

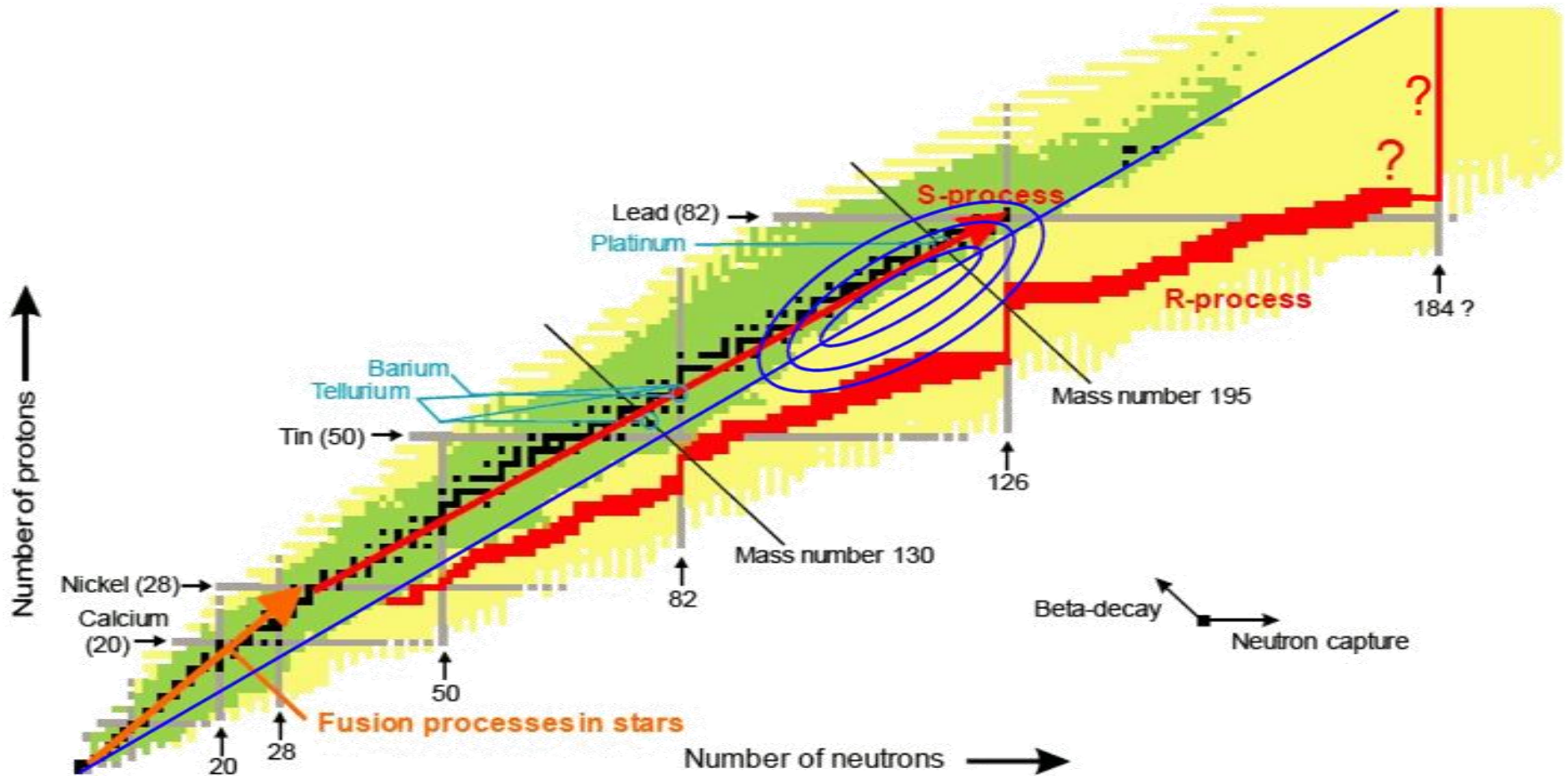
Details on two proposed experiments for ELI-NP

- I. Production of neutron-rich nuclei with $N \sim 126$
using a laser-accelerated Th beam
- experiment with high power laser

