Application of Accelerators to Nuclear Energy

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Fundamental Physics and Applications
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Outline

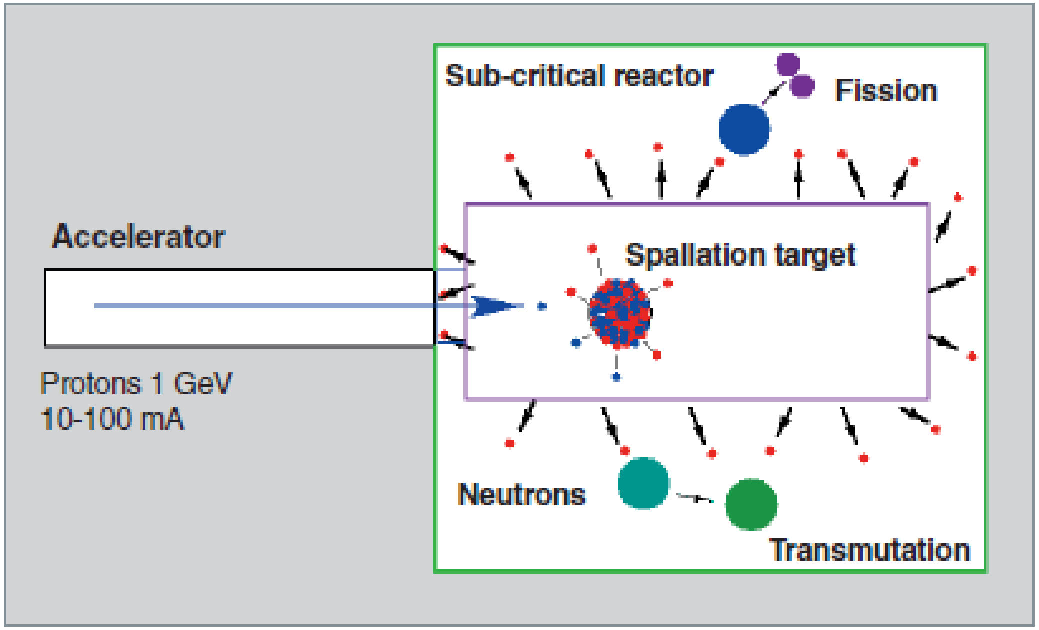
- ☐ **Introduction to ADS**
- ☐ **Physics of spallation**
- ☐ **Sub-critcal Reactor core physics**
- ☐ **Motivations and global constraints on ADS**

Principle of Accelerator-Driven Systems

- One way to obtain intense neutron sources is to use a hybrid sub-critical reactor-accelerator system called Accelerator-Driven System:

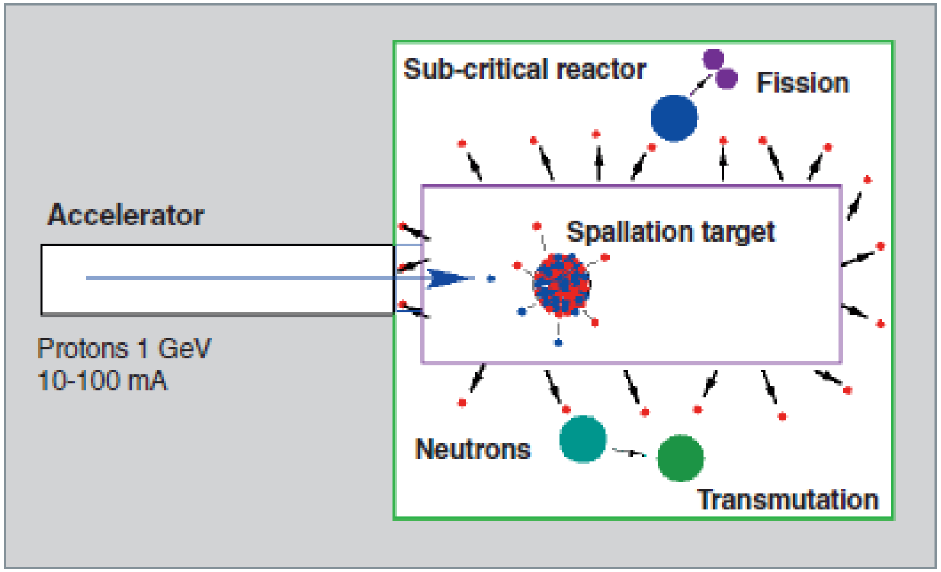
✰ The accelerator bombards a target with high-energy protons which produces a very intense neutron source through the spallation process.

🕐 These neutrons can consequently be multiplied in the sub-critical core which surrounds the spallation target.



Principle of Accelerator-Driven Systems

- **The high-energy neutrons produced by spallation act as a source for the following phase**, in which they gradually loose energy by collisions. The phenomenology of the second phase recalls that of ordinary reactors with however some major differences.

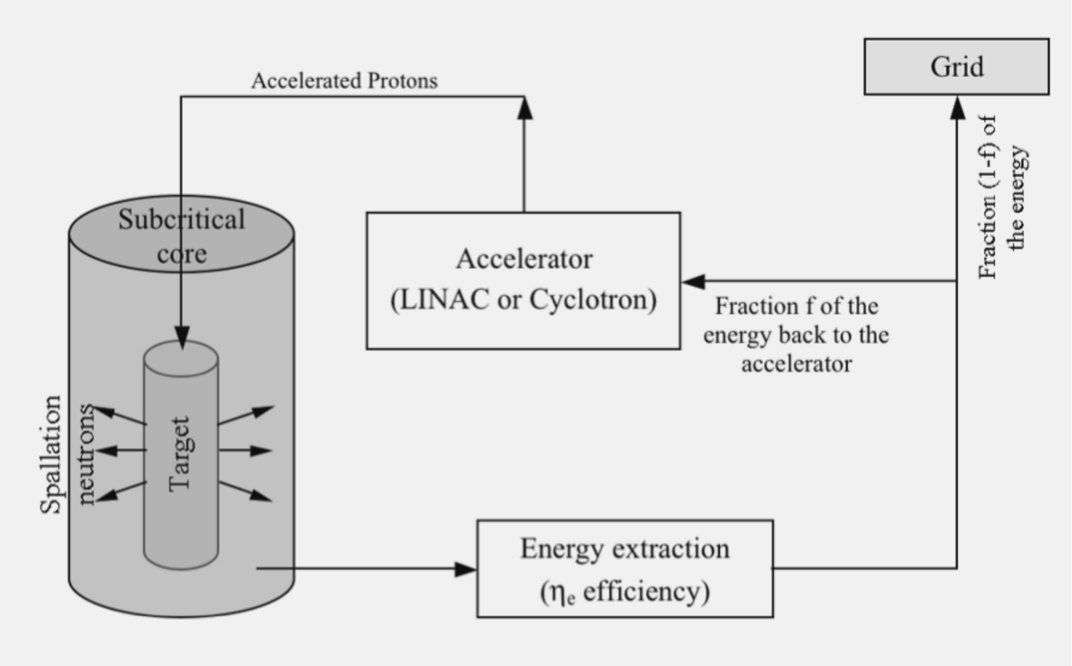


- **The presence of the second phase is essential for obtaining the high gains in energy.**

Principle of Accelerator-Driven Systems

In an accelerator driven, sub-critical fission device, like the **Energy Amplifier** (EA), the "primary" (or "source") neutrons produced via spallation by the interaction of the proton beam with a suitable target, initiate a cascade process.

The **source** is then **"amplified"** by a factor ***M*** and the **beam power** is "amplified" by a factor: **Gain**



$$G = G_0 M$$

Principle of Accelerator-Driven Systems

one can distinguish between two qualitatively different physical processes:

- A spallation-driven high-energy phase , commonly exploited in calorimetry
  - Complex processes
  - Cross sections not so well known
  - Parametrized in an approximate manner by phenomenological models and MonteCarlo simulations
- A low-energy neutron transport phase, dominated by fission
  - Diversified phenomenology down to thermal energies
  - Main physical process governed by neutron diffusion
  - Neutrons are multiplied by fissions and (n,xn) reactions

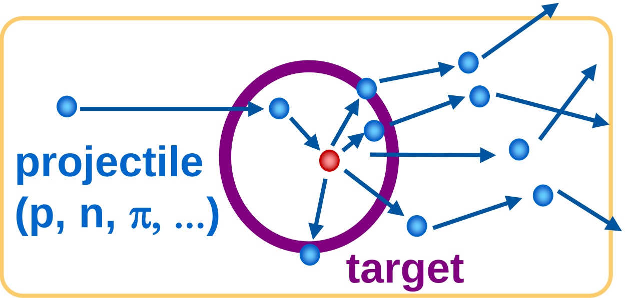
What is Spallation ?

Definition found in Nuclear Physics Academic press:

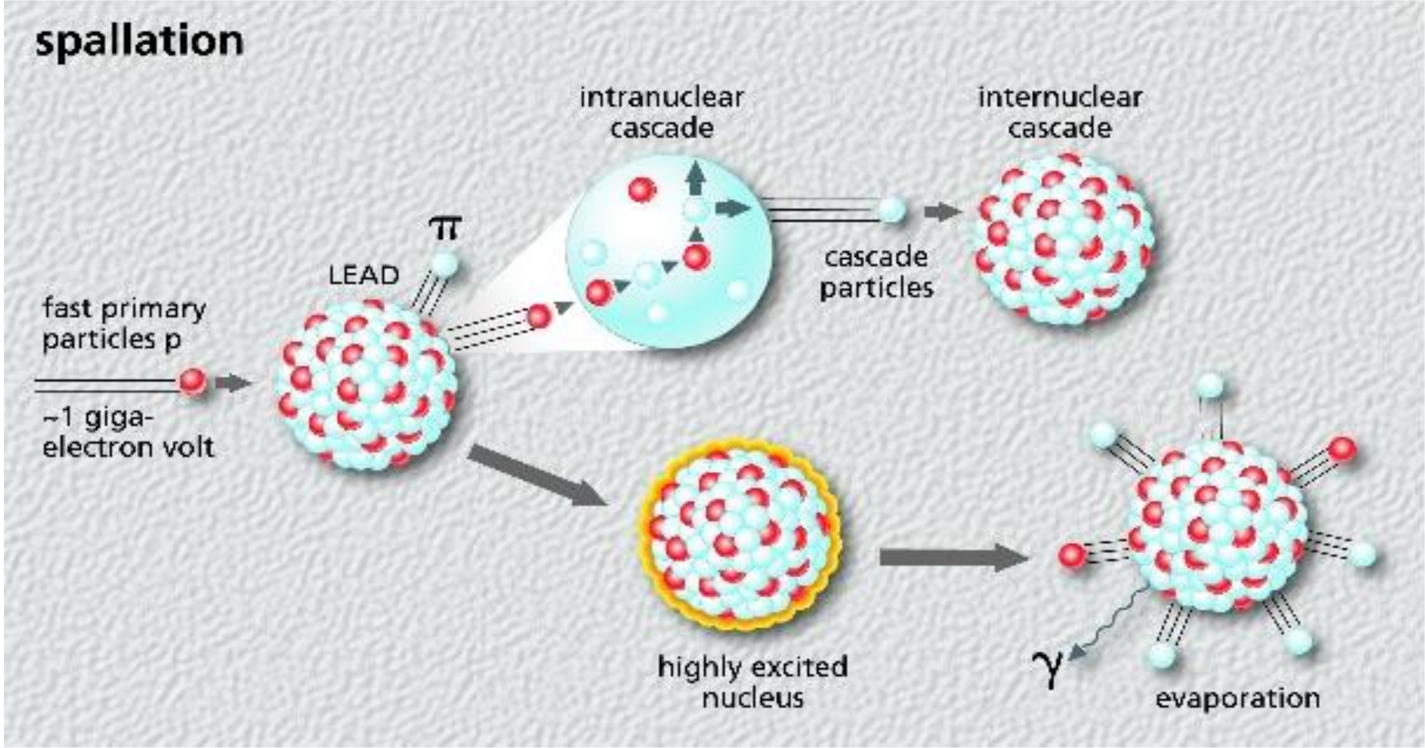
> "Spallation---a type of nuclear reaction in which the high-energy level of incident particles causes the nucleus to eject more than three particles, thus changing both its mass number and its atomic number."

