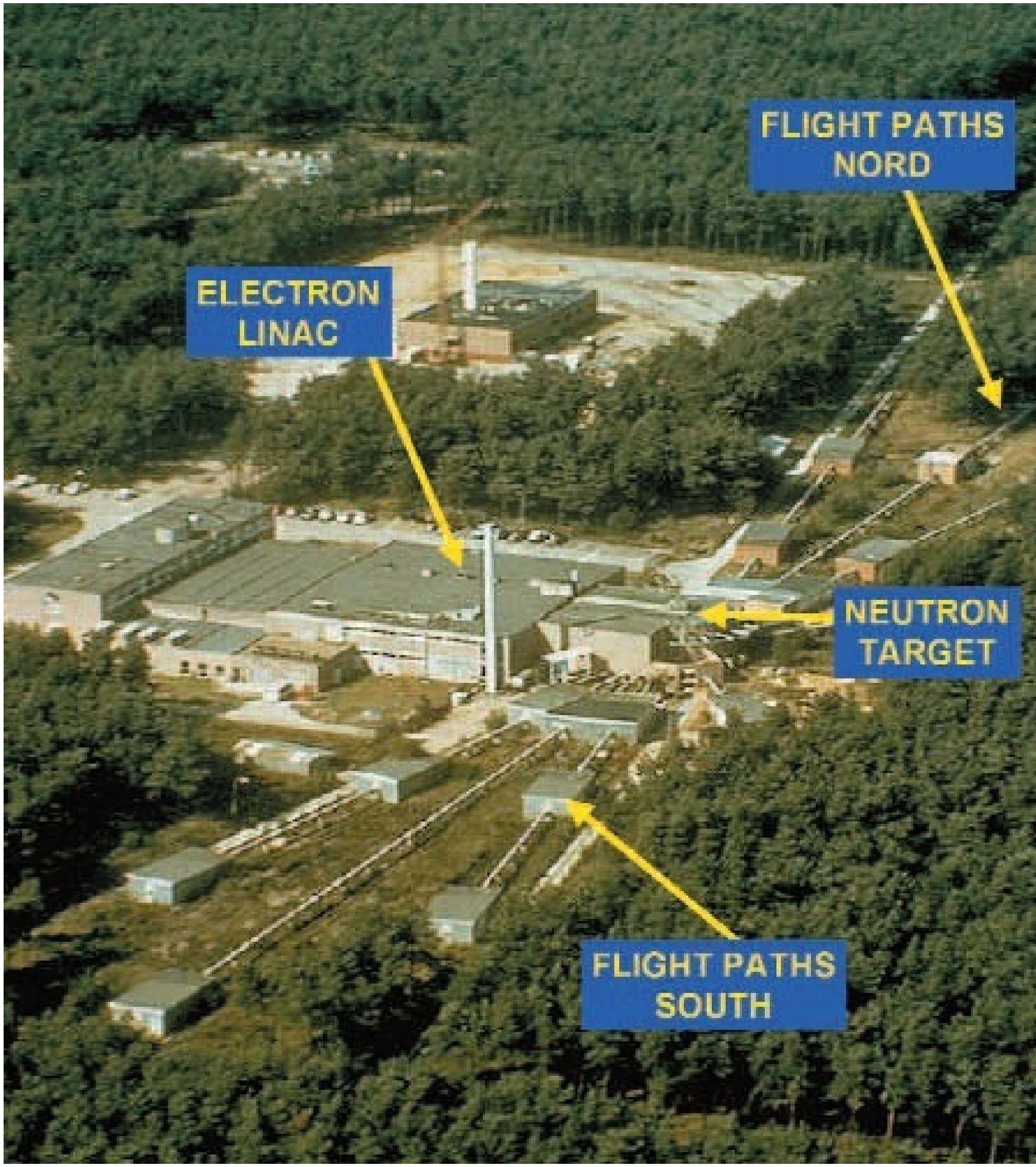


$$-\left(\frac{dE}{dx}\right)=\frac{NEZ(Z+1)e^2}{137m_0^2c^4}\left(4\ln\frac{2E}{m_0c^2}-\frac{4}{3}\right)$$

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

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)



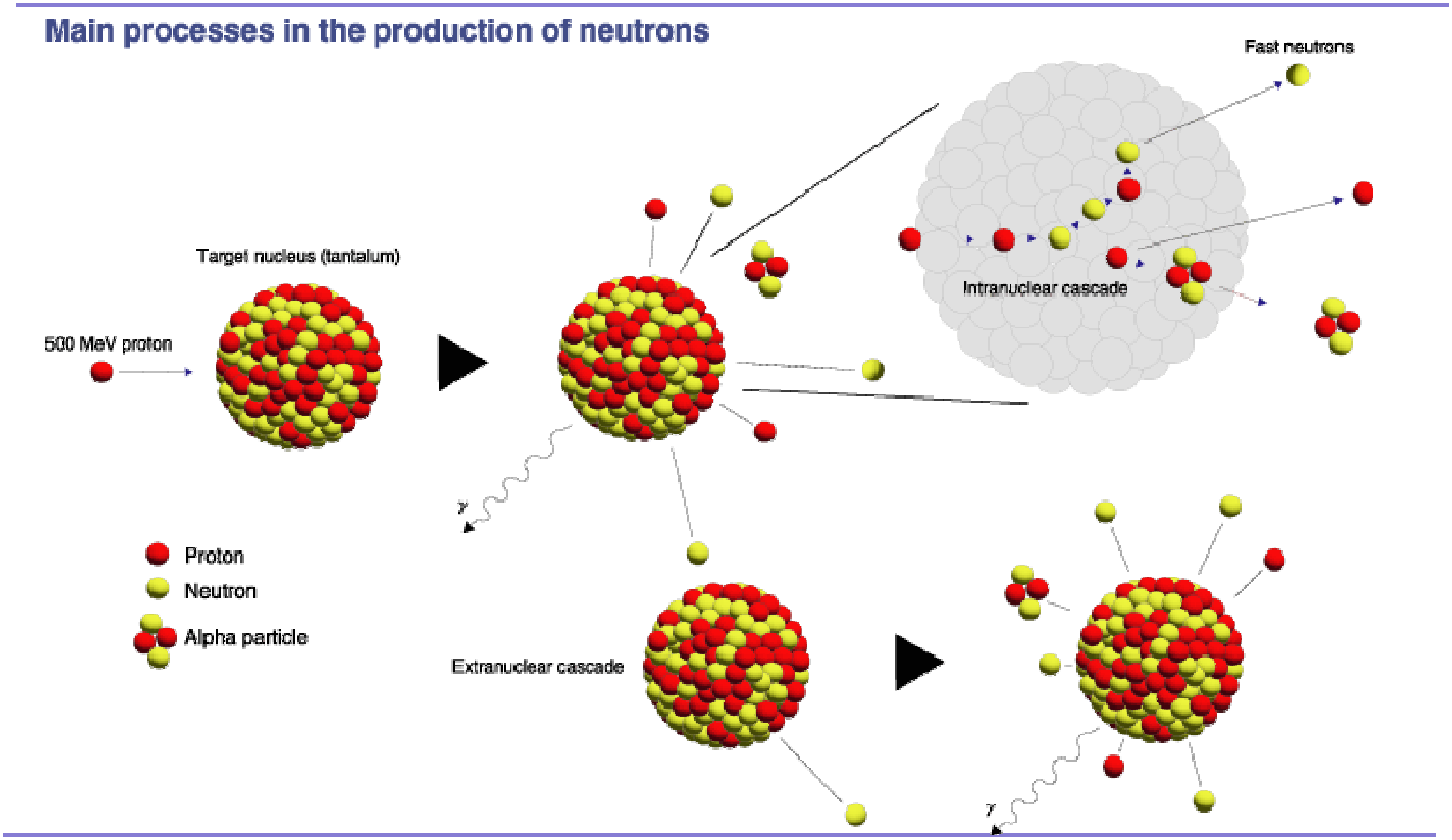
Neutron energy range:
1 meV-20 MeV

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

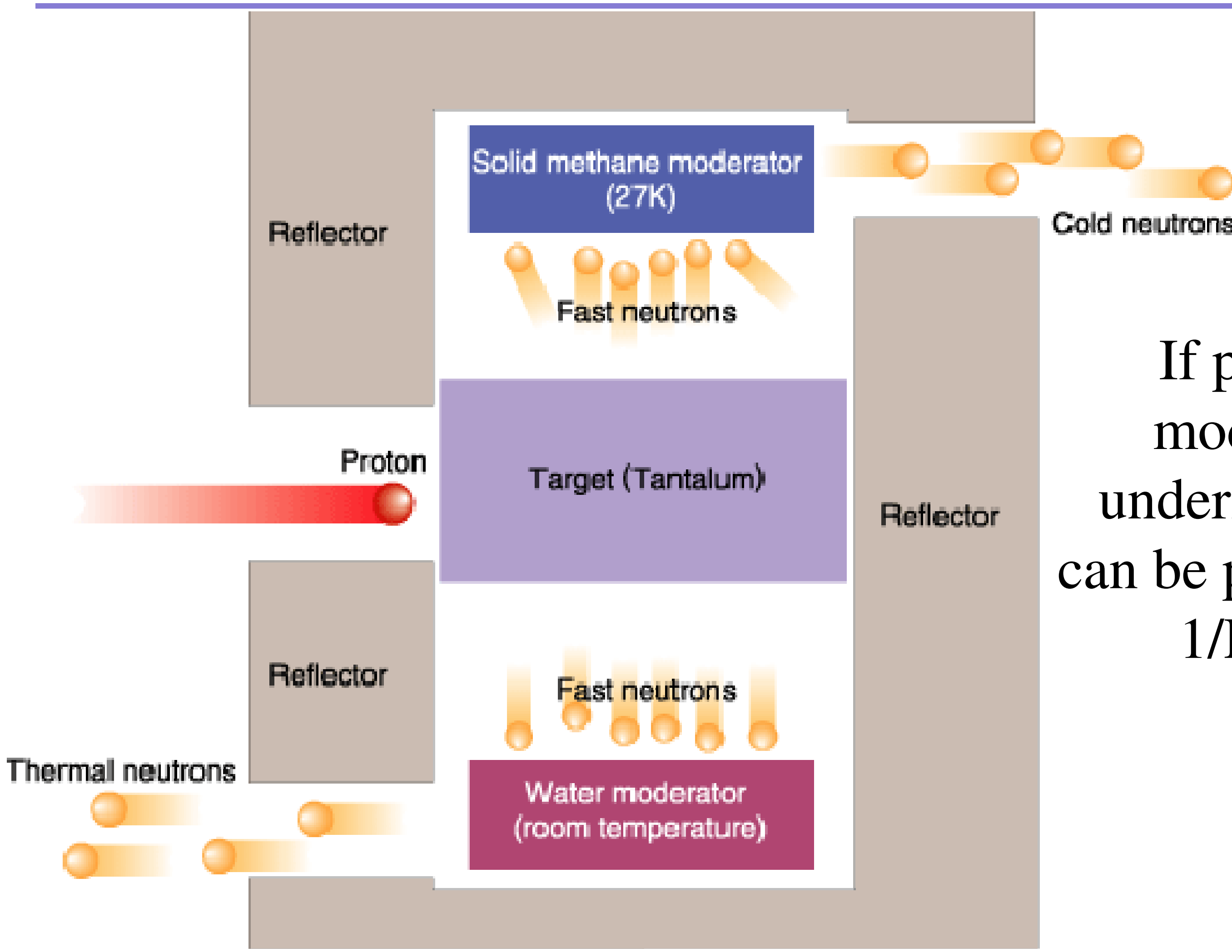


A comparison among neutron production mechanisms

	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

Neutronics of spallation neutron sources

Projectiles, targets and moderators



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

Why protons ?

$$P_n = 1 - \exp(-R/\lambda)$$ **R**: particle range [g cm^{-2}] λ: mean free path [g cm-^{2}]

λ= 33A$^{1/3}$ for E > 100 MeV it is almost constant and for heavy nuclei its value is about 200 g cm^{-2}

R(^{207}Pb) = 705 g cm^{-2} at ***E* = 1.1** GeV (protons). If ***d*** is the target's thickness,

d **= 3λ ⇒ P$_n$ = 0.95,** for ^{207}Pb ***d*** **= 60 cm** with ***E*** **= 1.1 GeV** protons

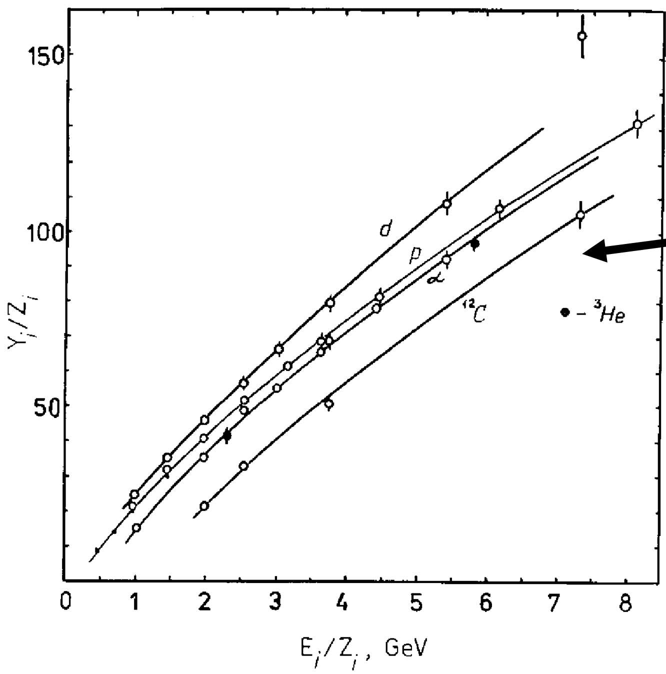


Figure 2. Measured neutron yield per charge, Y_i/Z_i, from a Pb target, 20 cm in diameter and 60 cm in length, bombarded by various light ions as a function of incident ion energy per ion charge, E_i/Z_i. For ^{3}He ions, only one measured point is given.