- II. A pulsed micro-beam of thermal neutrons without
moderation
- application of brilliant γ source

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Interest for N~126 neutron-rich nuclei



- Astrophysics: N=126 nuclei are a waiting point in R-process (explosive nucleosynthesis)
- Nuclear structure: magicity in neutron-rich nuclei (proved collapse of N=20 and 28)

Stopping power of high density bunches

Bethe-Bloch formula for individual ion:

$$-\frac{dE}{dx} = 4\pi n_e \frac{Z_{\text{eff}}^2 e^4}{m_e v^2} \left(\ln \left(\frac{m_e v^2}{e^2 k_D} \right) + \ln \left(\frac{k_D v}{\omega_p} \right) \right)$$

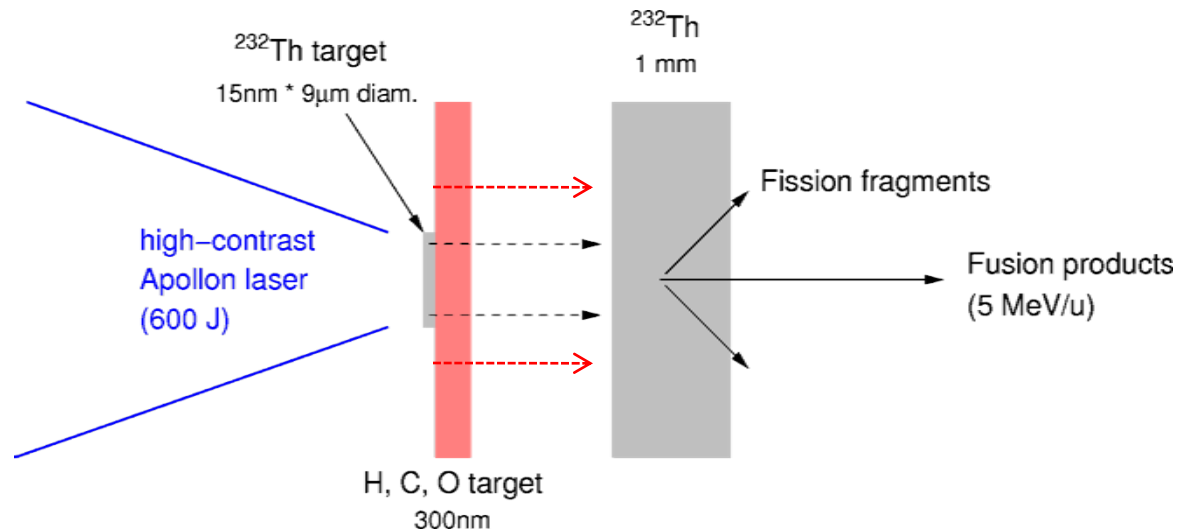
$k_D =$ Debye wave number

binary collisions long-range collective interaction
 $\omega_p =$ plasma frequency

Modified stopping of high density bunches

- a) enhanced stopping ($10^5 \times$) in low-density targets
dense bunch interacts with collective wake
→ **reduced fraction of nuclear reaction**
- b) reduced stopping in solid target
first electrons of bunch kick out electrons of foil like a snow plow.
→ **enhanced fraction of nuclear reactions.**