Definition (Encyclopedia Britannica): "high-energy nuclear reaction in which a target nucleus struck by an incident (bombarding) particle of energy greater than about 50 million electron volts (MeV) ejects numerous lighter particles and becomes a product nucleus correspondingly lighter than the original nucleus. The light ejected particles may be neutrons, protons, or various composite particles equivalent…"

- Nonelastic nuclear interaction induced by a high energy particle (> 50 MeV) producing numerous secondary particles.
- Spallation is the disintegration of a nucleus by means of high energetic proton induced reactions. Typically approximately 20 neutrons are created per incident GeV proton.

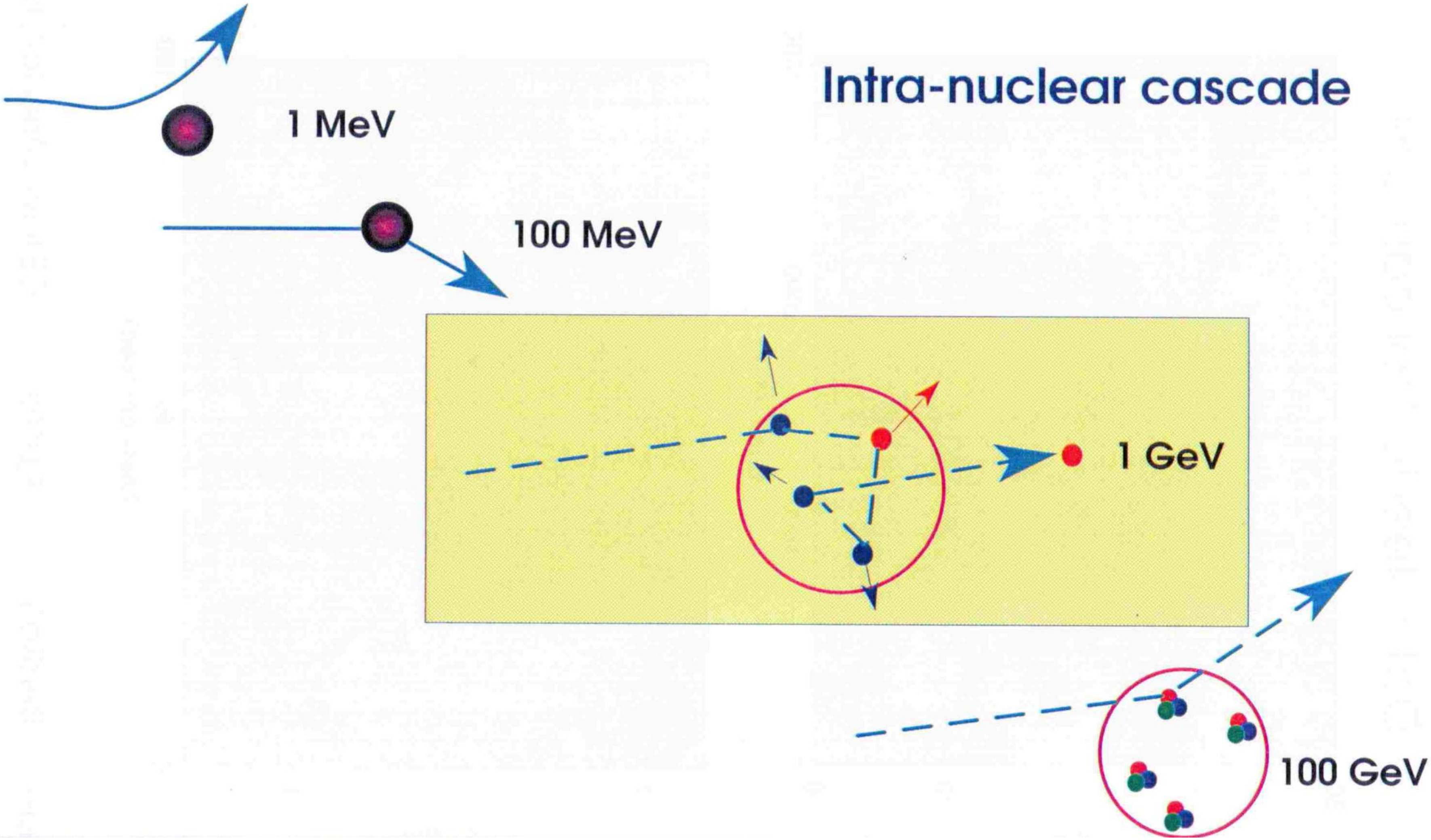


The Spallation Process

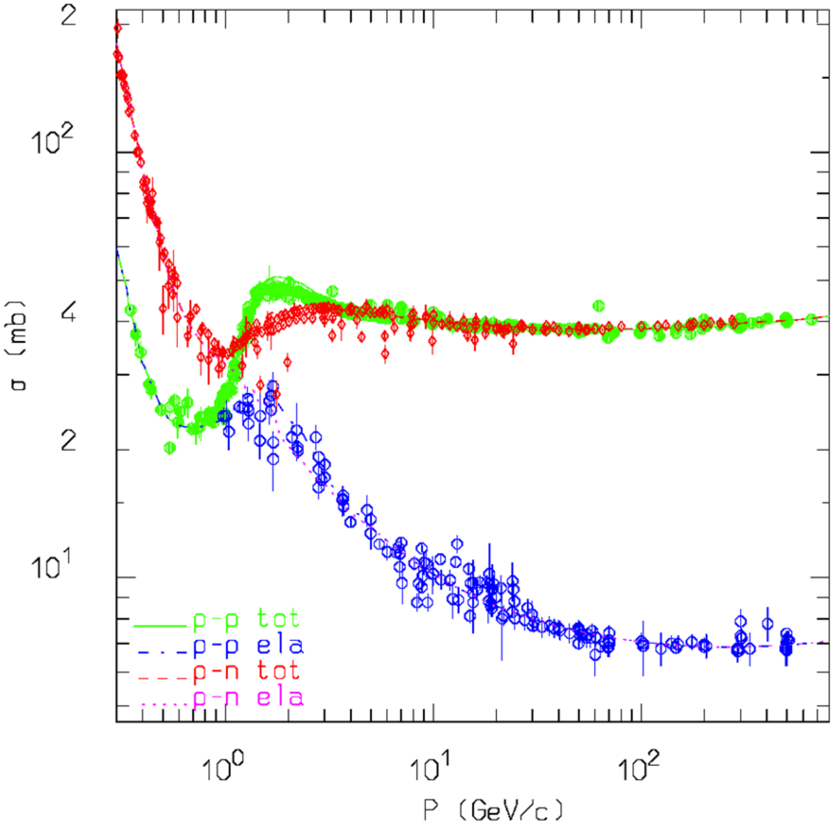


- ➢High energy hadron causing an intra-NC on a time scale ≈10^{-22}s
- ➢secondary particles (n,p,π) themselves produce secondaries creating an inter-NC placing many individual nuclei into highly excited states
- ➢Release energy by evaporating n, p, d, t, α, γ… on a time scale ≈ 10^{-18} to10^{-16}s