Fixing E, for a given ion **R ∝ A/Z^2**
Heavy ions are not suitable as projectiles as it is visible from the trend of the **Yield/charge** for different ions

Deuteron seems the best but one should considers the cost to accelerate heavy ions at about 1-2 GeV. Protons are more convenient

What energy has to be used ?

	Electrons (U target)	Protons (U target)	Reactors (U fissile target)
Reaction	Bremsstrahlung radiation	Spallation	Nuclear fission
Typical energy of the incident particles	100 MeV	800 MeV	-
Neutron Yield	5 x 10^{-2} n/e^{-}	30 n/p	1 n/fissione
Deposited Energy	2 GeV	55 MeV	180 MeV

Choice of the spallation target

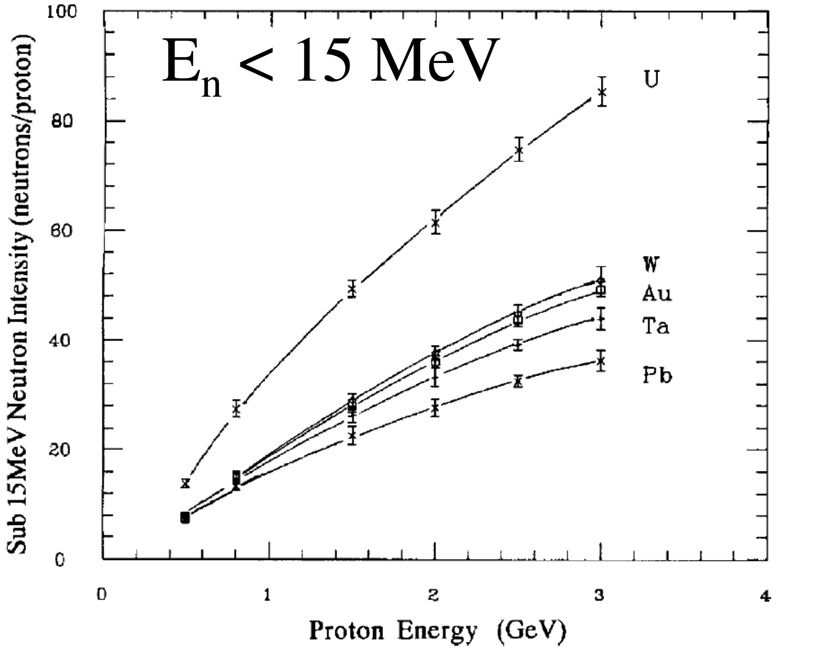
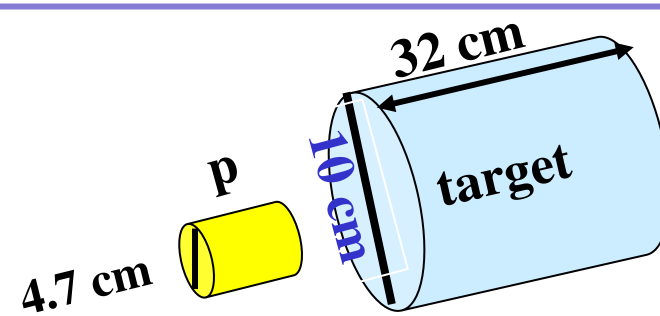


Figure 4. Calculated values of total leakage-neutrons, Y, from various bare targets as a functio of proton energy. 'Sub 15 MeV neutron' means that high-energy neutrons are not included: (onl sub 15 MeV neutrons are plotted). A cylindrical target, 10 cm in diameter and 32 cm in length, i assumed, with a cylindrical proton-beam profile of 4.7 cm in diameter.



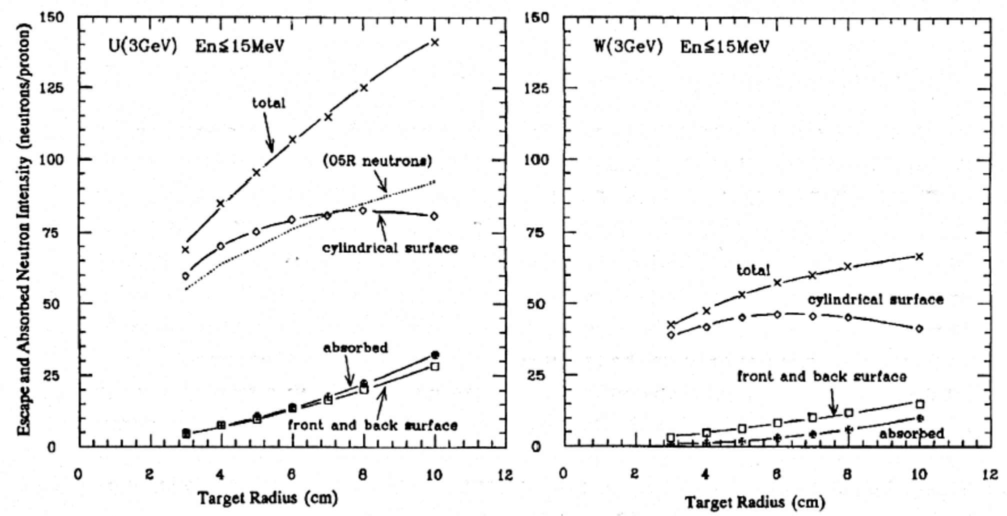
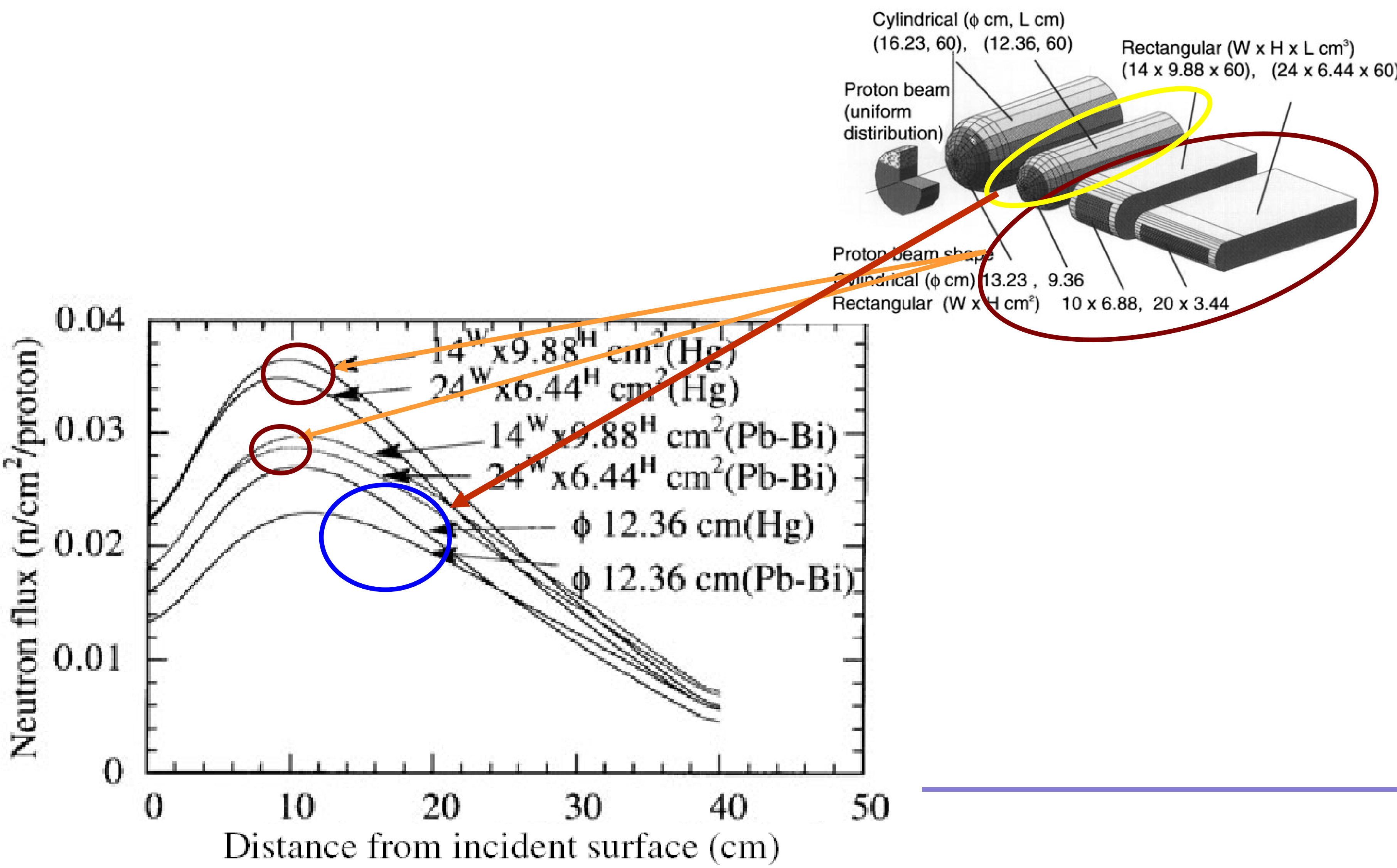


Figure 5. Calculated values of source neutrons (sub 15 MeV neutrons) directly produced by the spallation reaction (the so-called O5R neutrons), total neutron production in target including secondary neutron production by (n, xn) reactions, etc, neutron losses by absorption and escape from front and back surfaces, and resulting leakage-neutrons from cylindrical surface, as a function of target radius. Two different targets, U (left) and W (right), are compared for the case $E_p = 3$ GeV.

Effect of the geometry



Deposited power into the target

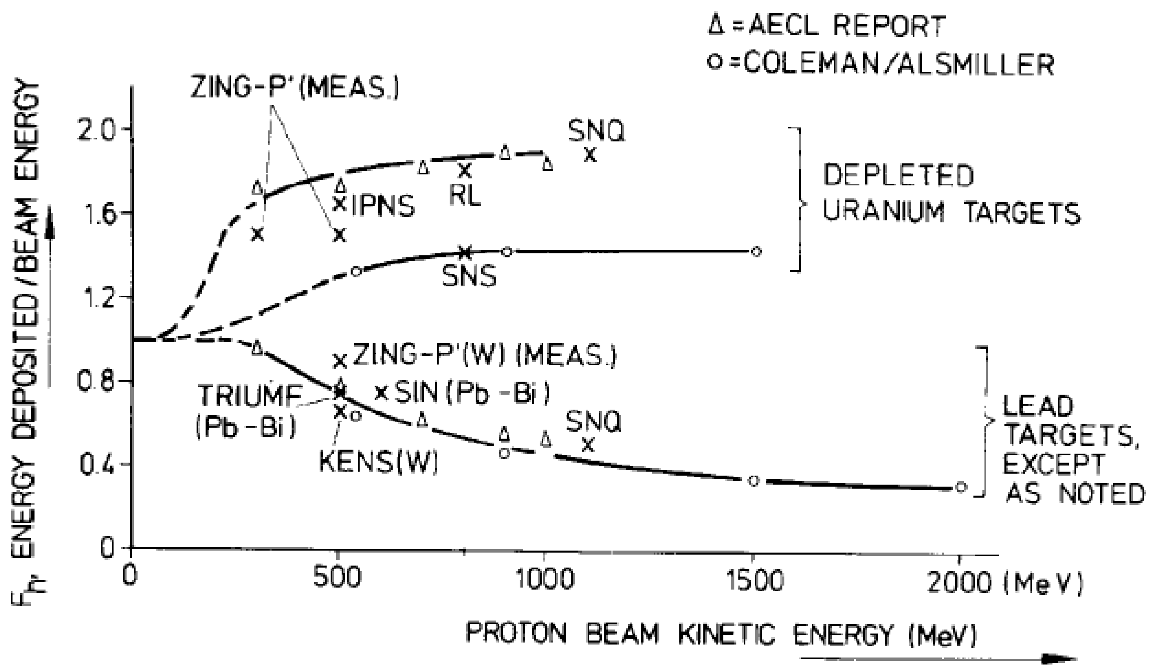
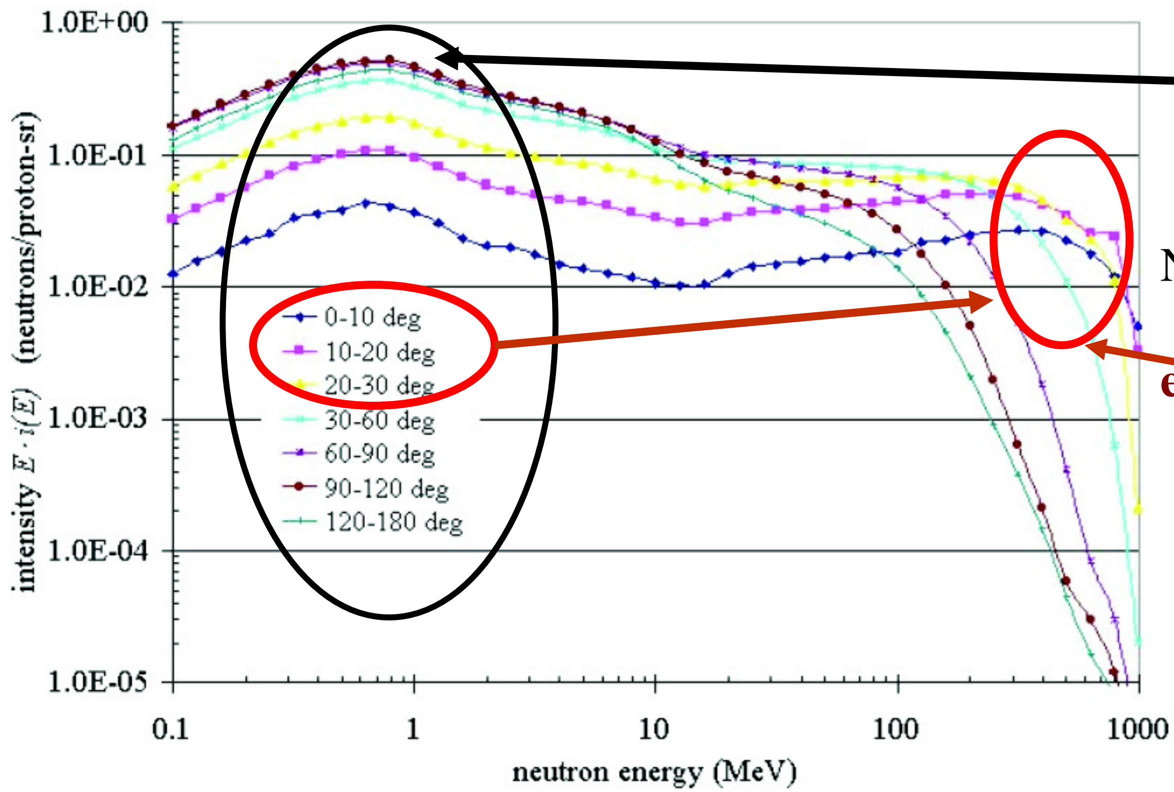


Figure 8. Calculated values of fractional energy deposition in the target to the proton-beam energy, F_h, as a function of proton kinetic energy (E_p). SNS and SIN mean the present ISIS and SINQ, respectively. Data labelled 'MEAS' are measured values.