Fission-Fusion Reaction Mechanism



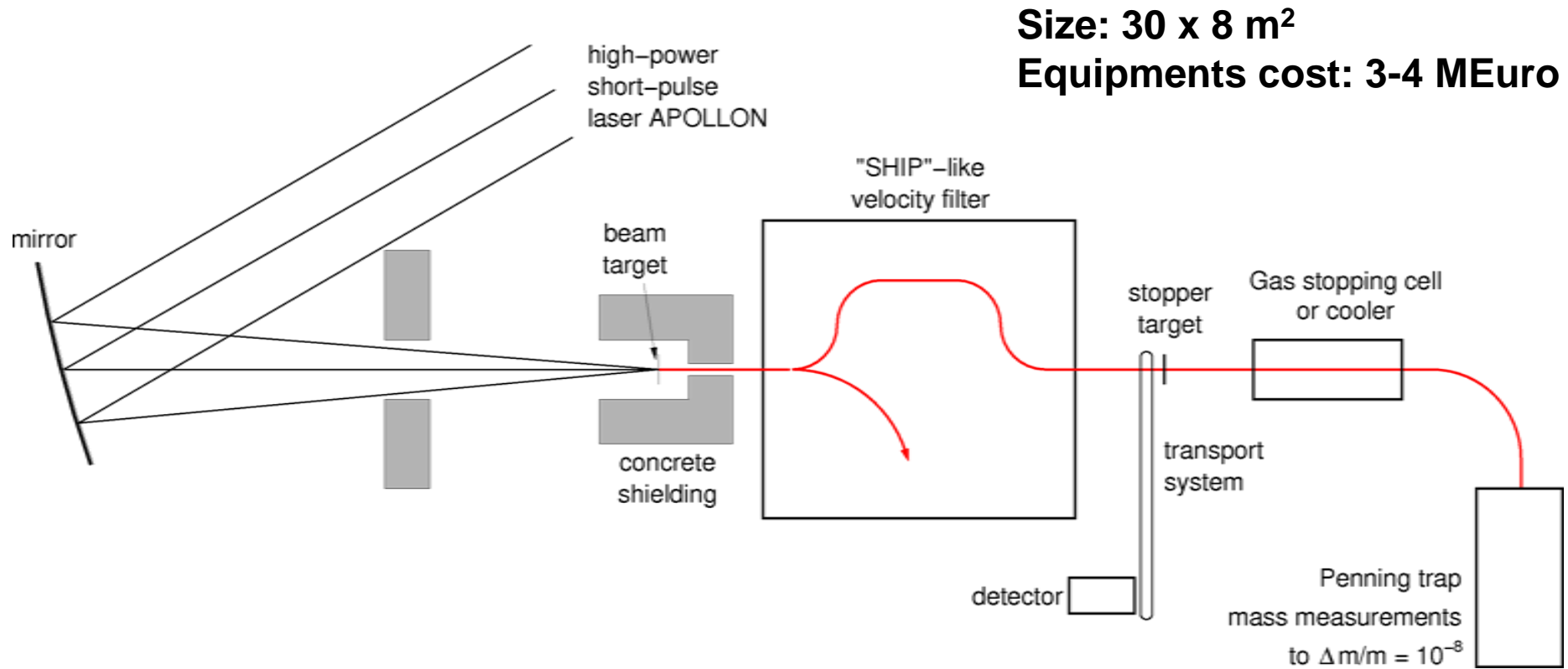
beam: ^{232}Th @ 10 MeV/u 5e+11 nuclei/shot
H,C,O @ 10 MeV/u 2e+13 nuclei/shot

a) **Fission** $\text{H, C, O} + ^{232}\text{Th} \rightarrow$ fission of target in $F_L + F_H$
 $^{232}\text{Th} + ^{232}\text{Th} \rightarrow$ fission of Th beam in $F_L + F_H$ ($\sigma =$ several barns)

b) **Fusion:** $F_L + F_L \rightarrow$ AZ around $^{182}75$ including nuclei close to N=126 waiting point
 $F_L + F_H \rightarrow$ ^{232}Th old nuclei
 $F_H + F_H \rightarrow$ unstable

Fission-fusion reaction rate: $10^4 - 10^6$ reac./shot
Yield for ^{198}Hf (N=126,Z=72) > 1/s ? (FAIR estimate)