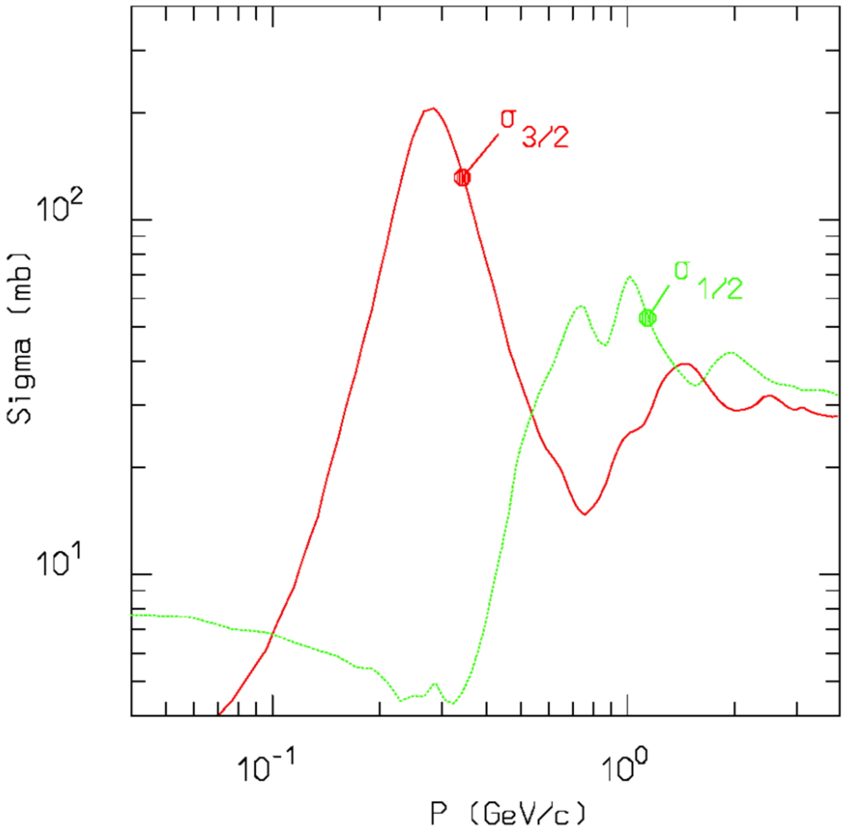
The Intra-Nuclear Cascade



Hadron-Nucleon Cross-Sections



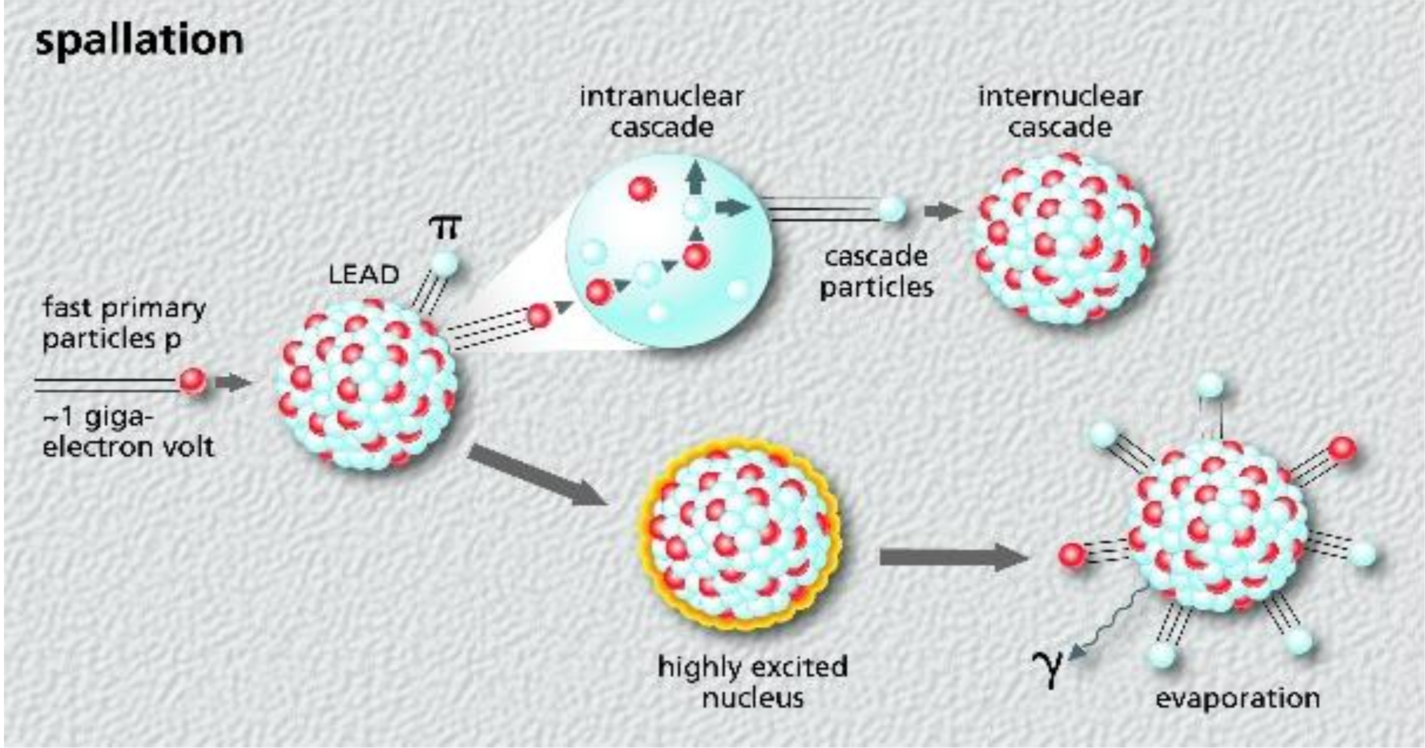
Total and elastic cross section for p-p and p-n scattering, together with experimental data



Isospin decomposition of π-nucleon cross section in the T=3/2 and T=1/2 component

Hadronic interactions are mostly surface effects ⇒ hadron nucleus cross section scale with the target atomic mass $A^{2/3}$

The Spallation Process



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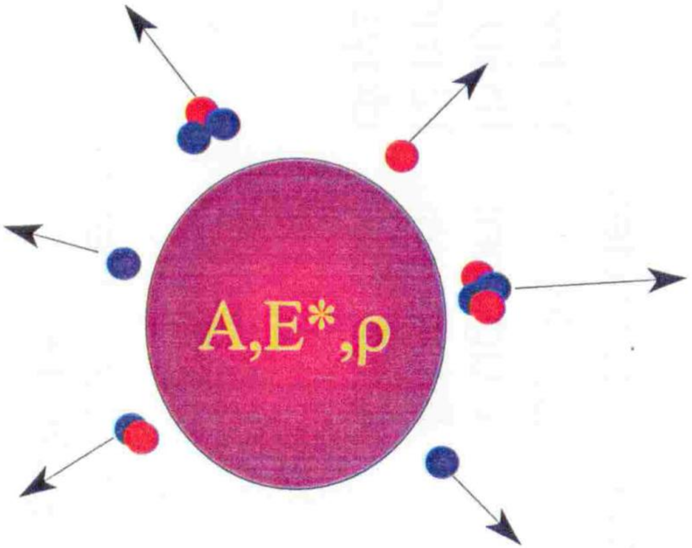
Evaporation Process

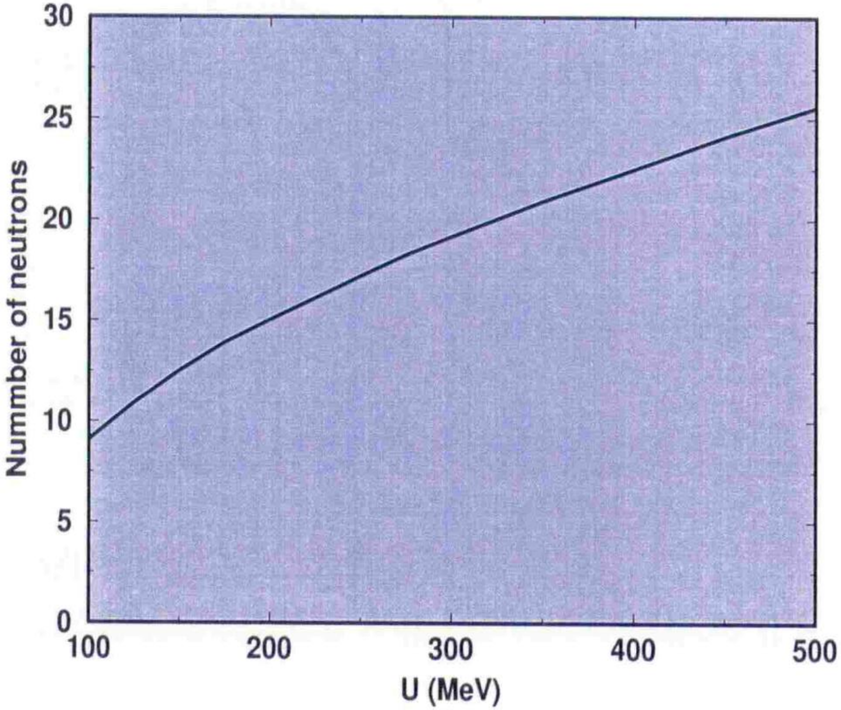
Highly excited residual nucleus after intra-nuclear cascade
Dissipation of the excitation energy by **particle** (n, p, d, t, ^{3}He, α) **evaporation** using the Wiesskopf-Ewing formula:

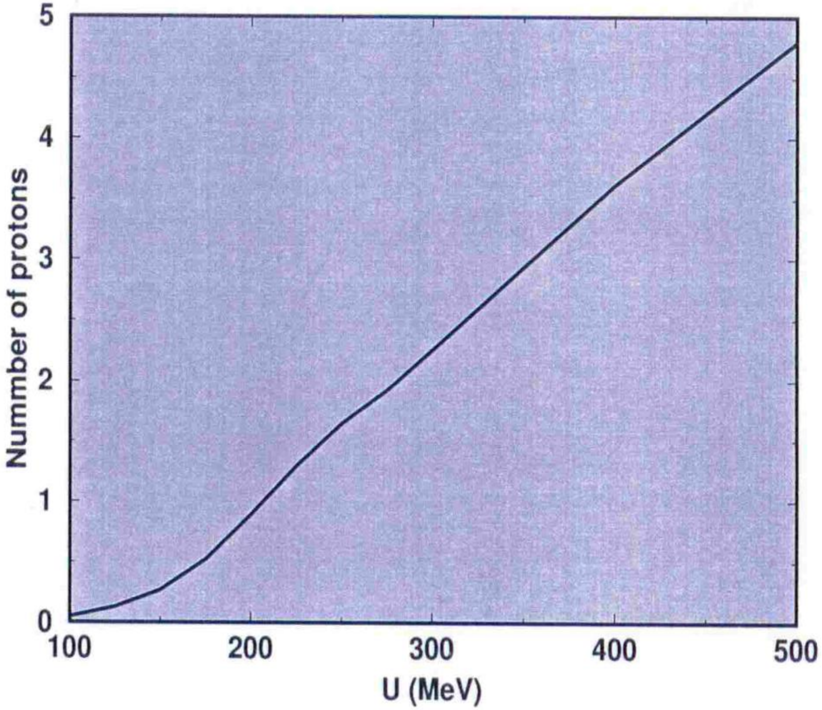
$$\Gamma_i = \int_{\varepsilon_{min}}^{\varepsilon_{max}} \Gamma_i(\varepsilon)\, d\varepsilon \qquad \text{with} \qquad \Gamma_i(\varepsilon)\, d\varepsilon = \frac{(2s_i+1)\mu_i}{\pi^2 \hbar^2 \rho_{cn}(E^*)}\, \varepsilon\, \sigma_{inv}(\varepsilon)\, \rho_i(E^*-B_n-\varepsilon)\, d\varepsilon$$