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.

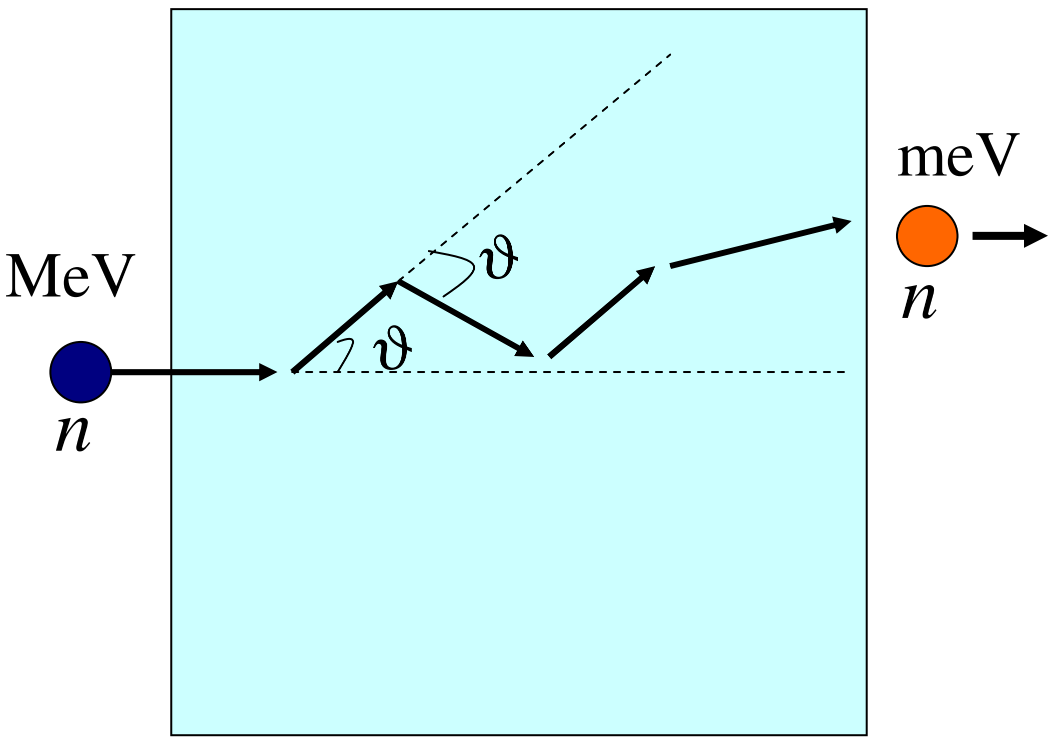


Neutrons from the evaporation phase (**low energy**) are mostly isotropically distributed

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

Moderators

Letargy



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

ξ: **<lnE$_0$/E>$_{d\Omega}$** 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

Target-moderator coupling

High fluxes but the input port of the beamline "sees" the target (intense n and γ background

Fluxes lower by a factor of about 2 but the beamline does not "see" the target (lower background)

Mostly used with vertically incident protons pulses

For a moderator at room
by semi

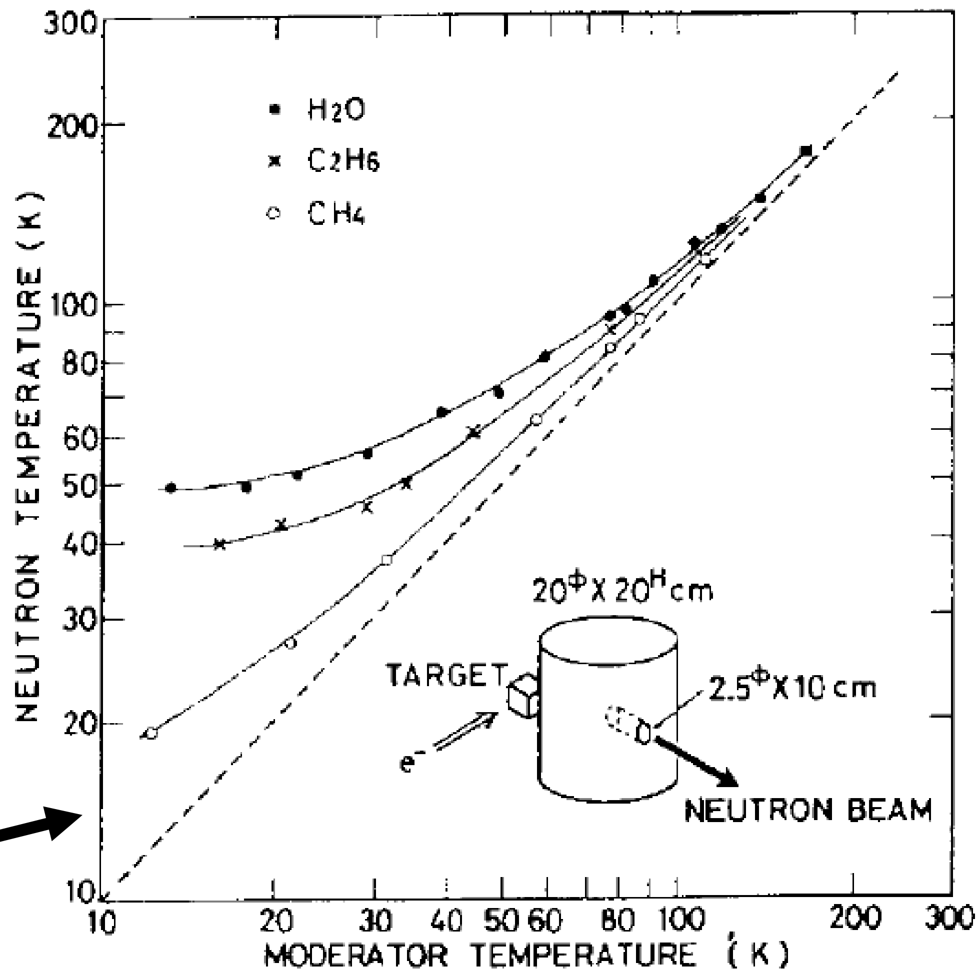
$$E\phi(E) = E\phi_{th}(E) + \Delta(E)\text{c}$$

$$E\phi_{th}(E) = J\left(\frac{E}{E_T}\right)^2 exp\left(-\frac{E}{E_T}\right.$$

$$E\phi_{epi}(E) = \phi_{1eV}\left(\boldsymbol{E}_{1eV}\right)^{\alpha}$$

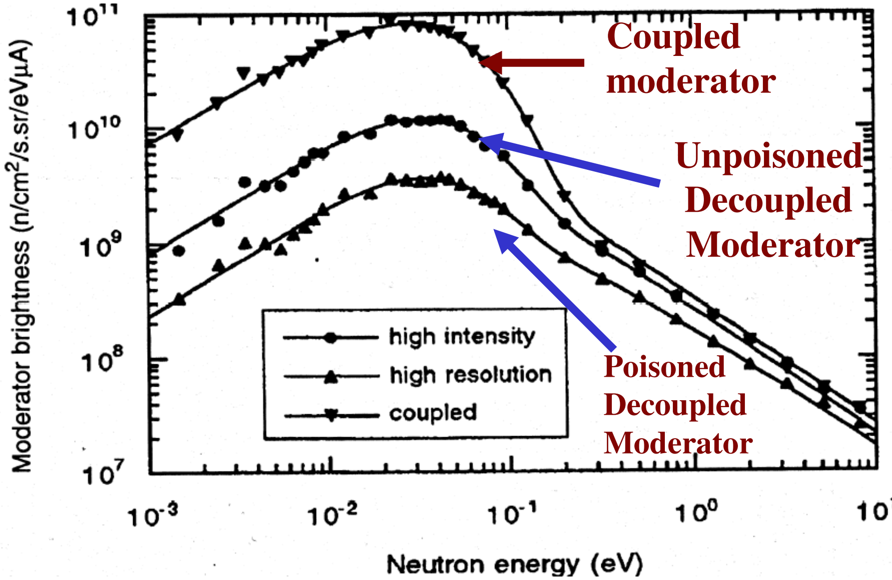
$$\Delta(E) = \left[1 + exp\left(aE^{-1/2} - b\right)\right]$$

$$E_T = k_B T_N$$



Energy Spectra

H_2O Moderator



H_2 Moderator

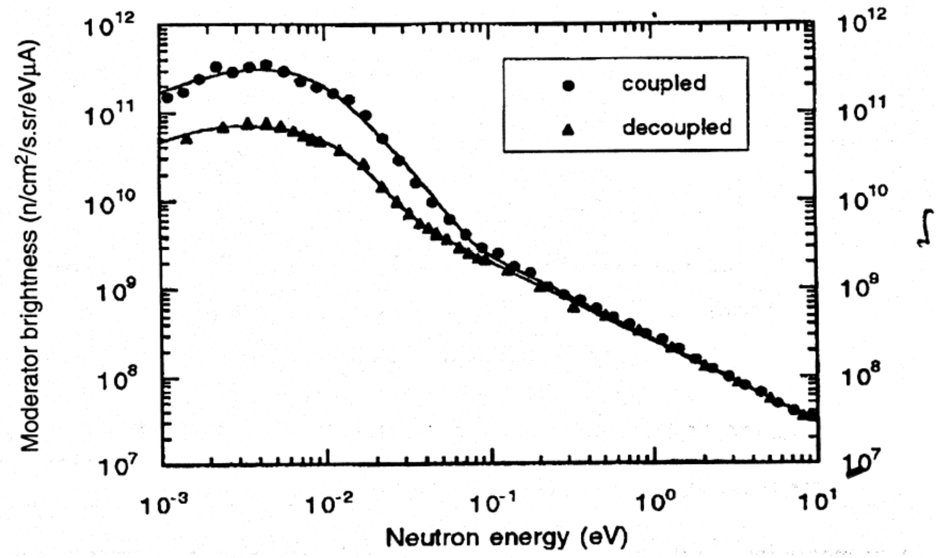
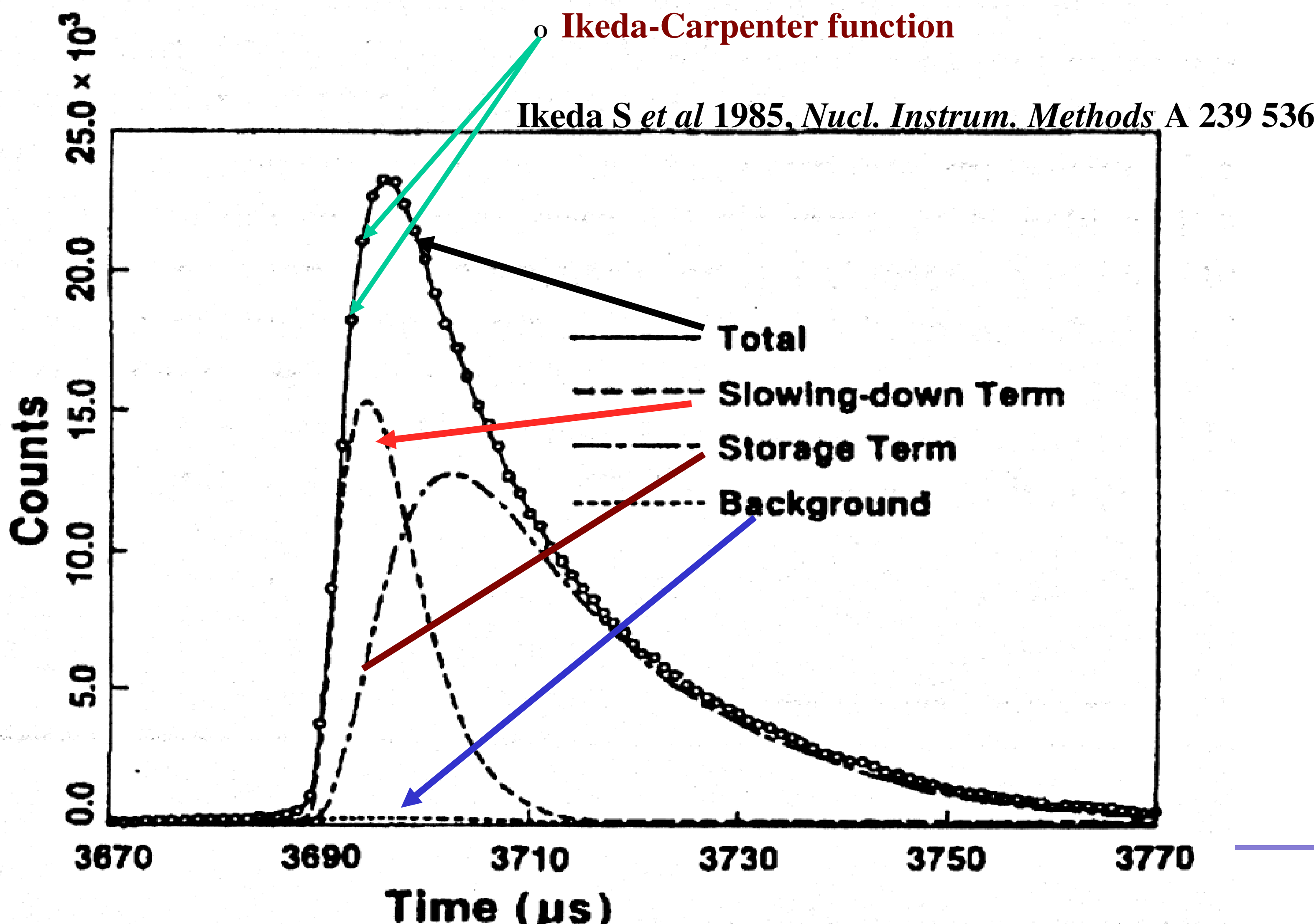