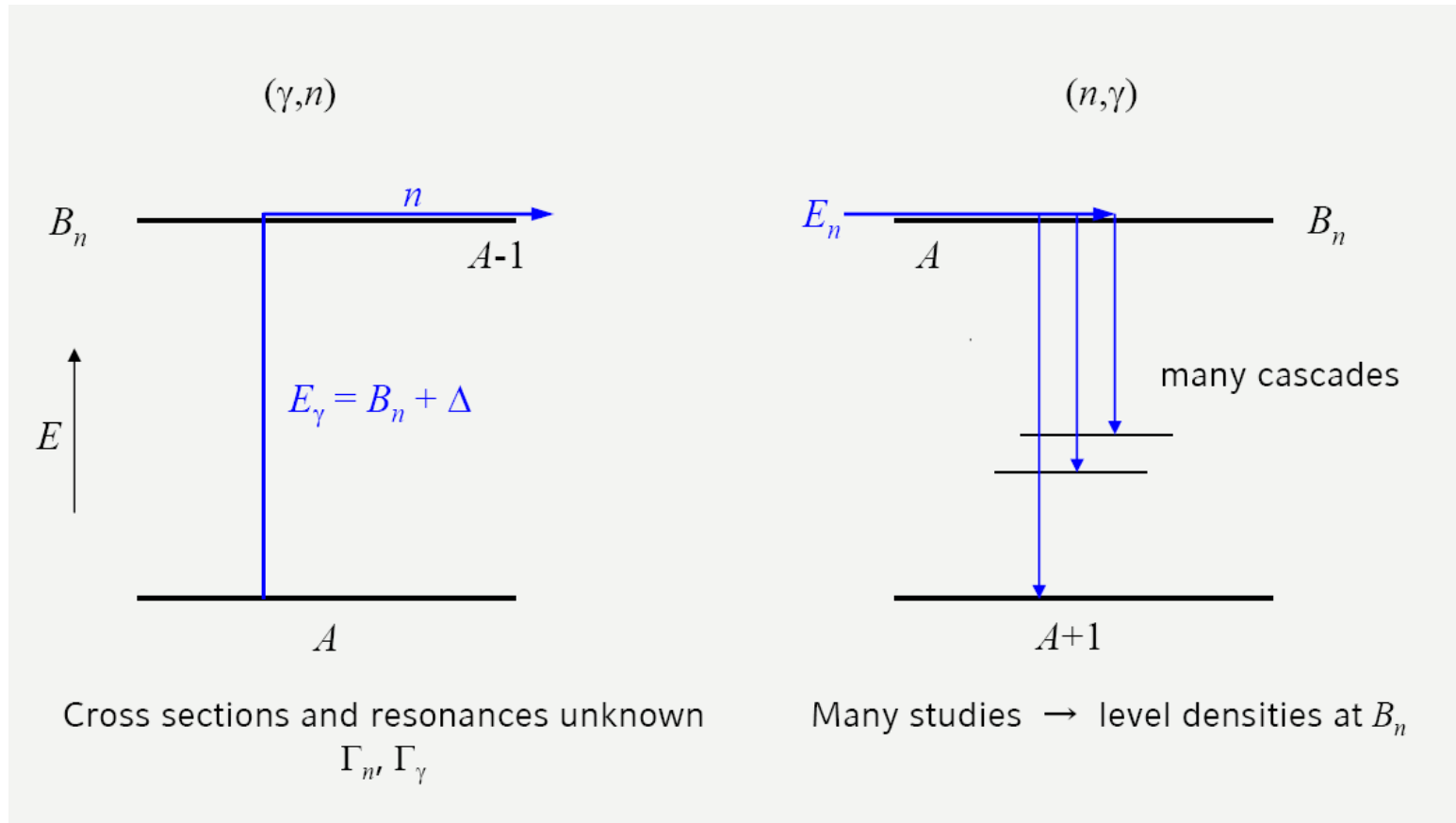
Experimental set-up



$\sim 10^{13}$ fast n/shot \Rightarrow 2-3 m concrete shielding required

First experiments for target & laser optimization:
use only tape transport system

(γ, n) Photonuclear Reactions



Cross section: Breit-Wigner resonance

$$\sigma(E_\gamma) = (\lambda_\gamma^2/4\pi) \cdot g \cdot \frac{\Gamma_n \Gamma_\gamma}{(E_\gamma - E_r)^2 + (\Gamma_n + \Gamma_\gamma)^2/4}$$

Good chances to find a heavy nucleus with $E_r = B_n + 100$ meV and $\Gamma_\gamma = 200$ meV

$$E_\gamma \sim 6 \text{ MeV} \Rightarrow \lambda_\gamma = 160 \text{ fm} \Rightarrow \sigma = 10^2 \text{ b}$$