And $$P_x = \frac{\Gamma_x}{\Gamma_f + \sum \Gamma_i}$$



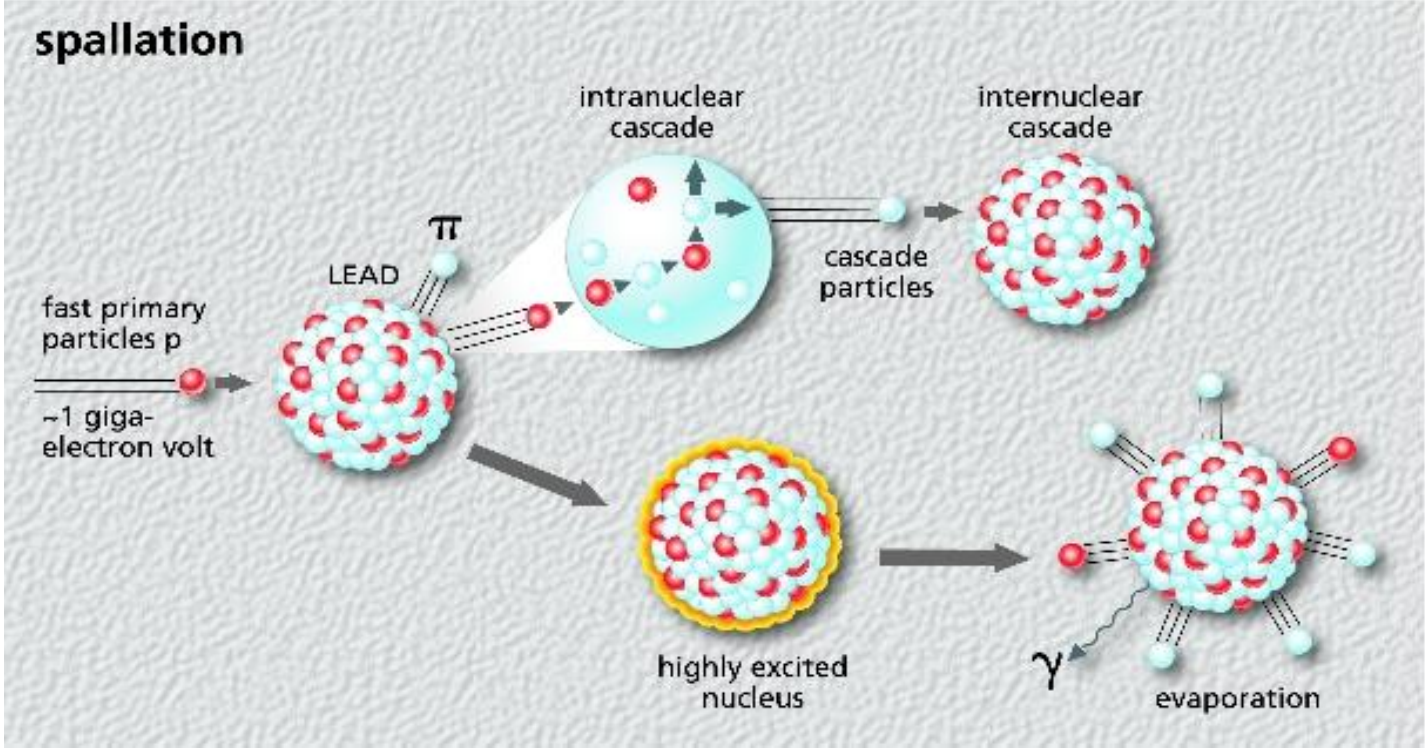
Nucleon Emission





$$\Delta U=20\ \mathrm{MeV} \Rightarrow \Delta n=1,\ \Delta p=0.25$$

The Spallation Process



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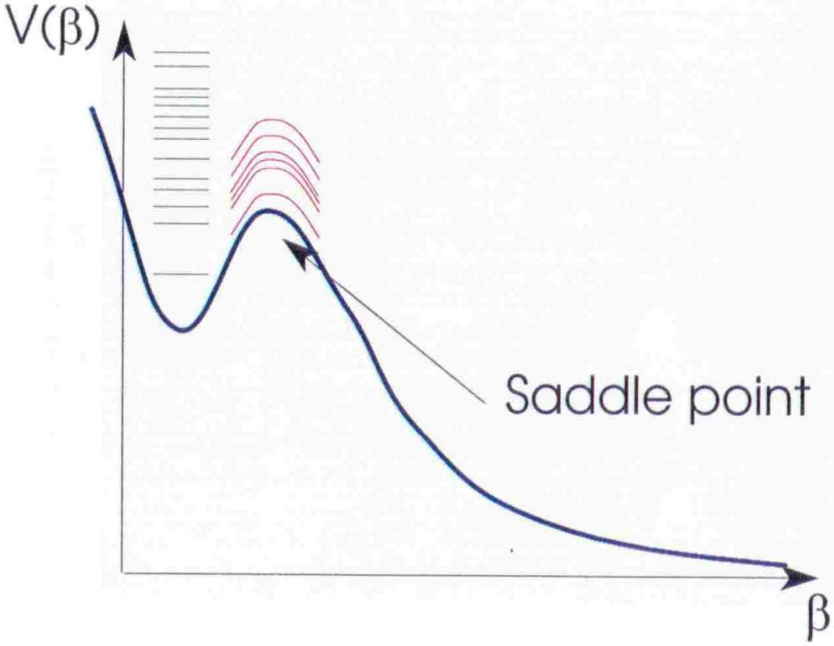
High-Energy Fission

In competition with evaporation if $E^*>B_f$
(Atchinson model)

$$P_f=\frac{\Gamma_f}{\Gamma_f+\sum\Gamma_i}$$

$$\Gamma_f=\frac{1}{2\pi\,\rho_{ground}(E^*)}\int_0^{E^*-B_f}\rho_s(E^*-B_f-\varepsilon)\,d\varepsilon$$

(transition state method (Bohr & Weeler))



High-Energy Transport Codes

CALOR	T. Gabriel et al., ORNL	HETC based
HERMES	P. Cloth et al., FZ-Jülich	HETC based
LCS	R. Prael et al., LANL	HETC based
GEANT4	S.Agostinelli et al., CERN	HETC based
MCNPX	LANL (Test-Version) ↙ CEM, 150 MeV x-sec.	HETC based
TIERCE	O. Bersillon, CEA	HETC based
PSI-HETC/O5R	P. Atchison, PSI	HETC based
PHITS/NMTC/JAM	K.Niita et al., JAERI/KEK	HETC,JQMD
FLUKA	A. Fasso et al., CERN, Milano*	
Cross Section Calculation and Evaluation		
ALICE	M.Blann, LLNL	
GNASH	P.G.Young, LANL, M.B.Chadwick, LLNL	
NJOY	R.E.MacFarlane, LANL	

Spallation vs ….

Process	Example	Yield	Energy Deposition [MeV/n]
DT solid target	400keV deuterons on tritium in Titan	4.0 x 10^{-5} n/d	10 000
Deuteron stripping	35 MeV deuterons on liquid Lithium	2.5 x 10^{-3} n/d	10 000
electrons Bremsstrahlung (Photo-neutrons)	100MeV electrons on U-238	5.0 x 10^{-2} n/e	2000
Fission	U-235 (n,f)	1 n/fission	180
DT-fusion	laser or ion-beams imploding pellets	1 n/Fusion	3
spallation	1 GeV protons on Pb	30 n/p	30

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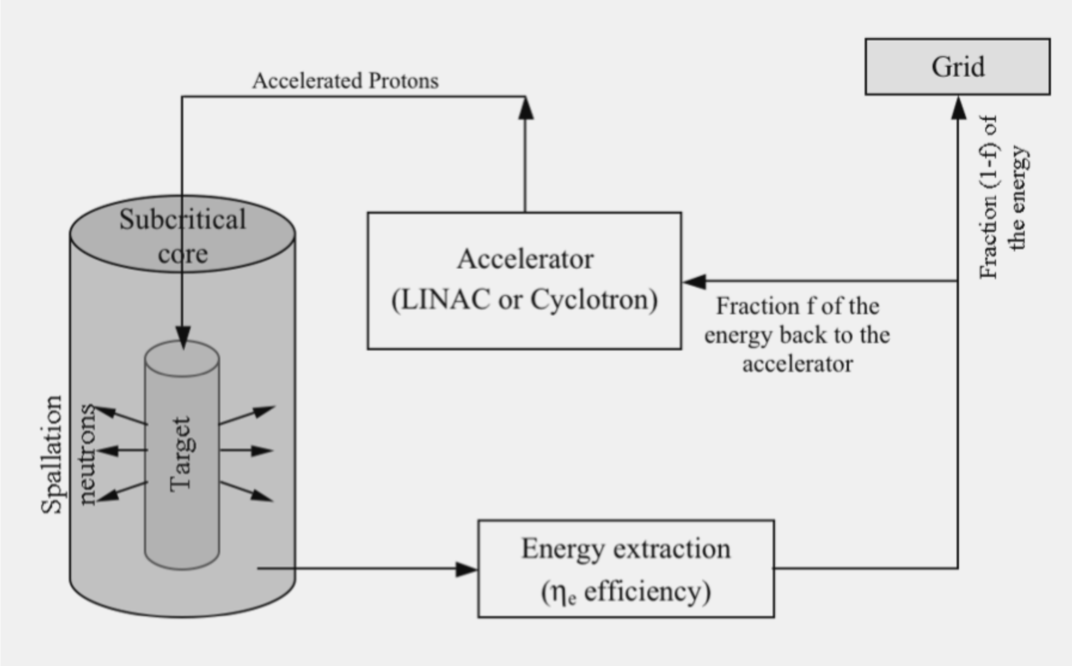


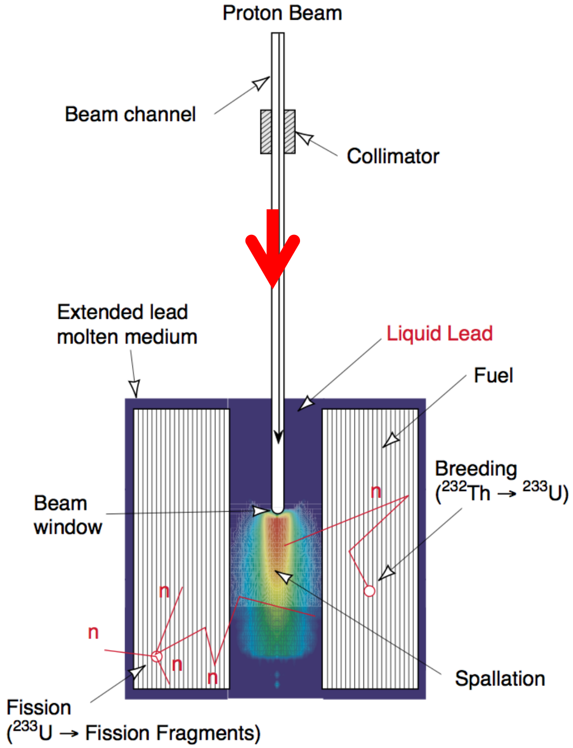
$$G = G_0 M$$

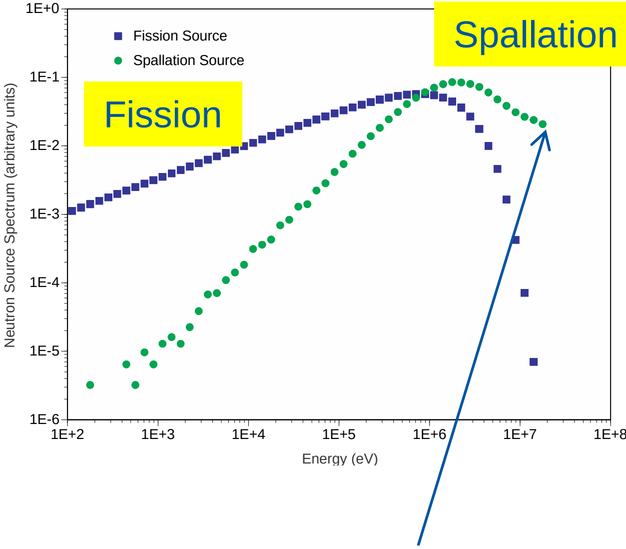
Simplified model of subcritical systems

Theory of subcritical systems is quite different from that of critical systems:

- Neutron spatial distribution
- Neutron energy distribution

External neutron source term in addition





Non negligible contribution from the high energy tail (n,xn)

$$\frac{\partial n(\vec{r},t)}{\partial t} = \nu \Sigma_f \Phi(\vec{r},t) + \boxed{C(\vec{r},t)} - \Sigma_a \Phi(\vec{r},t) + D\nabla^2 \Phi(\vec{r},t)$$

Fission

Spallation

Absorption

Leakage

Simplified model of subcritical systems

- Example of finite system at equilibrium:

Diffusion length

$$\frac{\partial n}{\partial t} = 0 \Rightarrow \nabla^2\Phi + \frac{(k_\infty - 1)}{L_c^2}\Phi = -\frac{C}{D} \qquad \text{with } k_\infty \equiv \frac{\nu\Sigma_f}{\Sigma_a} \quad L_c^2 \equiv \frac{D}{\Sigma_a}$$

- Two regimes corresponding to two classes of solutions:
  - $k_\infty < 1$: the system is intrinsically subcritical (FEAT experiment: $k_\infty \sim 0.93$) – **Solution is an exponential**
  - $k_\infty > 1$: subcriticality comes from the lack of confinement, it is a geometrical issue – **Solution is oscillatory** (C. Rubbia's EA: $k_\infty \sim 1.2$-1.3)

$$C(\vec{x}) = D\sum_{l,m,n} c_{l,m,n}\psi_{l,m,n}(\vec{x}) \rightarrow \Phi(\vec{x}) = L_c^2 \sum_{l,m,n} \frac{C_{l,m,n}}{1 - k_{l,m,n}} \Psi_{l,m,n}(\vec{x})$$

- All modes are excited

Theorem: $\forall\, i,\ k_i < k_1$

$$k_{l,m,n} \equiv k_\infty - L_c^2 B_{l,m,n}^2$$

Time dependence

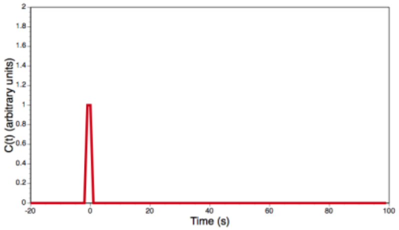
- Diffusion equation (with $\Phi = \beta n$, where β is the neutron velocity):

$$\frac{\partial n(\vec{x},t)}{\partial t} = \frac{1}{b}\frac{\partial \Phi(\vec{x},t)}{\partial t} = D\nabla^2\Phi(\vec{x},t) + (k_\infty - 1)\Sigma_a\Phi(\vec{x},t) + C(\vec{x},t)$$

- Case of a neutron pulse, given by $C_0\delta(t)$, and substituting

$$\Phi(\vec{x},t) = \sum_{l,m,n} \Phi_{l,m,n}\psi_{l,m,n}(\vec{x})\, f_{l,m,n}(t)$$

provides an equation for the time dependence:



$$\frac{df_{l,m,n}(t)}{f_{l,m,n}(t)} = -\beta\left[DB^2_{l,m,n} + (1-k_\infty)\Sigma_a\right]dt$$, and the general solution

$$\boxed{\Phi(\vec{x},t) = \sum_{l,m,n} \Phi_{l,m,n}\psi_{l,m,n}(\vec{x})\, e^{-\beta\Sigma_a(1-k_{l,m,n})t}}$$

- Characteristic decay time is shorter as modes become higher. At the criticality limit ($k_{1,1,1}=1$), the mode is infinitely long. Fermi used this to measure the approach of criticality in his Chicago Pile 1 in 1942, and the method can be used for an ADS.

Neutron multiplication factor

- The neutron multiplication factor depends on the source:

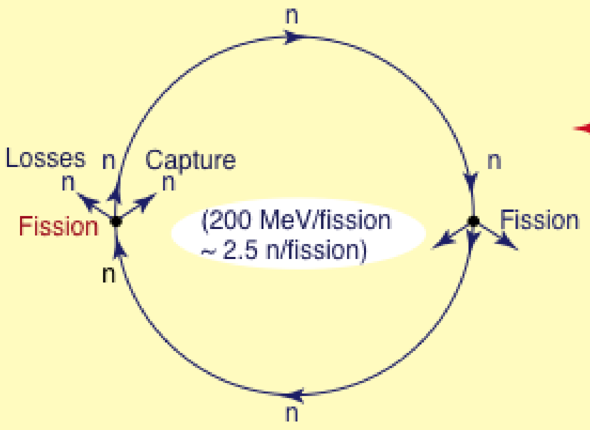
$$k_s \approx \frac{\overset{\text{Fission}}{\nu \Sigma_f \Phi(\vec{r},t)} + \overset{\text{Spallation}}{C(\vec{r},t)}}{\underset{\text{Absorption}}{\Sigma_a \Phi(\vec{r},t)} - \underset{\text{Leakage}}{D\nabla^2 \Phi(\vec{r},t)}} > k_{eff}$$

For fast neutron systems, (n,xn) reactions are not negligible, in particular for the source neutrons

- The CERN LHC beam can be switched off in three turns of the machine, that is up to 270µs. The CERN SPS can be switched off in 46 µs. On a (much) smaller machine, such as foreseen for ADS, the switching off time is much shorter. So the reaction time will not be limited by the accelerator. The typically response time of a critical system to reactivity insertion is of the order of 5 ms.
- Switching off the neutron source not only stops the main power generation, but also moves the system to a smaller k, from k_s to k_{eff}.

Critical versus Subcritical Systems

Chain Reaction



Critical Reactor ← → **Energy Amplifier**

Effective neutron multiplication factor

$$k = \frac{\text{Production}}{\text{Absorption} + \text{Losses}}$$

Self-sustained process:

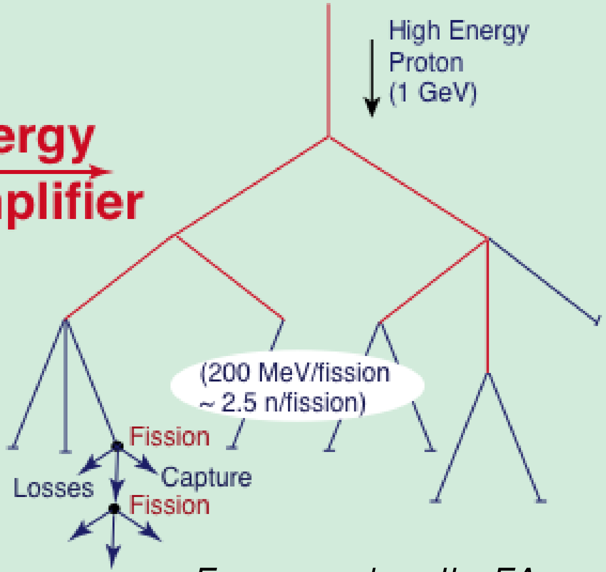
k = 1

(if k < 1 the Reactor stops

if k > 1 the Reactor is supercritical)

⇒ The time derivative of the power kept equal to zero by control

Nuclear Cascade



$$\text{Energy gain}(G) \equiv \frac{\text{Energy produced by EA}}{\text{Energy provided by beam}} = \frac{G_0}{(1-k)}$$

Externally driven process:

k < 1 (k = 0.98)

$$E_{tot} = G \times E_p$$

Energy Produced

Beam Energy

⇒ Constant Energy Gain

$$N_0\left(1 + k + k^2 + k^3 + k^4 + \ldots + k^n\right) = N_0 \frac{k^{n+1} - 1}{k - 1} \approx \frac{N_0}{1 - k}$$

ADS energy gain

- A source neutron is multiplied by fissions and (n,xn) reactions. Since $k_s<1$, neutron production stops after a limited number of generations:

$$N_0\left(1+k_s+k_s^2+k_s^3+k_s^4+\ldots+k_s^n\right)=N_0 M=N_0\,\frac{k_s^{n+1}-1}{k_s-1}\approx\frac{N_0}{\left(1-k_s\right)}$$

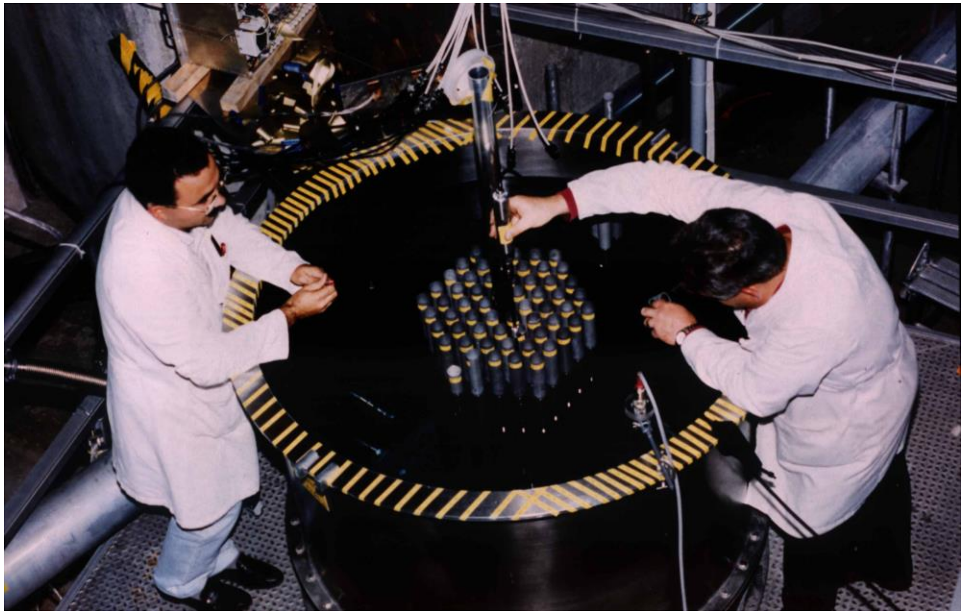
- The energy gain G is a characteristic of ADS:

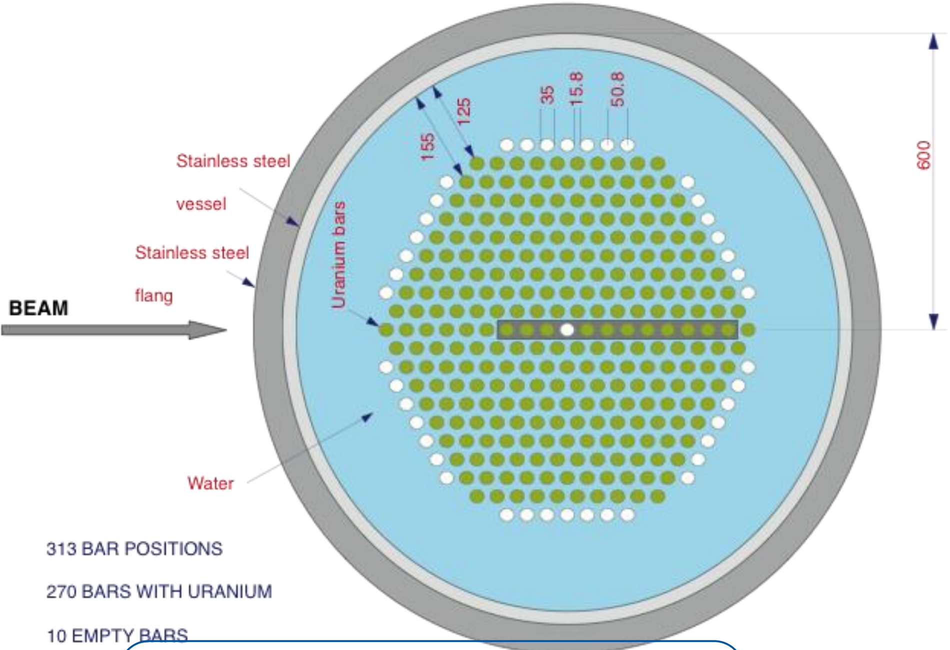
$$G\equiv\frac{\textit{Energy produced in EA}}{\textit{Energy injected by the beam}}=\frac{\overset{\text{Energy/fission}}{0.18}\,k_s\overset{\text{n/p}}{N_0}}{\underset{\text{n/fission}}{\nu}\left(1-k_s\right)\underset{\text{Beam energy}}{E_b}}=\frac{G_0 k_s}{\left(1-k_s\right)}\approx\frac{G_0}{\left(1-k_s\right)}$$

- G_0 includes information from the spallation process (G_0 ~ 3 for uranium; G_0 ~ 2.7 for lead, etc.)

FEAT at the CERN PS (1994)

- The goal of the **F**irst **E**nergy **A**mplifier **T**est (**FEAT**) at the CERN PS was to check the **basic concept of energy gain**, and **validate simulation**



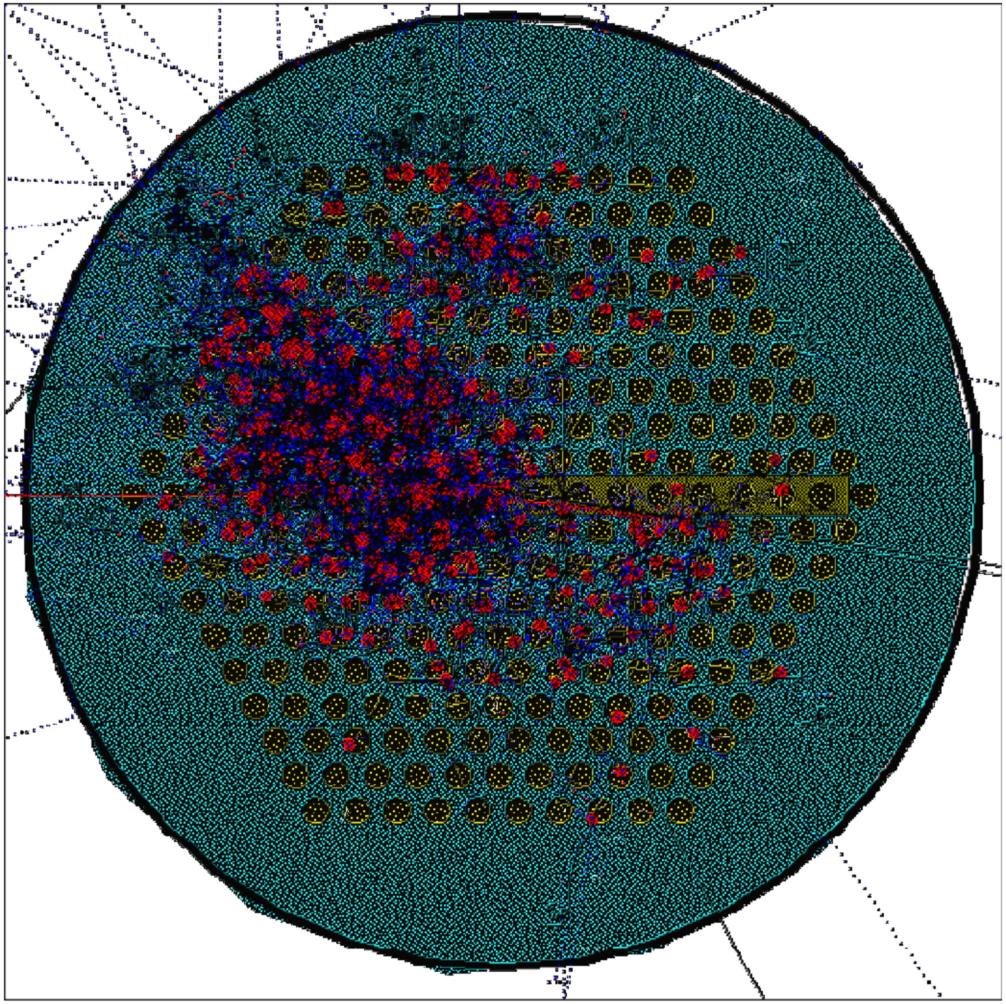


3.62 t of natural uranium; $k_{eff} \sim 0.9$

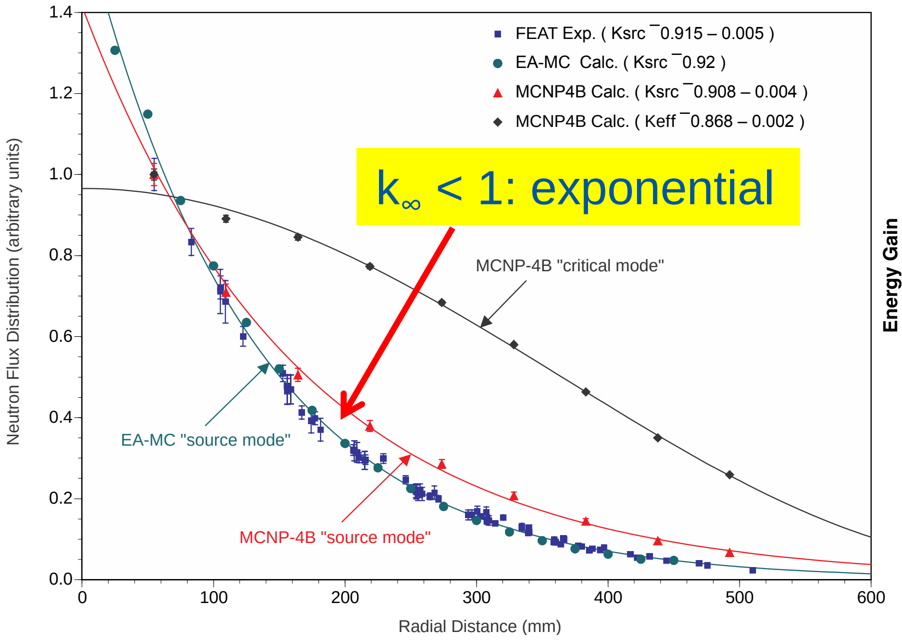
- Count fissions
- Measure temperature

FEAT at the CERN PS (1994)

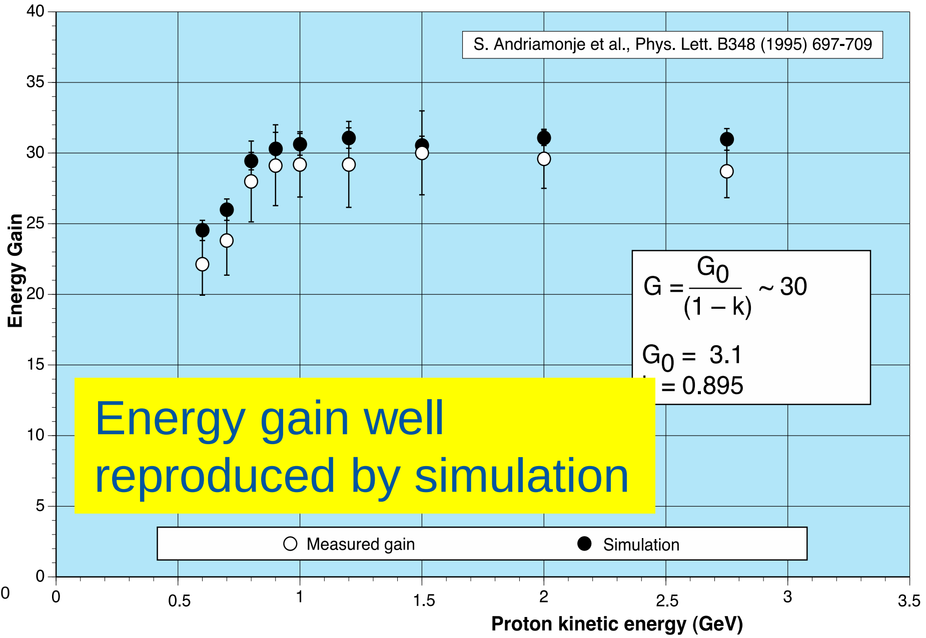
- Example of a secondary shower produced by a single proton