Figure 19. Measured energy spectra from three H_2O moderators with fits by equation (5.1) (upper) and those from two H_2 moderators with fits (lower). For the definition of coupled and decoupled moderators, see section 5.2: 'high intensity' and 'high-resolution' mean decoupled unpoisoned and poisoned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

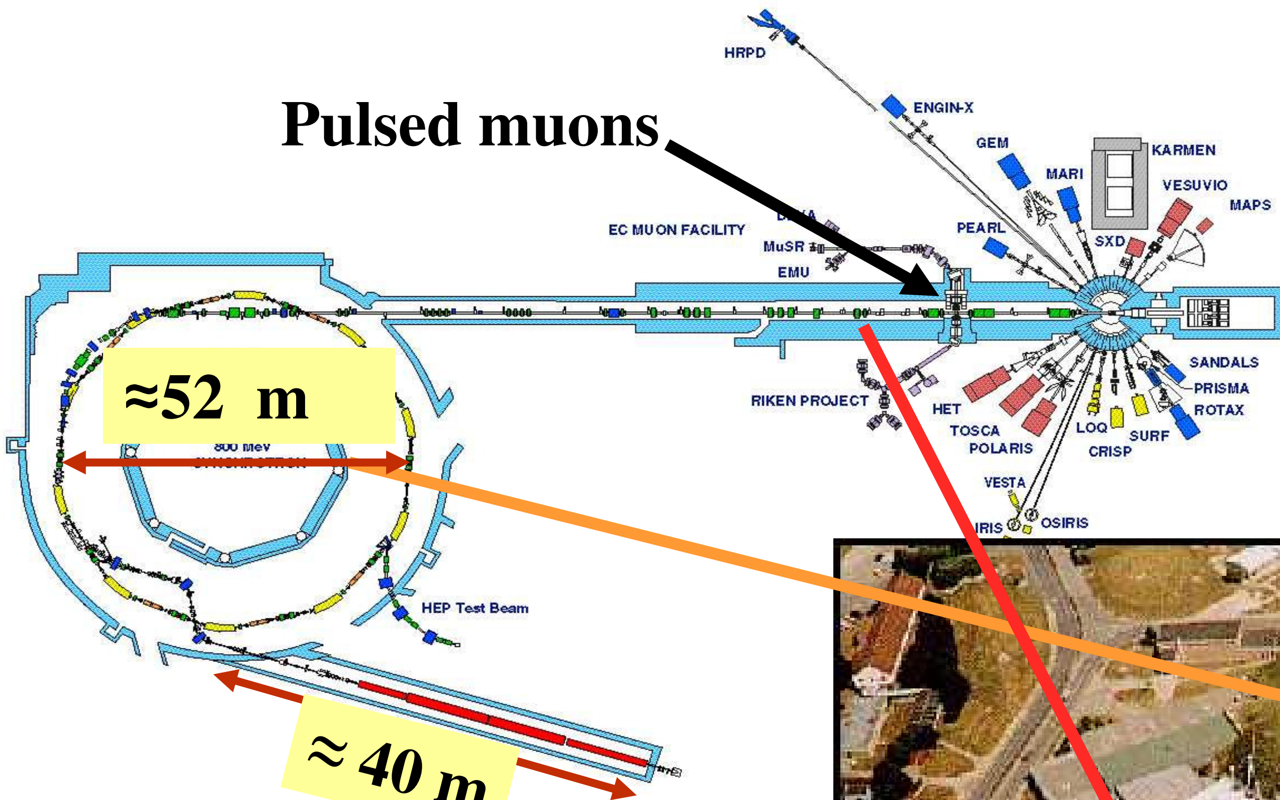
$$\tau_p = \frac{1.2}{\sqrt{E(eV)}}\,\mu\text{s}$$

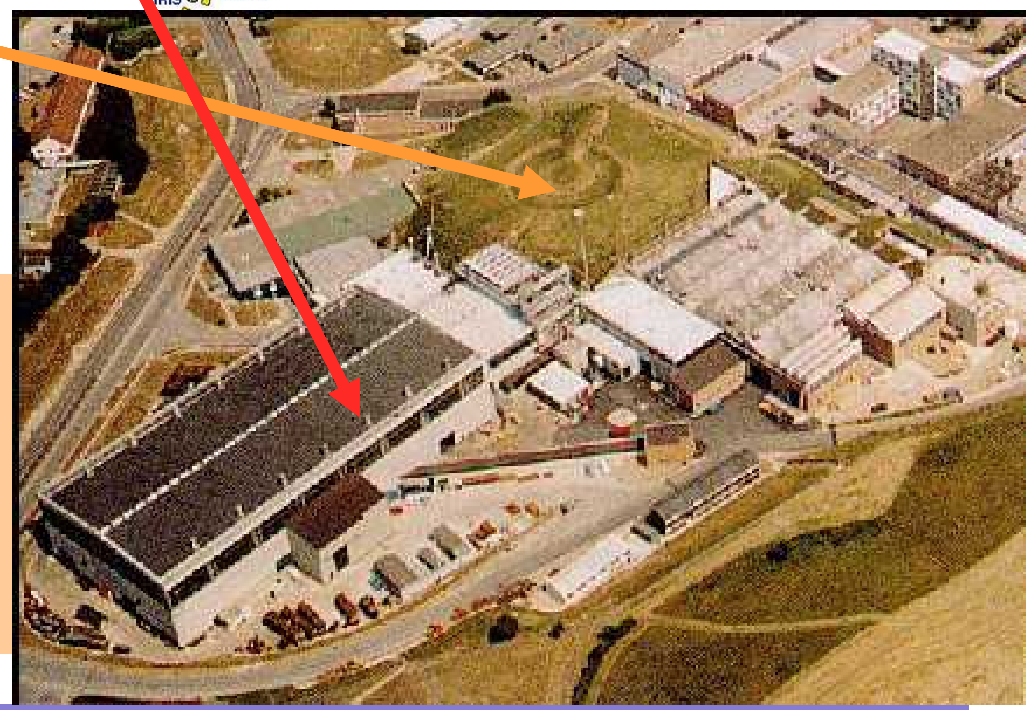
FWHM of the neutorn pulòse at the energy *E* in the "slowing down" region

Pulse shape of neutrons



ISIS pulsed neutron source





Neutron production at ISIS:

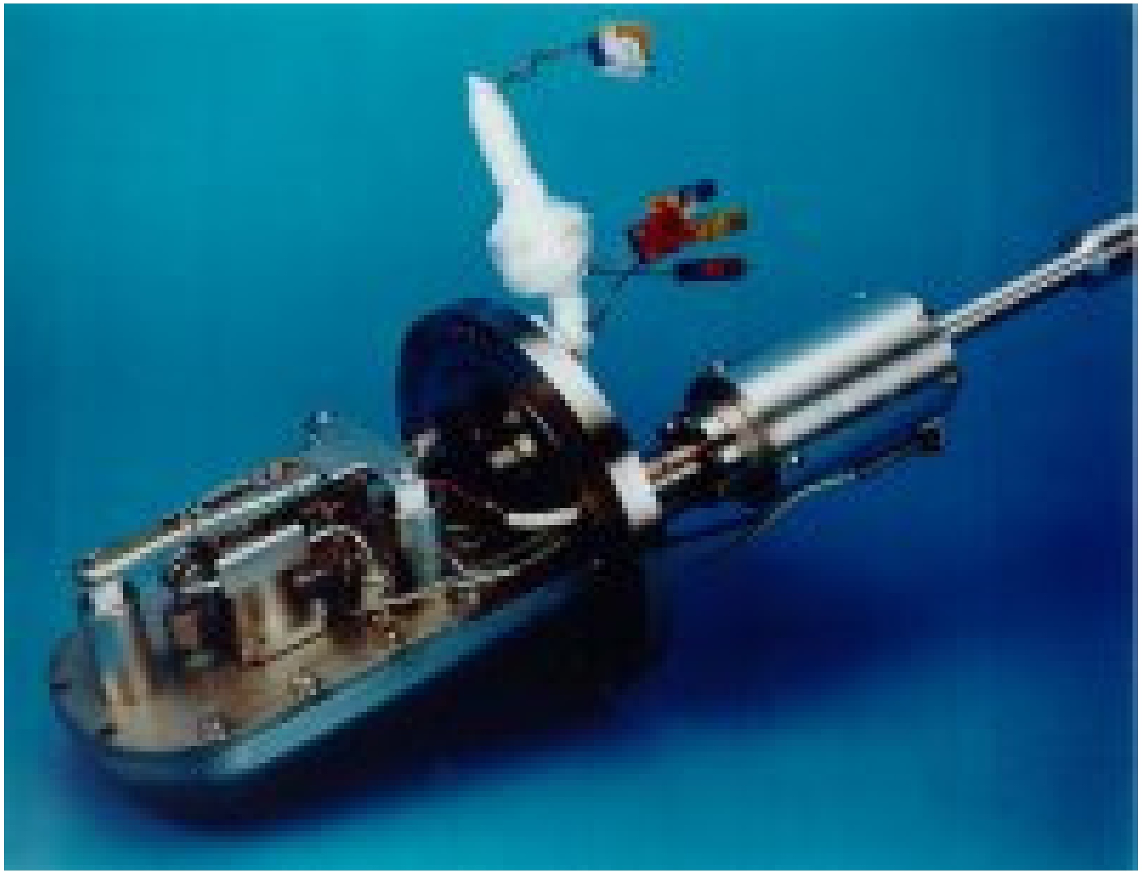
800 MeV protons

I ≈ 200 μA

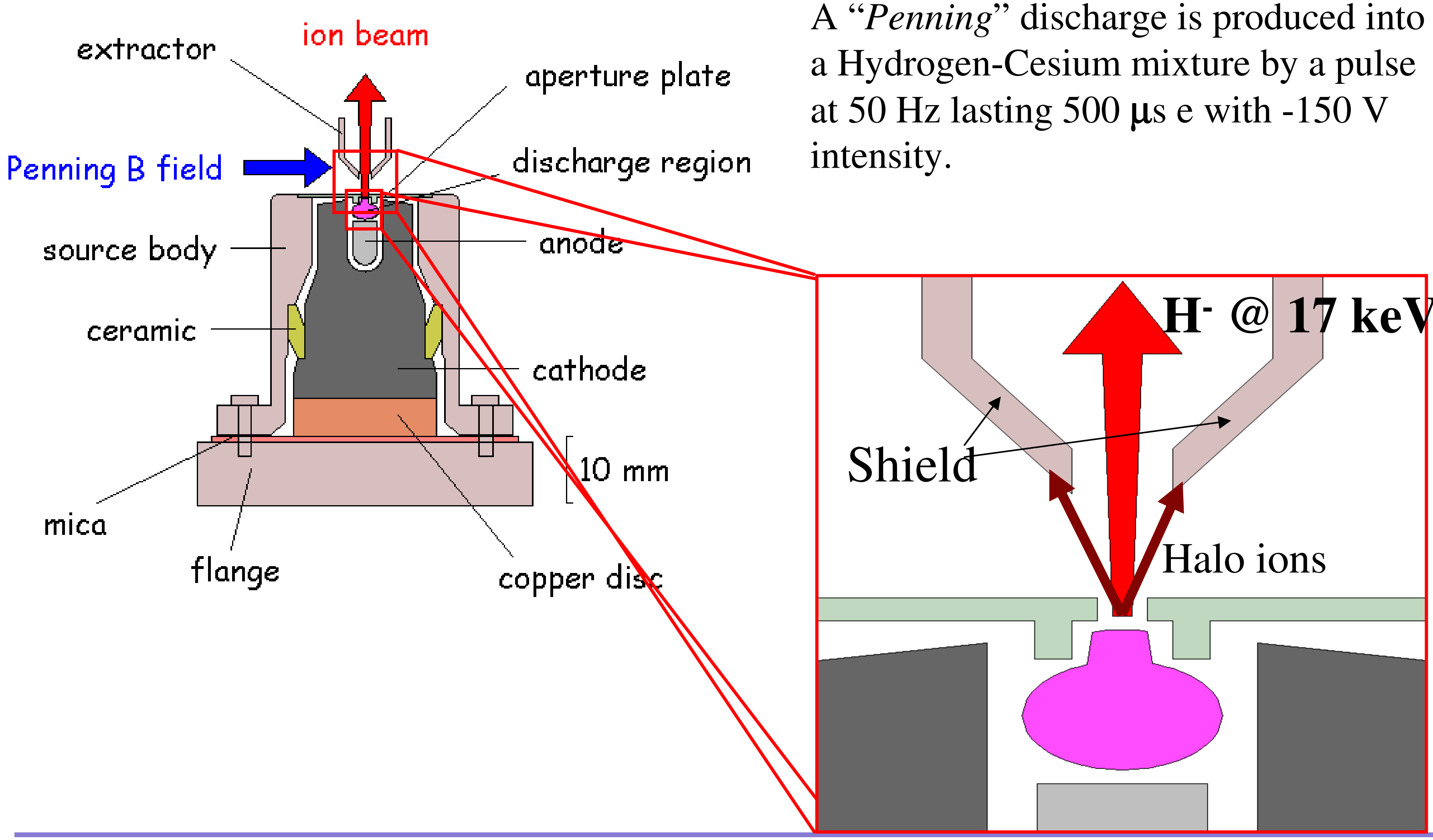
P = 160 kW Power deposioted onto the W target