Calculated neutron flux

Gamma source: $10^{15} \gamma/s$ $E_\gamma = 6 \text{ MeV}$
Bandwidth = $\Delta E_\gamma / E_\gamma = 0.1\%$
Peak brilliance = $10^{23} / (\text{s mm}^2 \text{ mrad}^2 0.1\% \text{ BW})$
Pulse length = 20 ps

Usefull E_γ range:
200 meV = $3 \times 10^{-5} \text{ BW}$

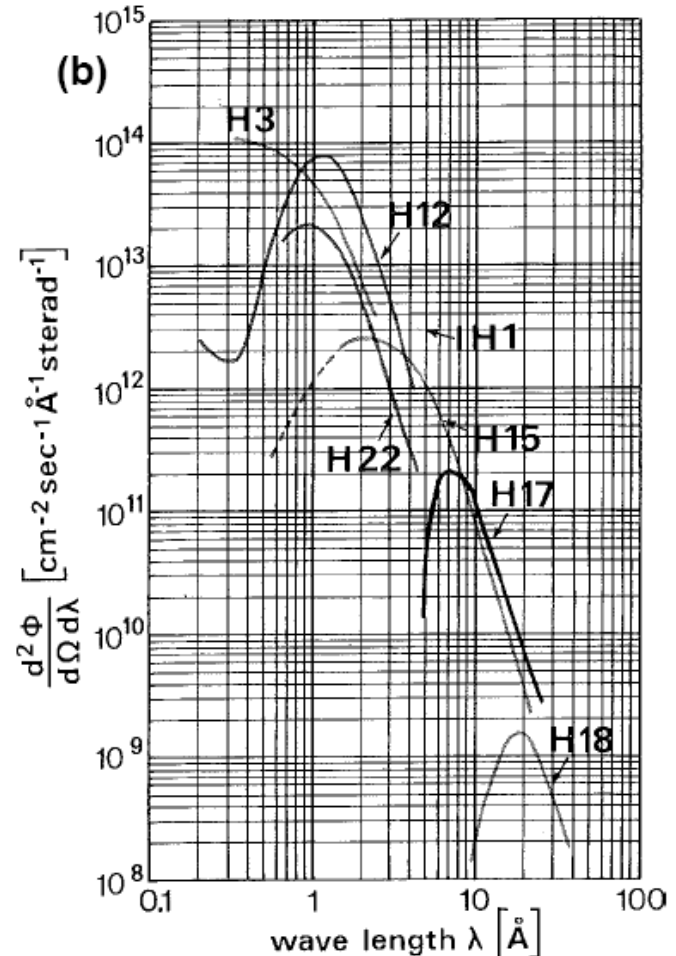
Target size = neutron source size
= $100 \mu\text{m} \times 100 \mu\text{m} \times 300 \mu\text{m}$

Neutron yield: 10^{10} n/s in 4π

Refocalized on sample with supermirrors
(preserving path length = only one reflection)
 $10^{11} - 10^{12} \text{ n}/(\text{cm}^2 \text{ s})$