Main results from FEAT



$k_\infty < 1$: exponential



Energy gain well reproduced by simulation

- Two important results from FEAT:
  - **Optimum beam energy reached at about 900 MeV**, with slow decrease at higher energies (ionization vs nuclear cascade production). Above 900 MeV, the neutron yield scales with proton energy. At much higher energies the gain drops because of pion production.
  - **Simulation validated** from spallation to energy production

Energy gain in ADS systems

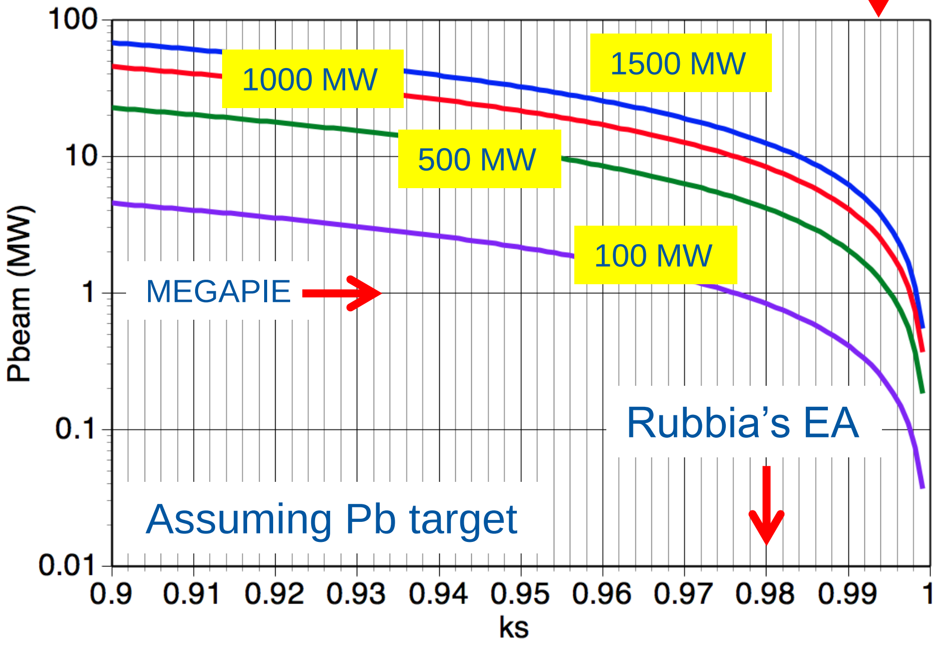
$$G = \frac{G_0\left(E_b, Material, Geometry\right)}{1-k_s}$$

$$P_{beam} = \frac{\left(1-k_s\right)}{k_s G_0} P_{ADS}$$

- For a given power output, the energy gain (choice of k_s and G_0) determines the accelerator power. **Trade-off between accelerator power and criticality margin**
- Modulating the beam intensity allows variations in the power output (complementary with a fluctuating renewable energy source)

With PSI separate turns cyclotron (3 mA and 1.8 MW, with 0.59 GeV protons).
P_{ADS} = 243 MW_{th} with k = 0.98
P_{ADS} = 486 MW_{th} with k = 0.99.

Margin of present PWR



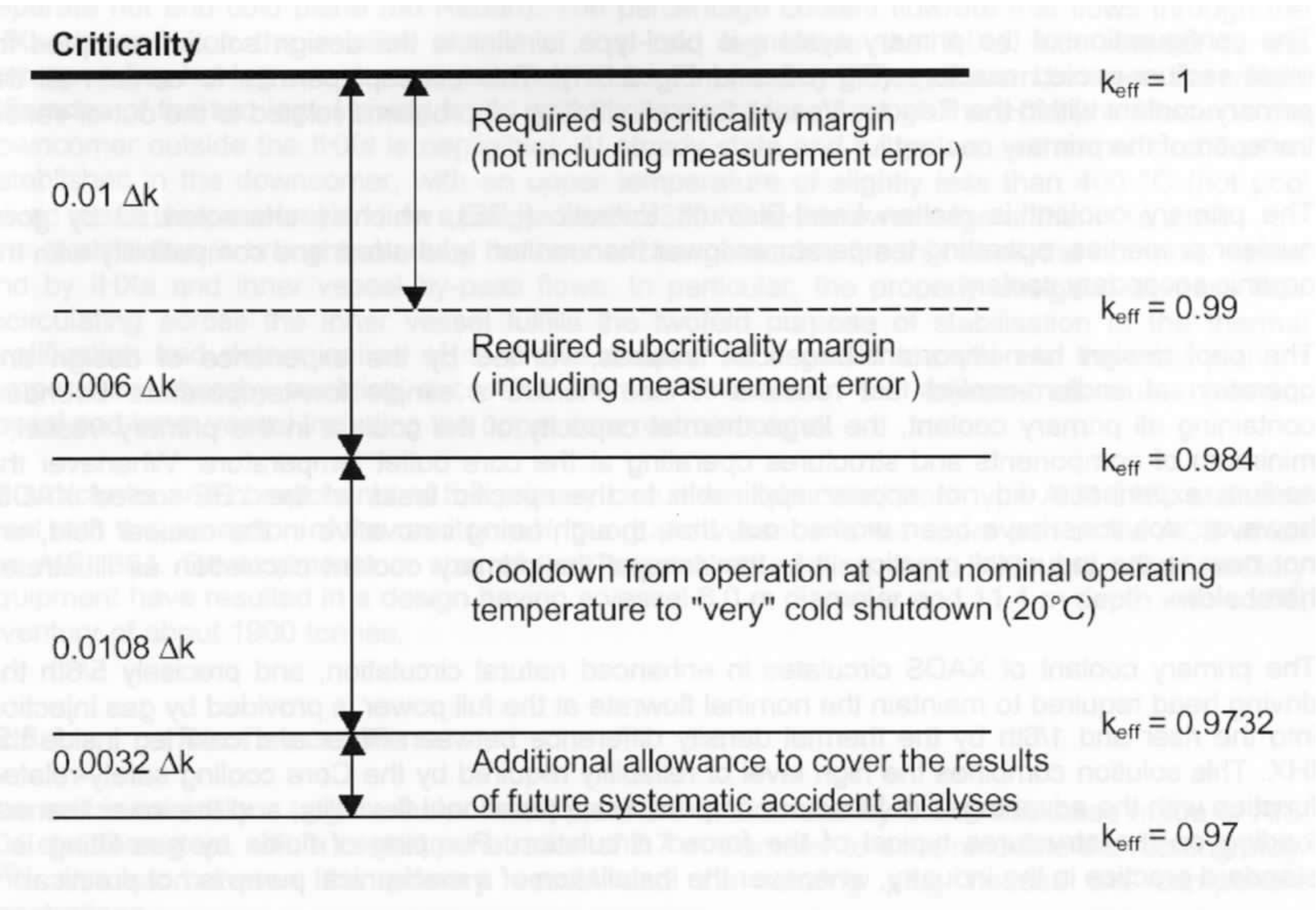
MEGAPIE

Rubbia's EA

Assuming Pb target

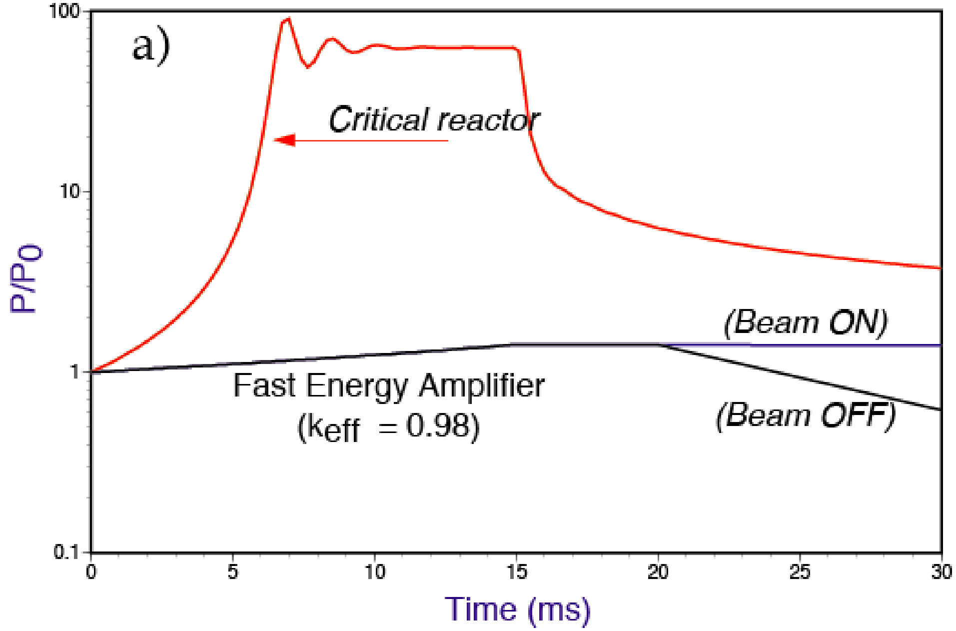
Determination of the Sub-critical Level

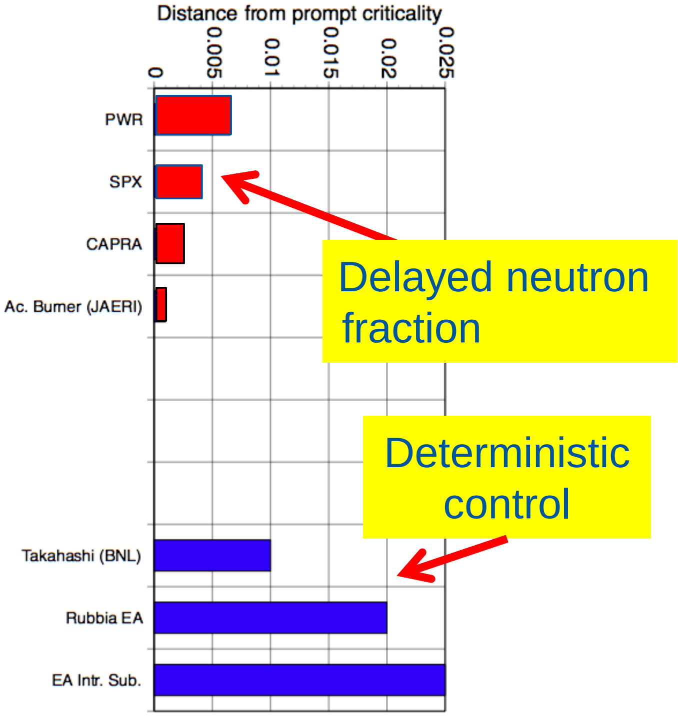
⇨*Safety:* The sub-criticality ($k \approx 0.95 \div 0.98$) condition is guaranteed at all times.