$\phi \sim 2 \times 10^{16}$ n/s

The ion source



Ions formation from a plasma

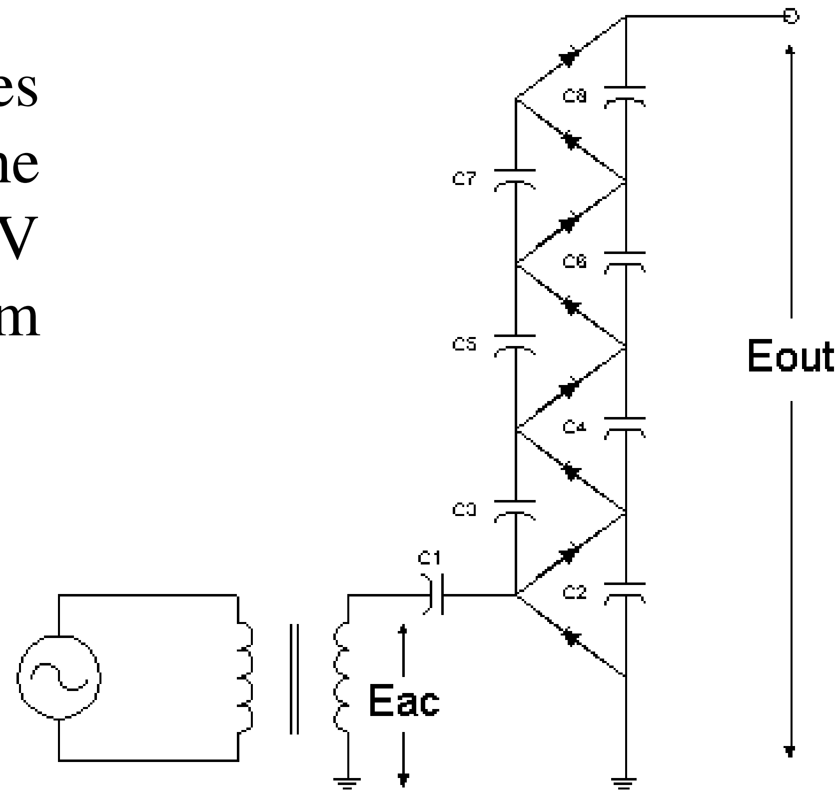


A "*Penning*" discharge is produced into a Hydrogen-Cesium mixture by a pulse at 50 Hz lasting 500 μs e with -150 V intensity.

The OLD Cockcroft-Walton

- DC accelerator
- 10-stage voltage multiplier (5.5 kHz)

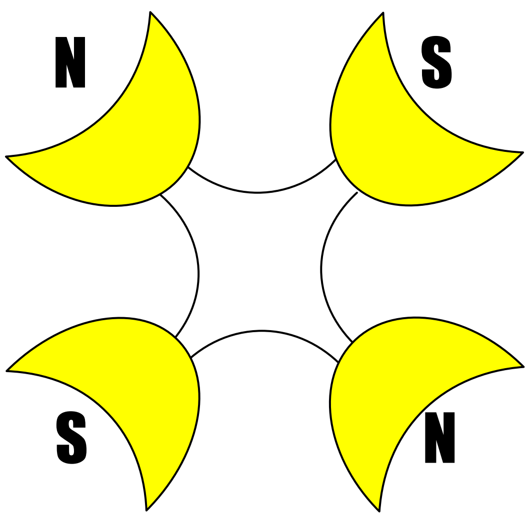
Cockcroft-Walton accelerates H^- ions from 6 keV (from the source) to about a circa 665 keV (I ≈35 mA) before beam injection into the **LINAC.**



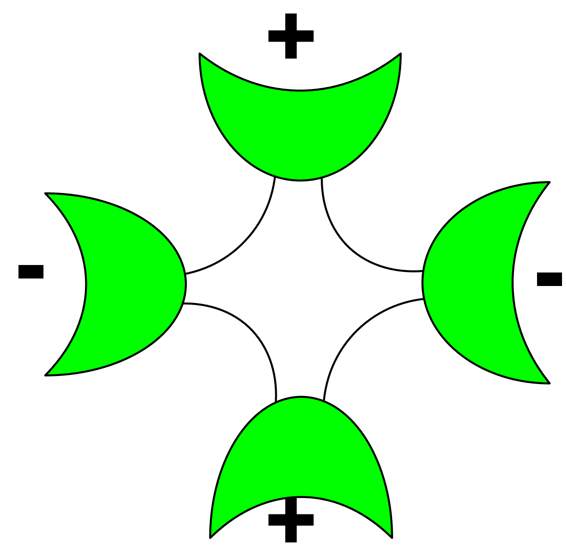
The RFQ Acceleration stage

The Quadrupole Lens

Magnetic Quadrupole Lens

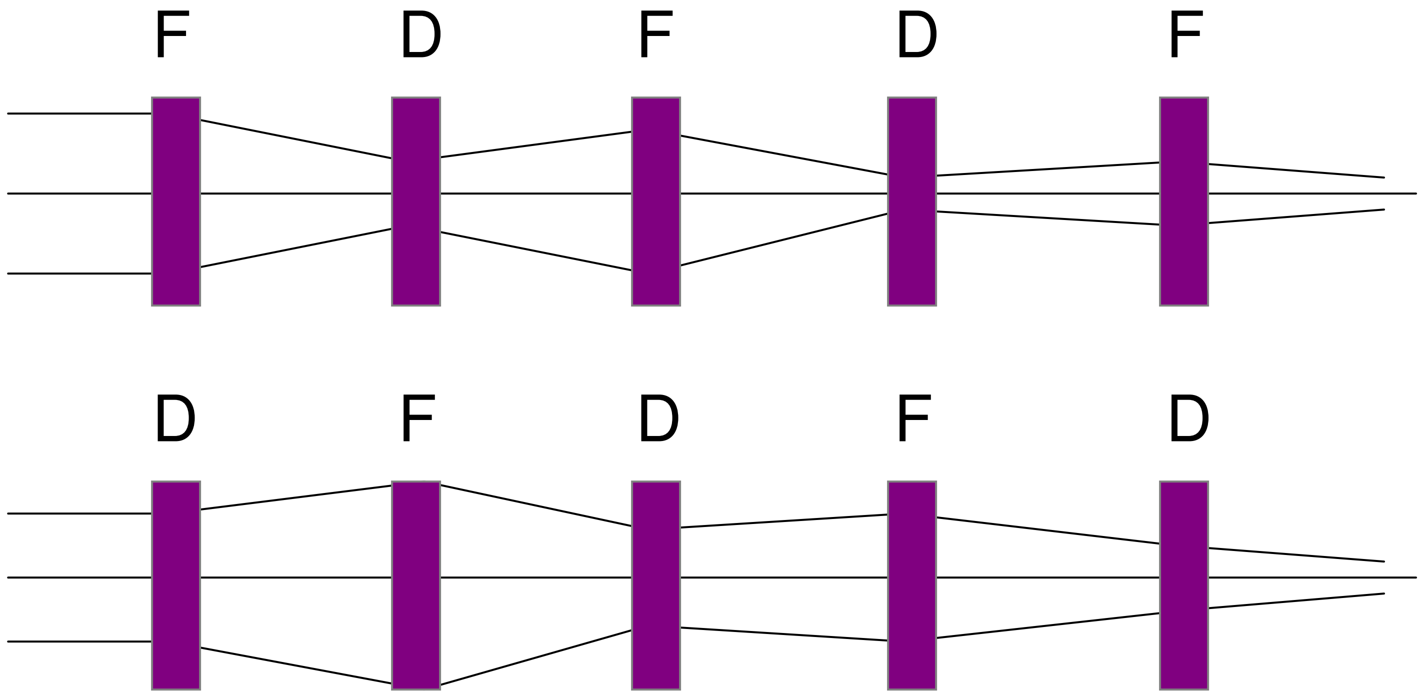


Electric Quadrupole Lens



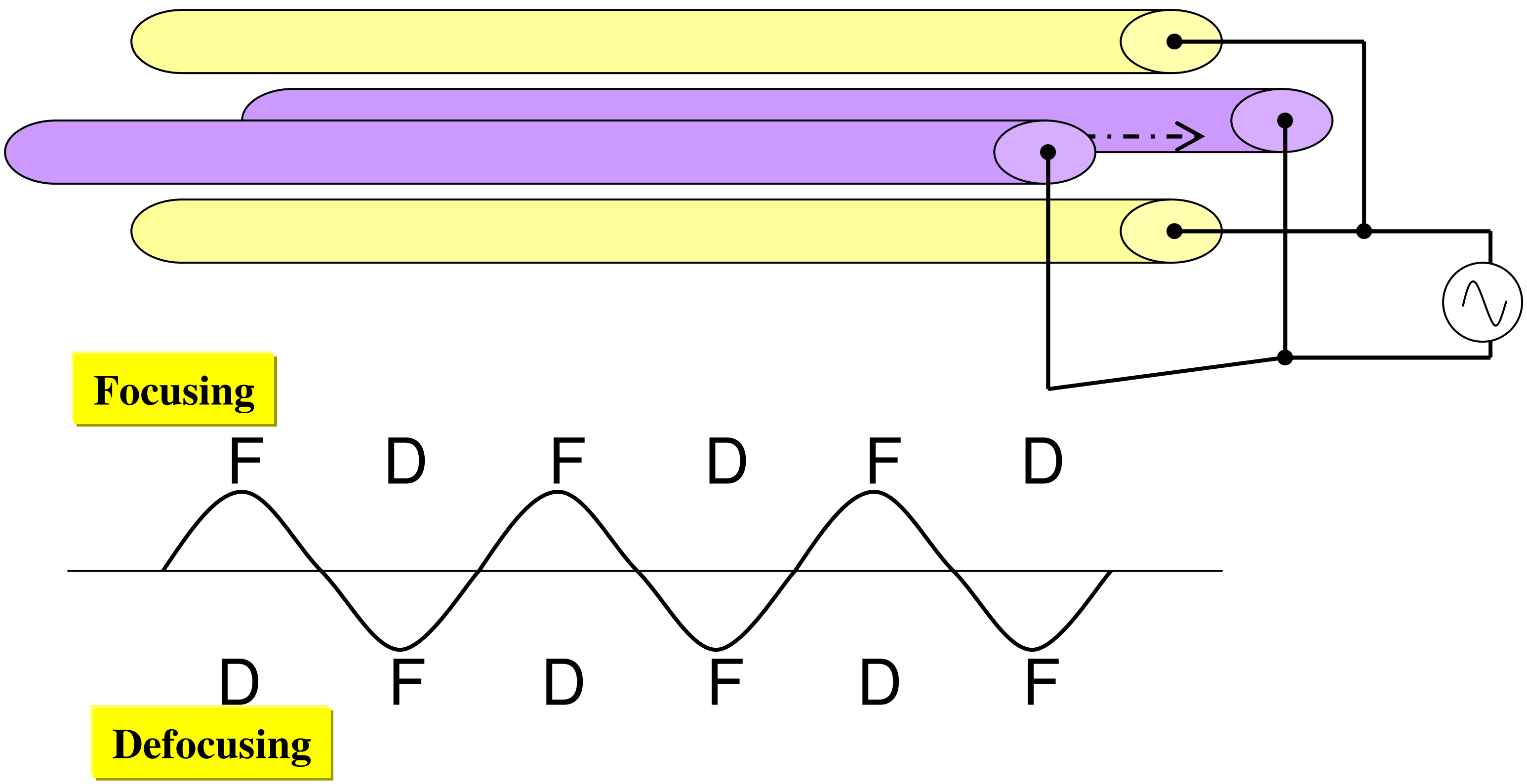
Focusing in one plane, de-focusing in the other