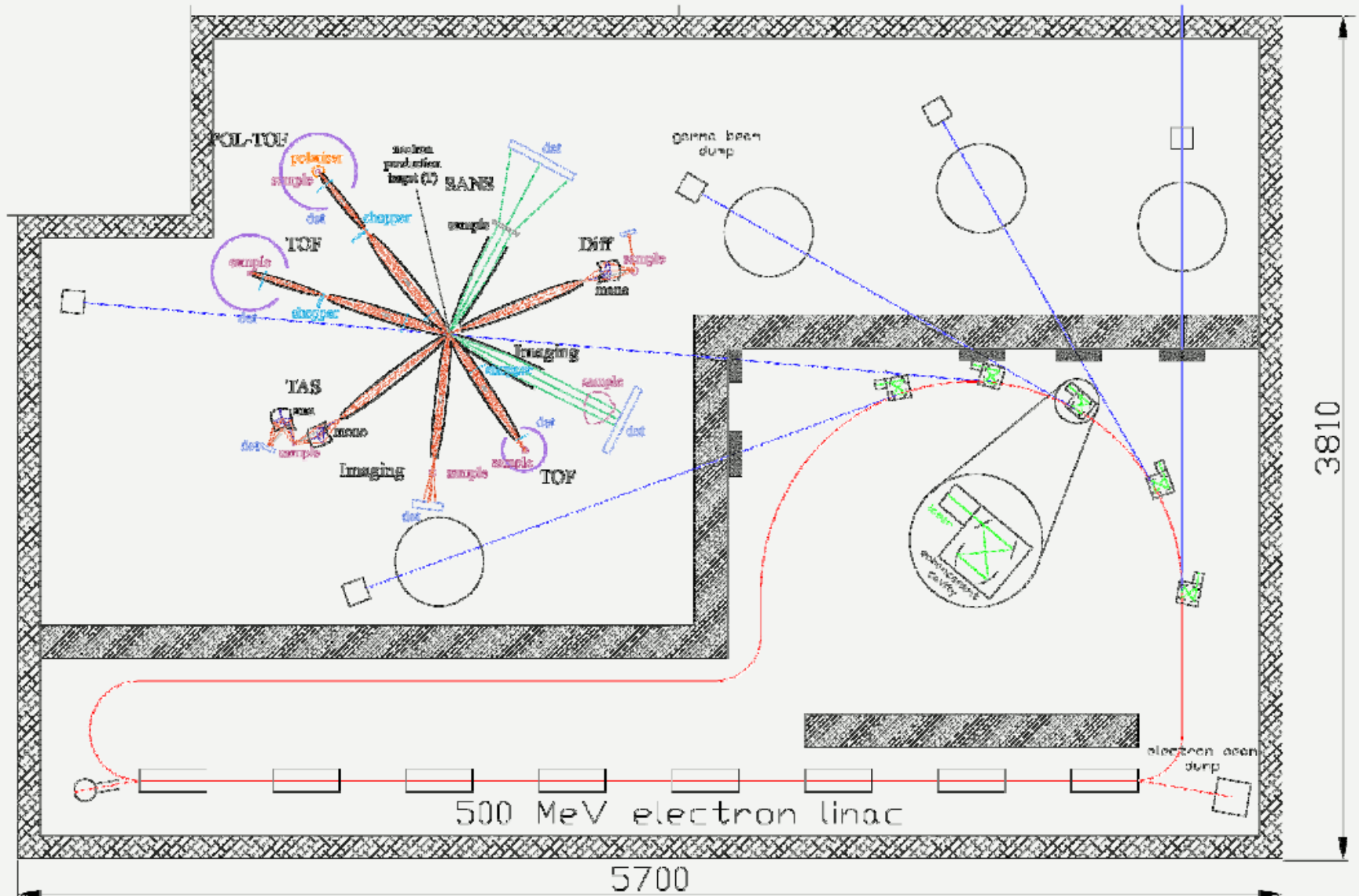
Advantages:

- low cost
- no chopper reducing flux
- very good timing for TOF measurements



ILL High flux reactor (58 MW)

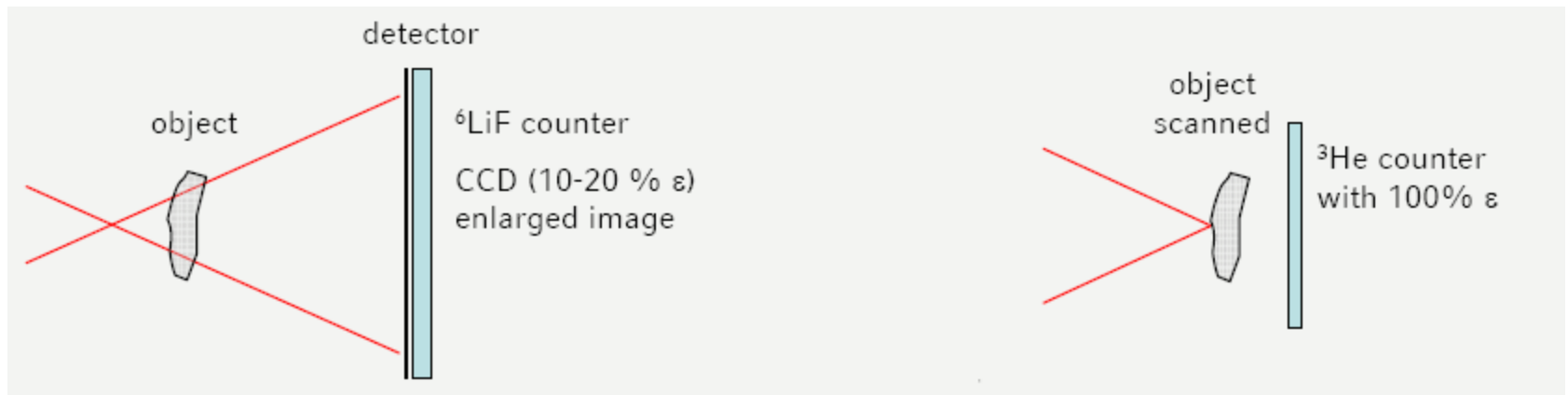
Experimental set-up



Cost of equipments for neutron experiments

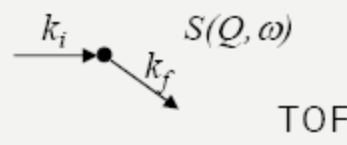
Nr.	Instrument / sample environment	Physics	Costs
1	POL-TOF intermediate focusing	magnetism, superconductivity	7000 k€
2	TOF + chopper + interm. foc.	lattice dyn., diffusion, tunneling	6000 k€
3	TAS + monochr. + analyser	collective excitations, order param.	2000 k€
4	Imaging + foc. + spin analysis	macrosc. magn. distrib., domains	800 k€
5	TOF + chopper	structure, diffraction	5000 k€
6	Imaging with parallel beam	industrial applications	700 k€
7	Diffractometer + monochromator	structure, industrial applications	1500 k€
8	SANS	soft matter, supercond. biophys.	4000 k€
9	Reflectometry + chopper	heterostructures, soft matter	3000 k€
10	Reflectometry + monochromator	heterostructures, order parameters	1500 k€
11	Irradiation station	cancer therapy	1000 k€
12	large magnetic fields	magnetism, phase transitions	1500 k€
13	high-pressure cells	geoscience, phase transitions	200 k€
14	biomedical cell setup	dynamics in cells	100 k€
15	gas handling systems	chemistry, energy research	200 k€
16	in-situ reflectometry	heterostructures, spintronics, GMR	600 k€
17	cryogenics	all fields of research	2000 k€
Total			37100 k€

Tomography with neutron micro-beams



The diagram illustrates two experimental setups for neutron tomography. On the left, an 'object' is placed between a source and a 'detector'. The detector consists of a ${}^6\text{LiF}$ counter and a CCD with a 10-20% efficiency (ϵ), which produces an enlarged image of the object. On the right, an 'object scanned' is placed between a source and a ${}^3\text{He}$ counter with 100% efficiency (ϵ).

- polarized $\gamma \rightarrow$ polarized neutron \rightarrow magnetic imaging
- cw neutron beam (Munich, Berlin, PSI)
- pulsed neutron source (SNS Oak Ridge, JPARC Japan, ESS Lund)
studying Larmor precession, spin echo.



The diagram shows a neutron scattering process. An incident neutron with wave vector k_i is scattered by a sample, resulting in a final wave vector k_f . The scattering function is denoted as $S(Q, \omega)$. The technique is labeled as TOF (Time-of-Flight).

Neutron scattering

Other applications of neutron micro-beams

- Study of quantum phase transitions
 - very high pressures ($3 \cdot 10^5$ bar)
 - very high magnetic fields } small samples
- Many new applications for beams with much higher brilliance
 - nm beams in biology, studying the motion of subsections of cells
- Study of engines (BMW, Daimler), all time dependent
 - injection nozzle
 - lubrication of piston
- Study of rotor blades, turbines
 - cracks, stress