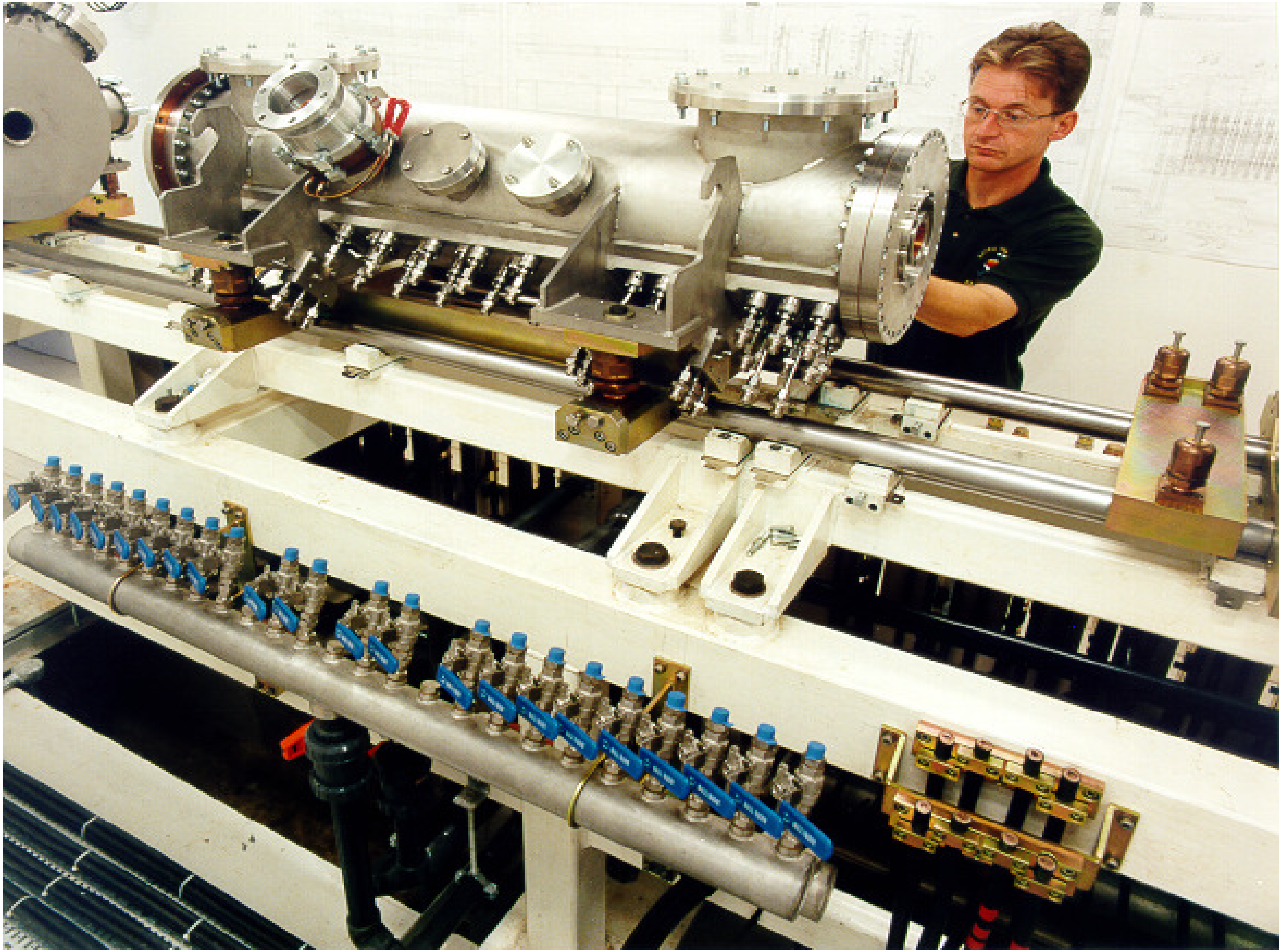
Alternating Gradient Focusing



Net focusing can be achieved by a system of focusing and defocusing elements

Radio Frequency Quadrupole





The LINAC

Caratteristiche principali

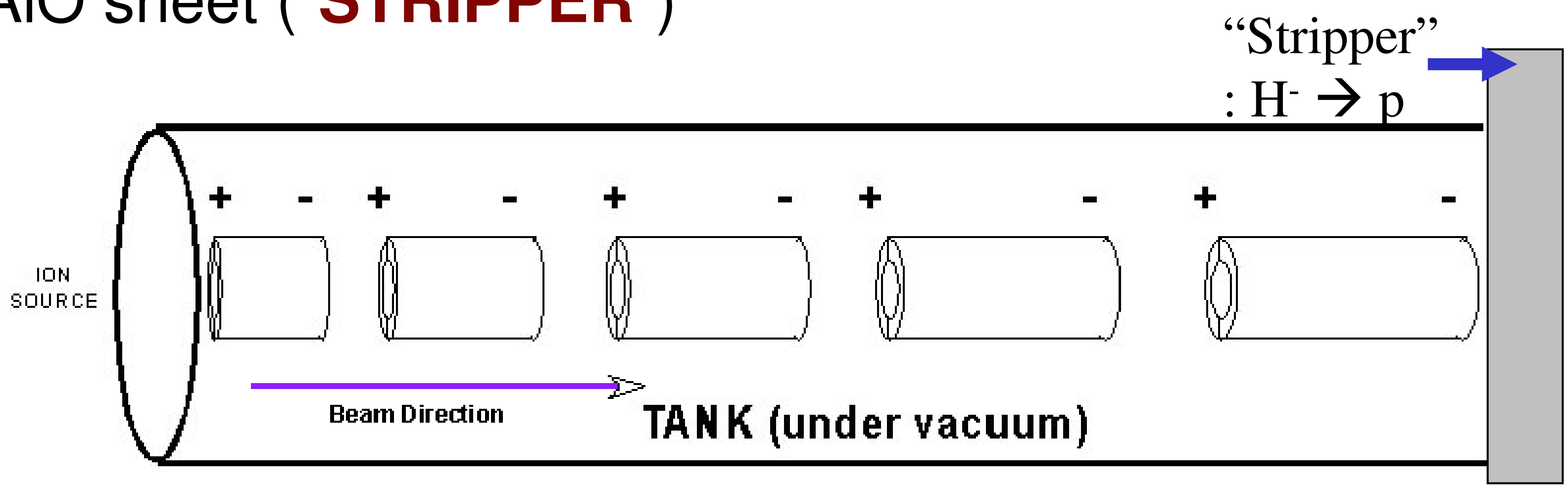
$L_{Linac} \approx$ 40 m

4 accelearation stages "drift tubes": **$L_{DT} \approx$ 10 m, $\phi \approx$ 1 m**

Acceleration method: **RF @ 202.5 MHz**

$E_{f,H^-} \approx$ 70 MeV

Before injection into the synchrotron $H^- \rightarrow p$ by means of a AlO sheet ("**STRIPPER**")



The Synchrotron

Caratteristiche principali

$R_{eff} \approx$ 26.0 m

Magnets: to tilt the proton trajectory (Lorentz force)

$B \approx 0.17–0.71$ T

RF electric fields to accelerate protons

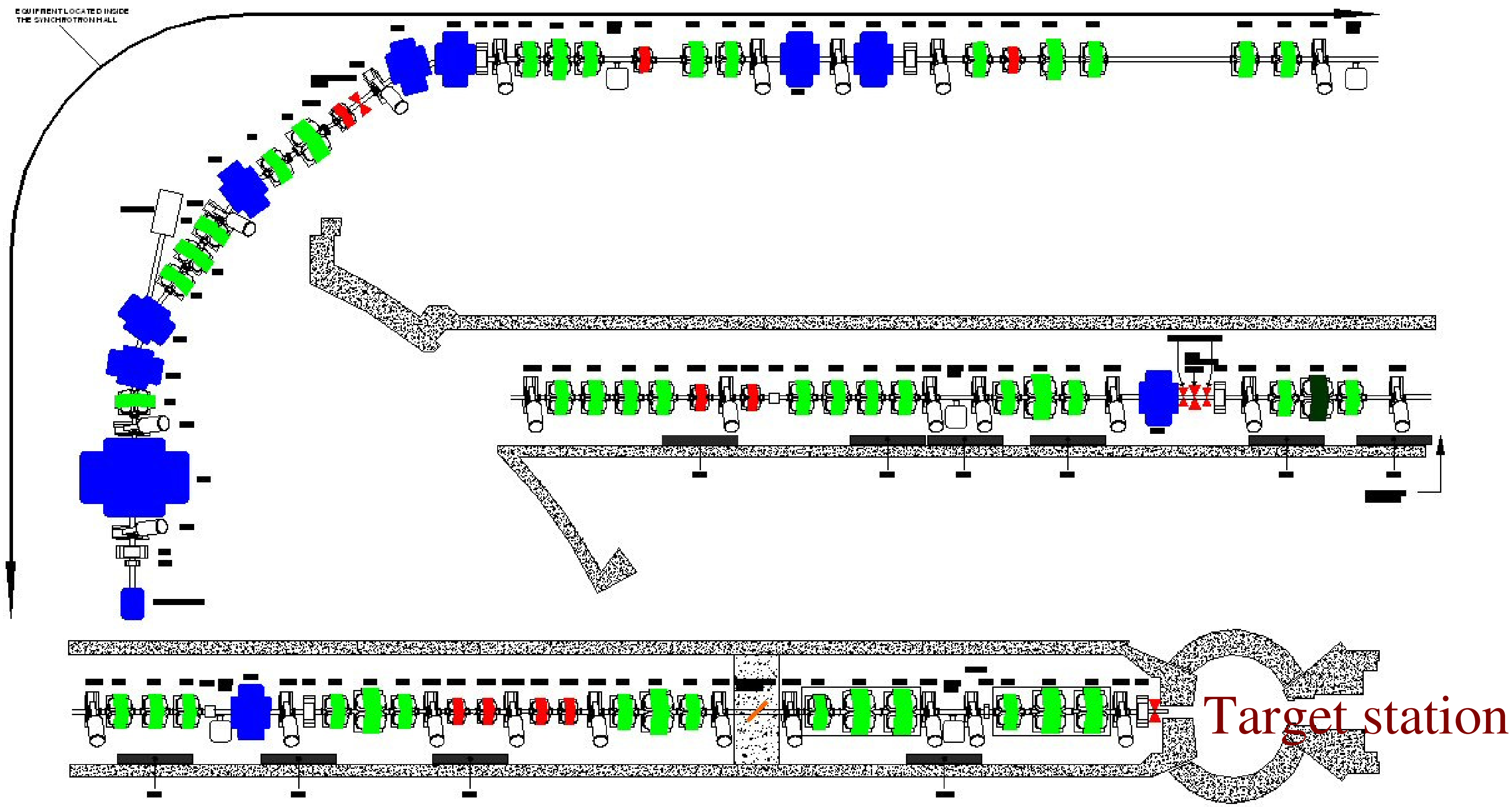
RF: 1.3–3.1 MHz

Intensity of the magnetic field, the frequency, the amplitude and pahse of the RF have to synchronised to obtain proper acceleration. The synchrotron packs protons into bunches.

F = 50 Hz

$E_{f,p} \approx$ 800 MeV

$P \approx$ 1 MW max



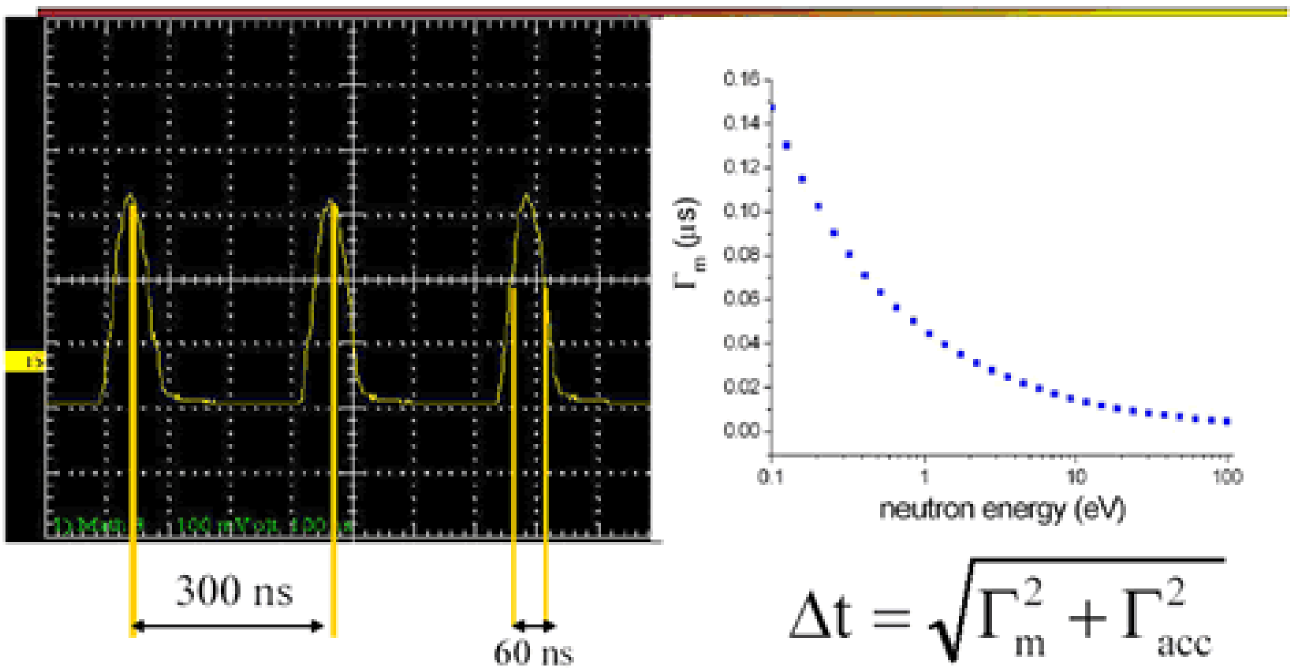
EXTRACTED PROTON BEAMLINE

All beam in synchrotron extracted in one turn

β = v/c = 0.84, 163 m circumference $\rightarrow$ revolution time = 0.65 μs

4 μC ÷ 0.65 μs $\rightarrow$ 6 A circulating current

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



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

The target station

Caratteristiche

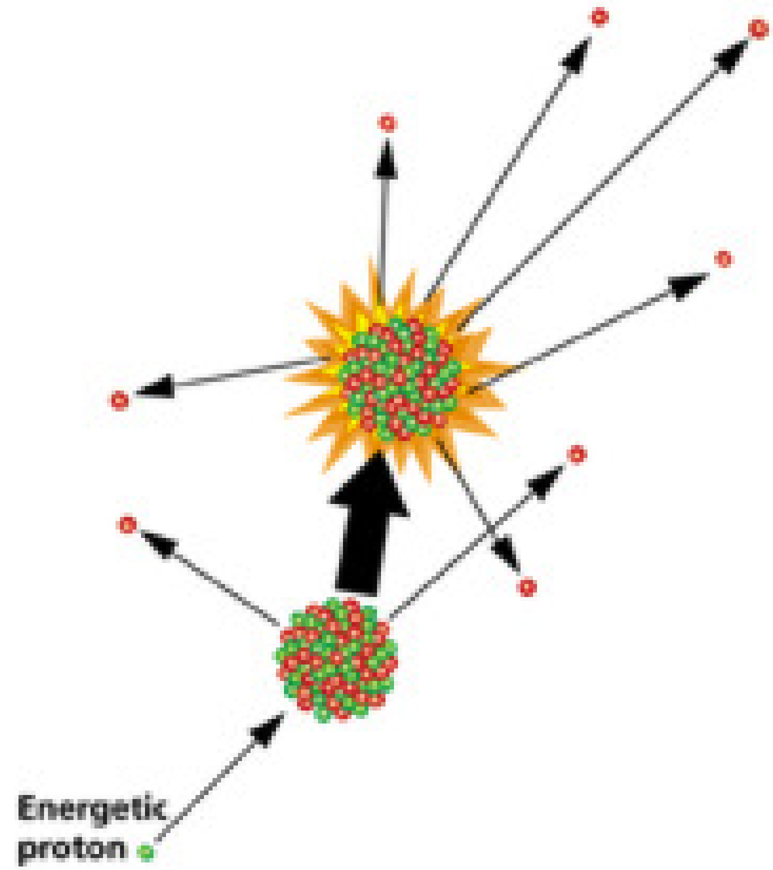
~**2.5×10^{13} protons**

(Q ≈4 μC) per pulse onto a W target

(50 pps → F = 50 Hz)

~**15–20 neutrons/ proton**

~**4×10^{14} neutrons/pulse**



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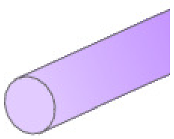

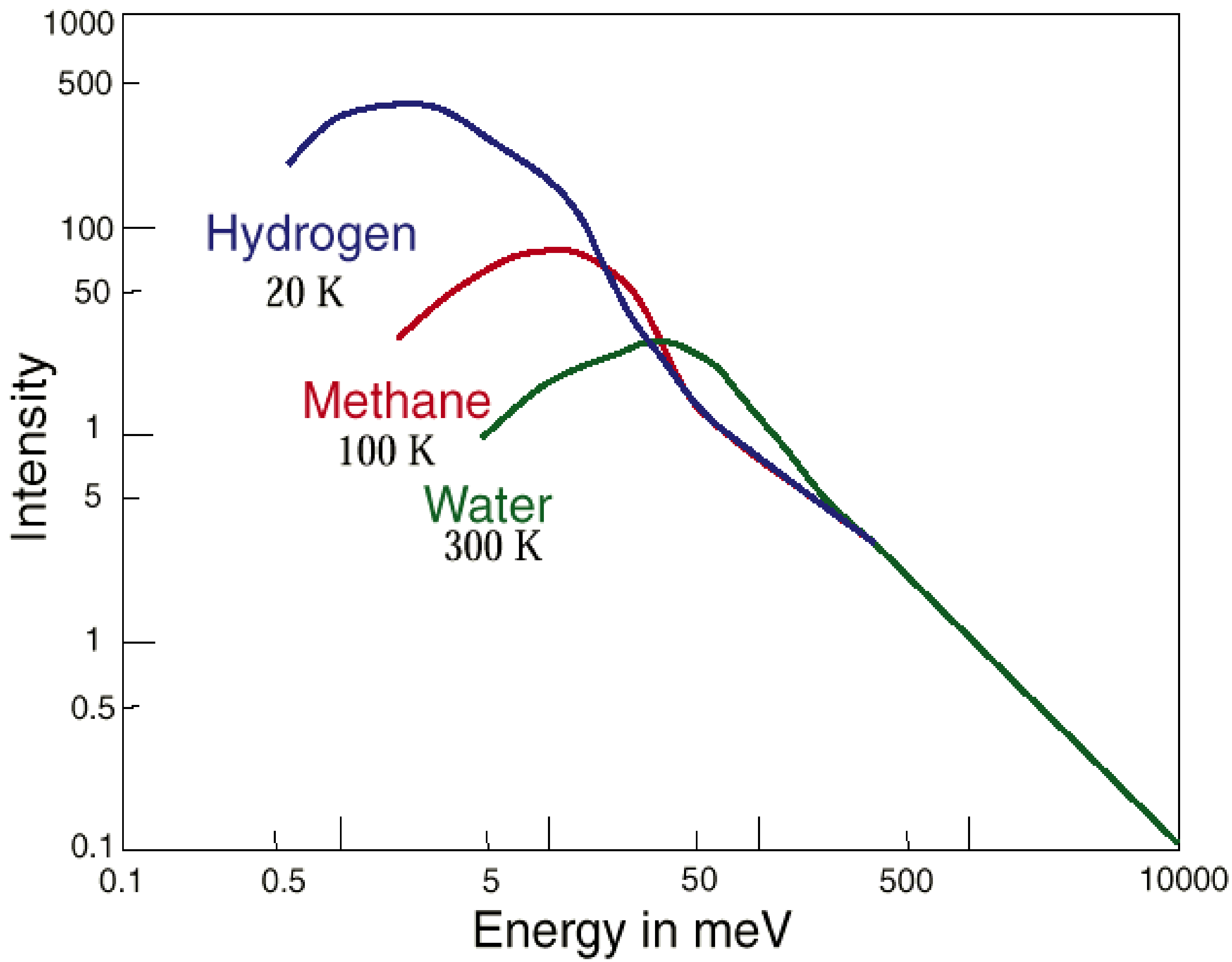

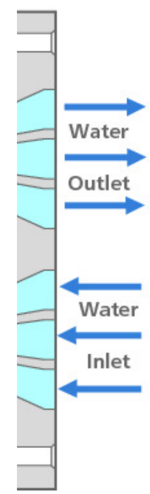

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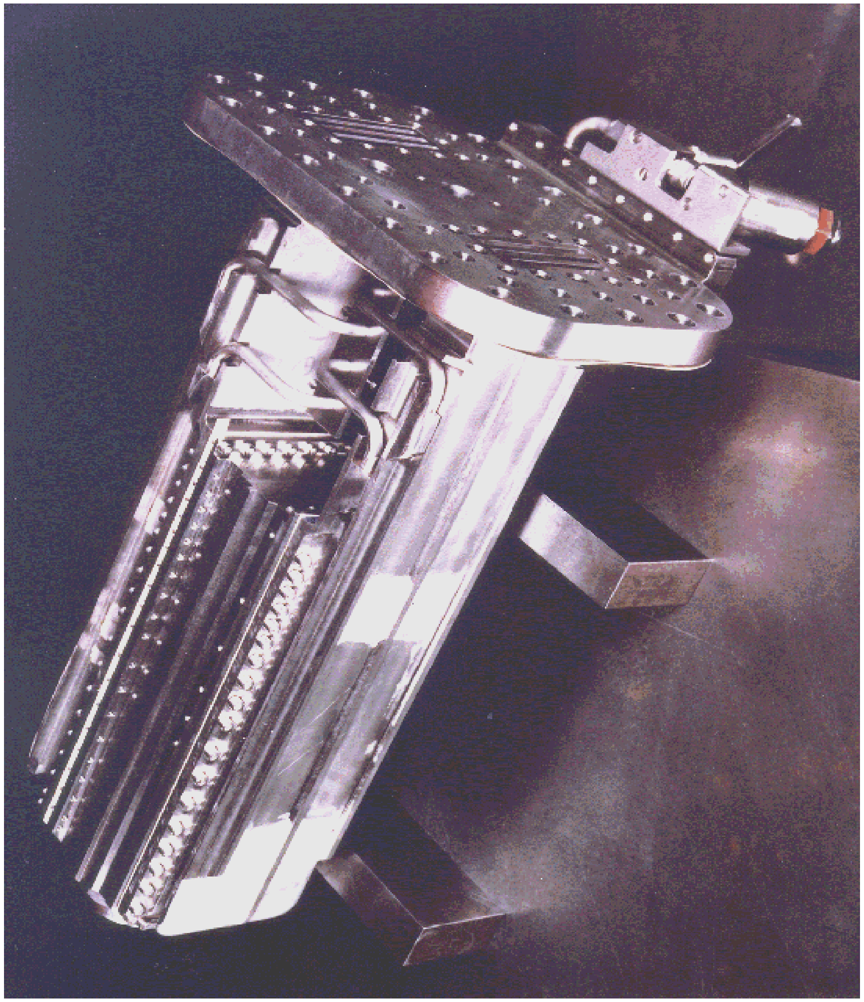
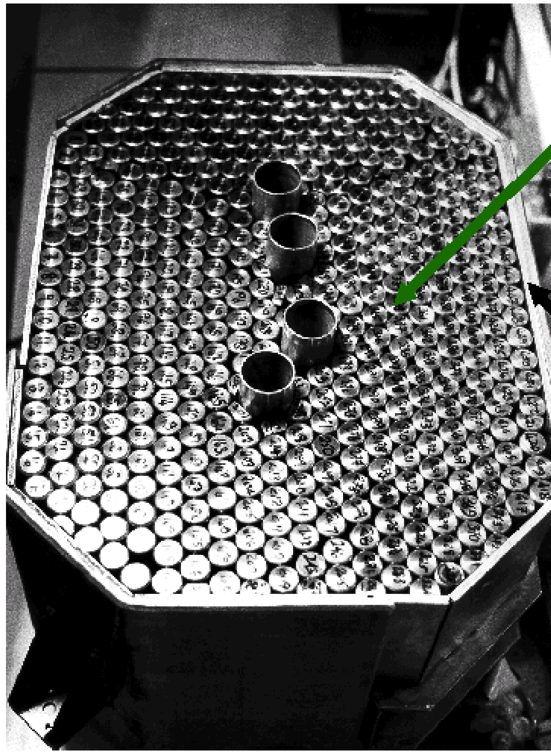
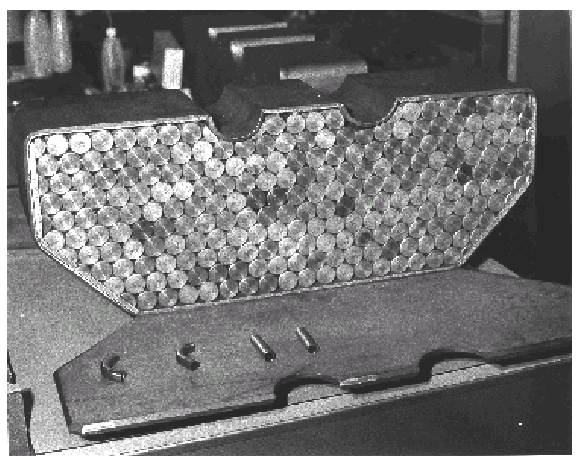
THE ISIS TARGET



The ISIS Reflector





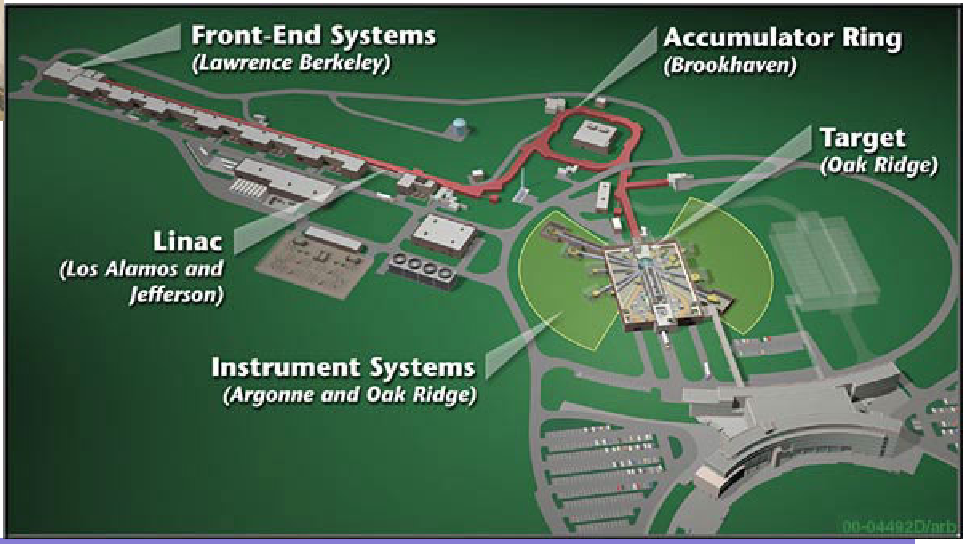
ISIS spallation neutron source

Spallation sources worldwide

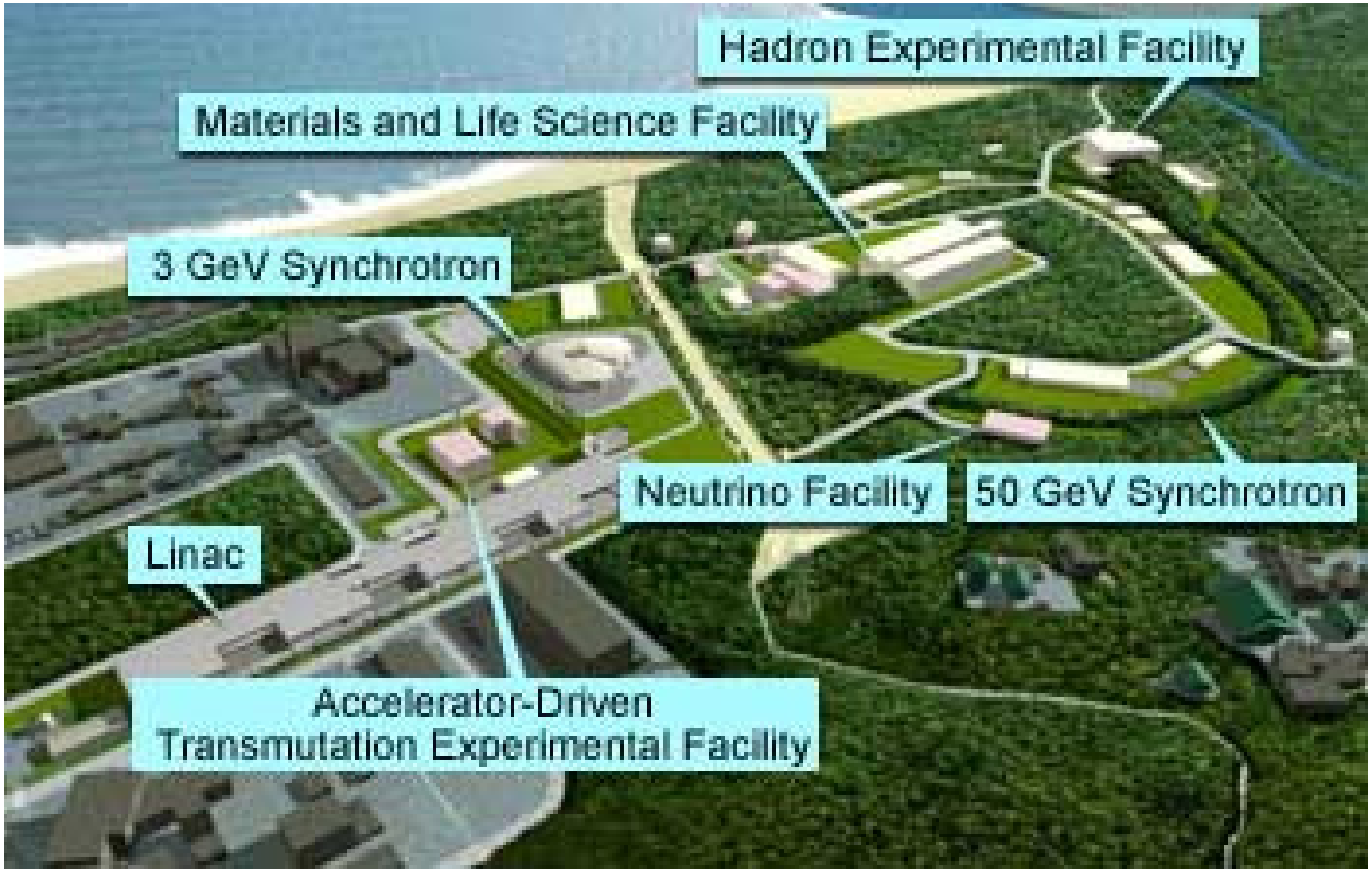
………present and future

STFC-ISIS
United Kingdom

Spallation Neutron Source (SNS) United States of America

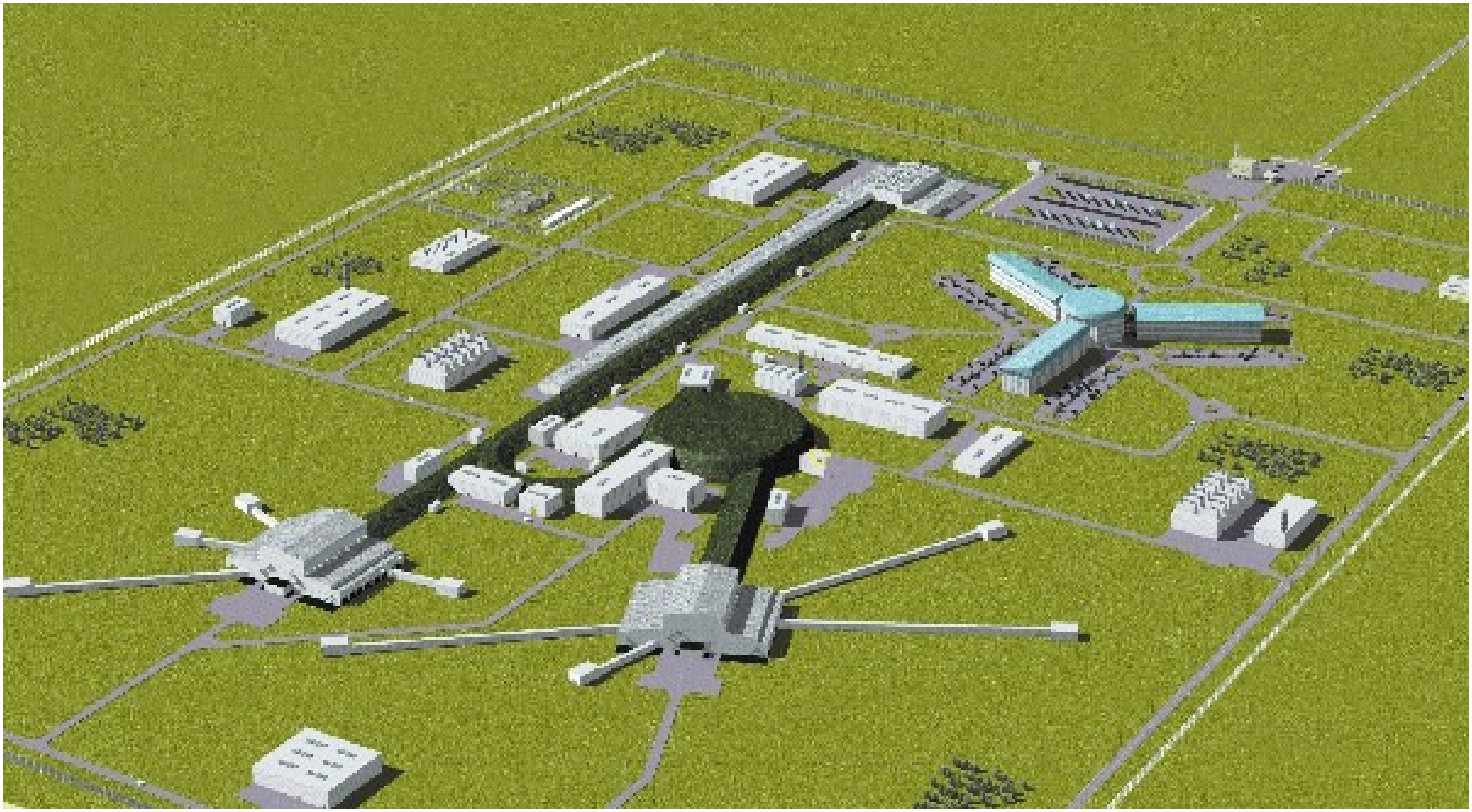


J-PARC
Japan



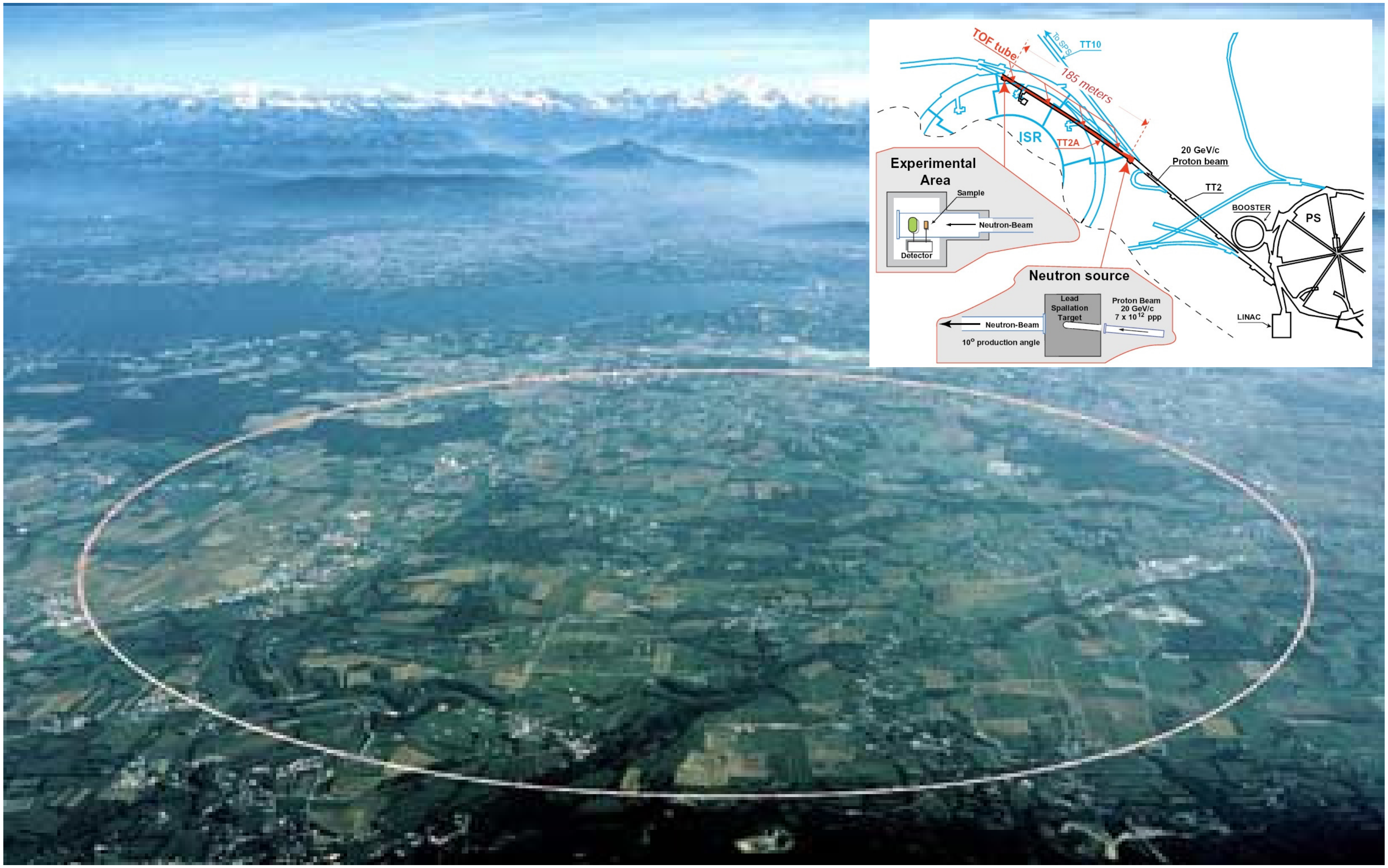
Hadron Experimental Facility
Materials and Life Science Facility
3 GeV Synchrotron
Neutrino Facility
50 GeV Synchrotron
Linac
Accelerator-Driven
Transmutation Experimental Facility

European Spallation Source (ESS) Sweden



Paul Sherrer Institute (PSI)
Switzerland

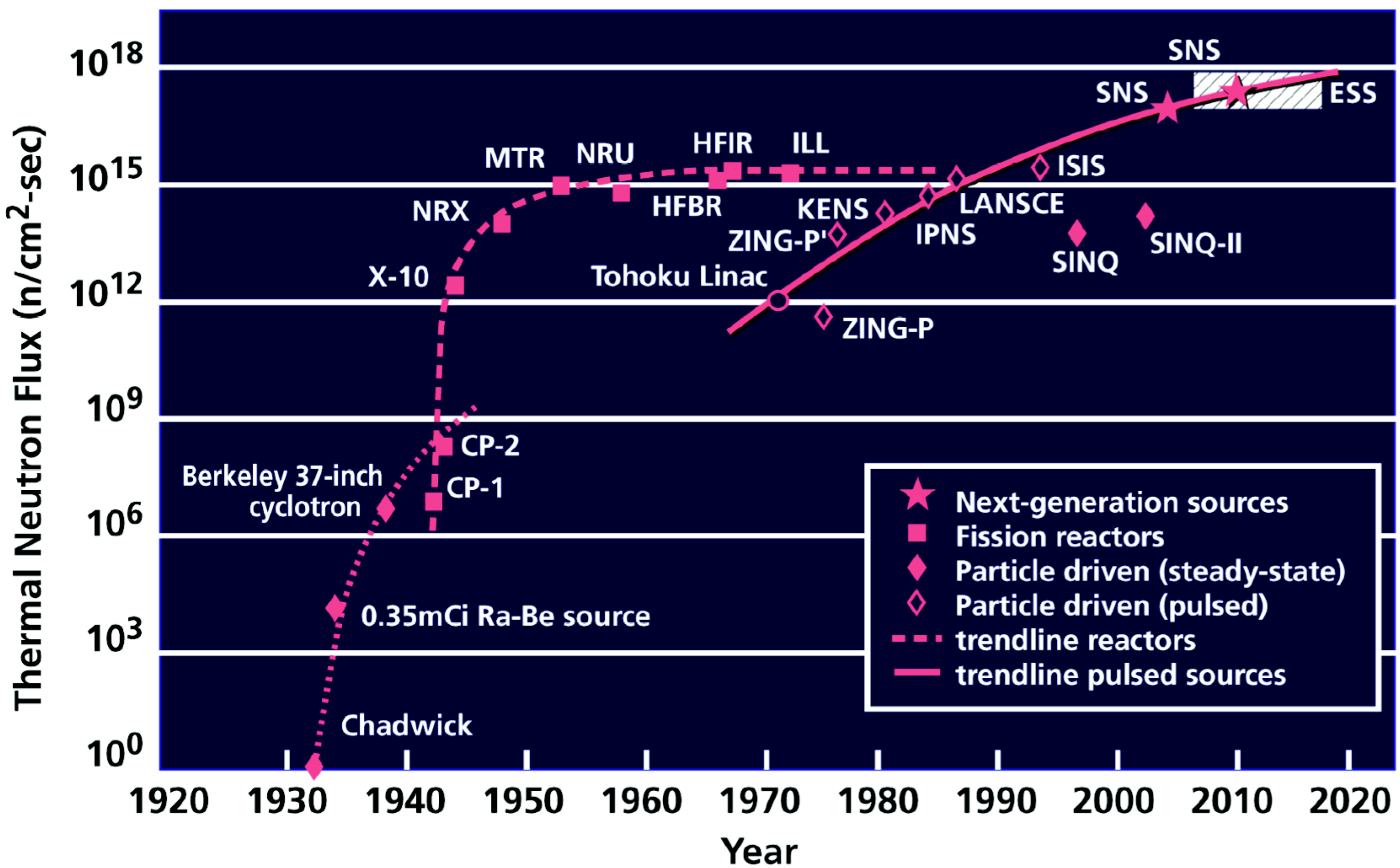
nTOF @ CERN
Switzerland



China Spallation Neutron Source (CSNS) China

In coclusion……………..

Development of spallation sources



A few useful references

- C. G. Windsor, "*Pulsed Neutron Scattering*", Taylor & Francis LTD (1981);
- N. Watanabe, "*Neutronics of spallation sources*", Rep. Progr. Phys. **66**, 339 (2003);