Features of subcritical systems

- Subcritical systems are insensitive to delayed neutron fraction (β); **safety margin** (distance from prompt criticality) **is a design choice**, it is not imposed by Nature!
- k_s = 0.975 makes the system subcritical under all conditions (after ^{233}Pa decay)
- The reactivity changes only very slowly; the beam can be switched off very quickly, reducing k_s to k_{eff}. It is possible to choose a higher k_s in order to reduce the load on the accelerator
  (Takahashi, k_s = 0.99)





Delayed neutron fraction

Deterministic control

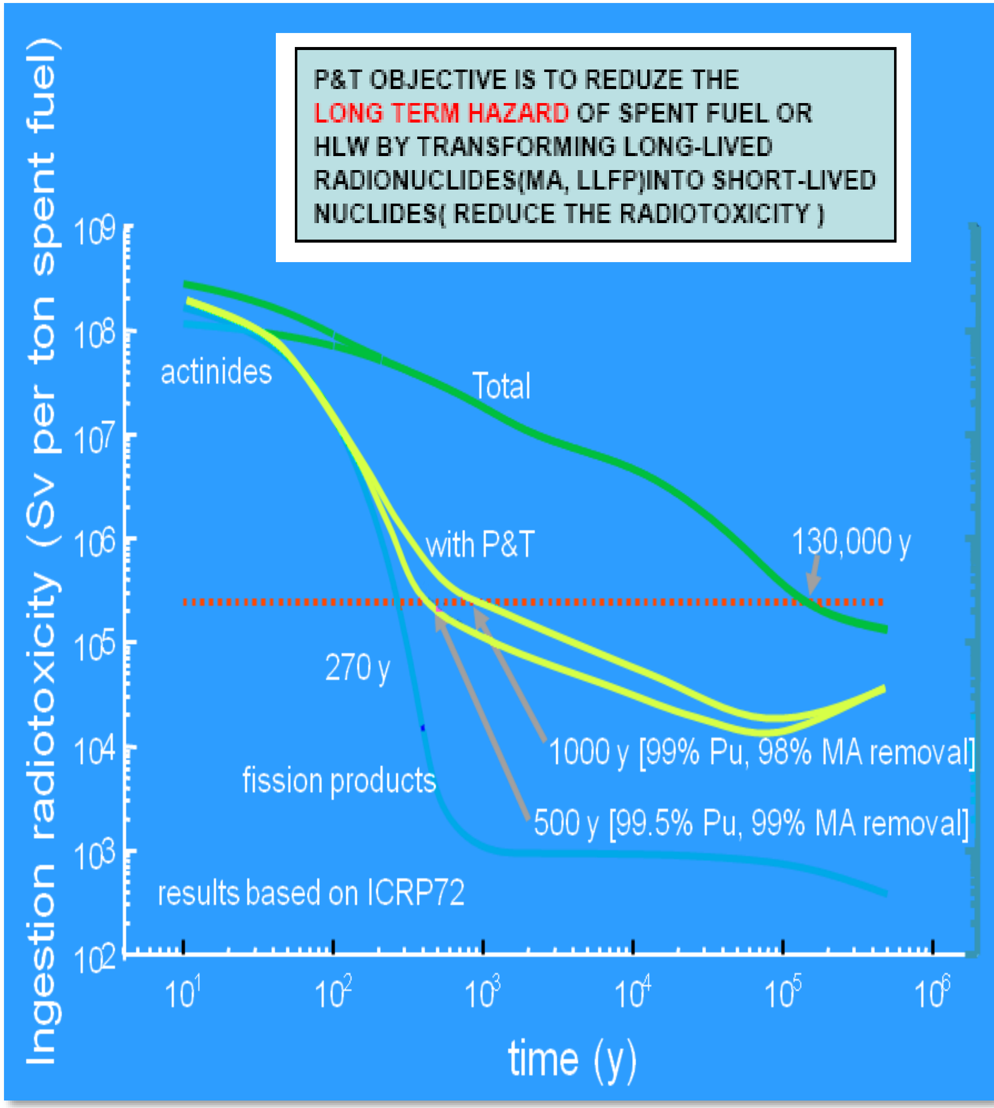
Guidelines for ADS parameters choice

- **Safety**:
  - Eliminate criticality accidents by making the system subcritical (void coef., T coef., β_{eff} no longer “critical” parameters)
    This requires an external proton source!

- **Waste management:**
  - Use (1) fast neutrons, (2) thorium fuel, and (3) recycle long-lived transuranic actinides (TRU) to minimize waste.

Partitioning &Transmutation

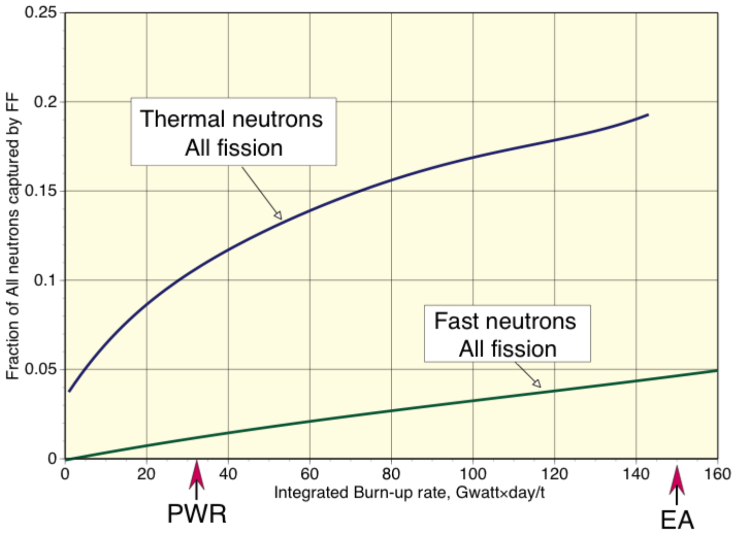
- P/T applies to **TRU** (**Pu** and **M**inor **A**ctinides) and **L**ong **L**ived **F**ission **P**roducts.
- It should be kept in mind that Plutonium is a special case: it can be considered as a valuable resource or part of the wastes.
- However, P/T technologies must apply to all fuel cycles.



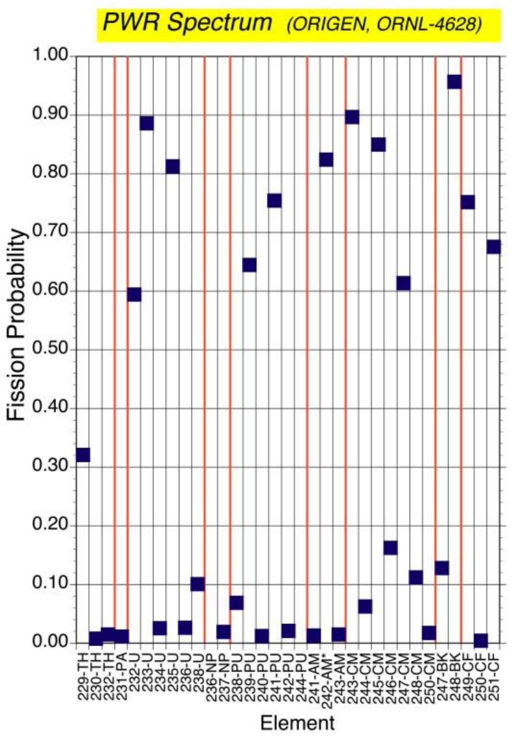
P&T OBJECTIVE IS TO REDUZE THE LONG TERM HAZARD OF SPENT FUEL OR HLW BY TRANSFORMING LONG-LIVED RADIONUCLIDES(MA, LLFP)INTO SHORT-LIVED NUCLIDES(REDUCE THE RADIOTOXICITY)

Use of Fast Neutrons

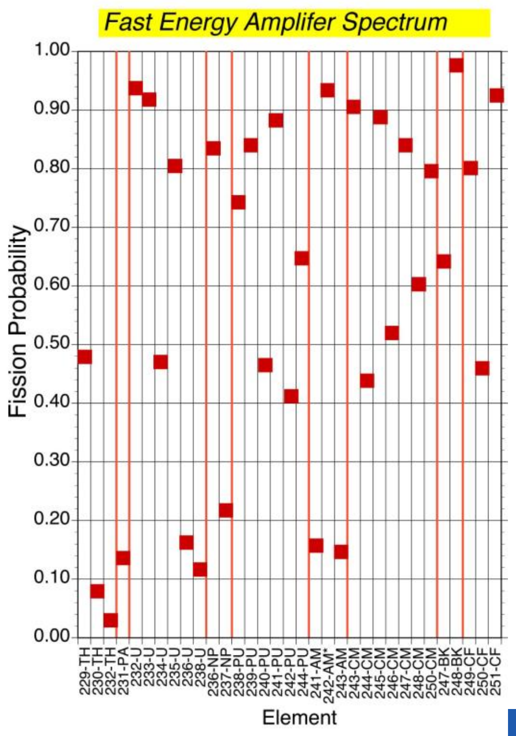
- Enhances TRU fission probability
- No need to separate out Pu!
  (**Pyro-Electro reprocessing**)
- Reduces captures on FF, extends burnup
  (120 GW.day/t achieved in fast electro-breeder at Argonne N.L., in EA simulation)

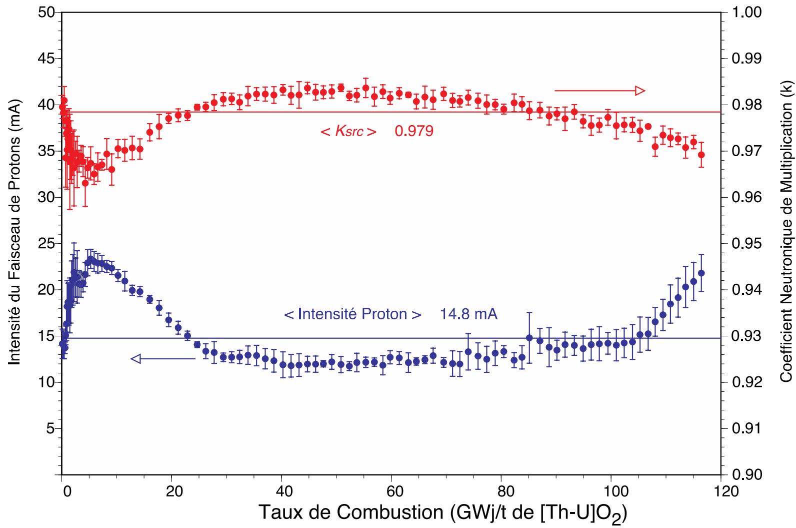


Thermal Neutrons



Fast Neutrons

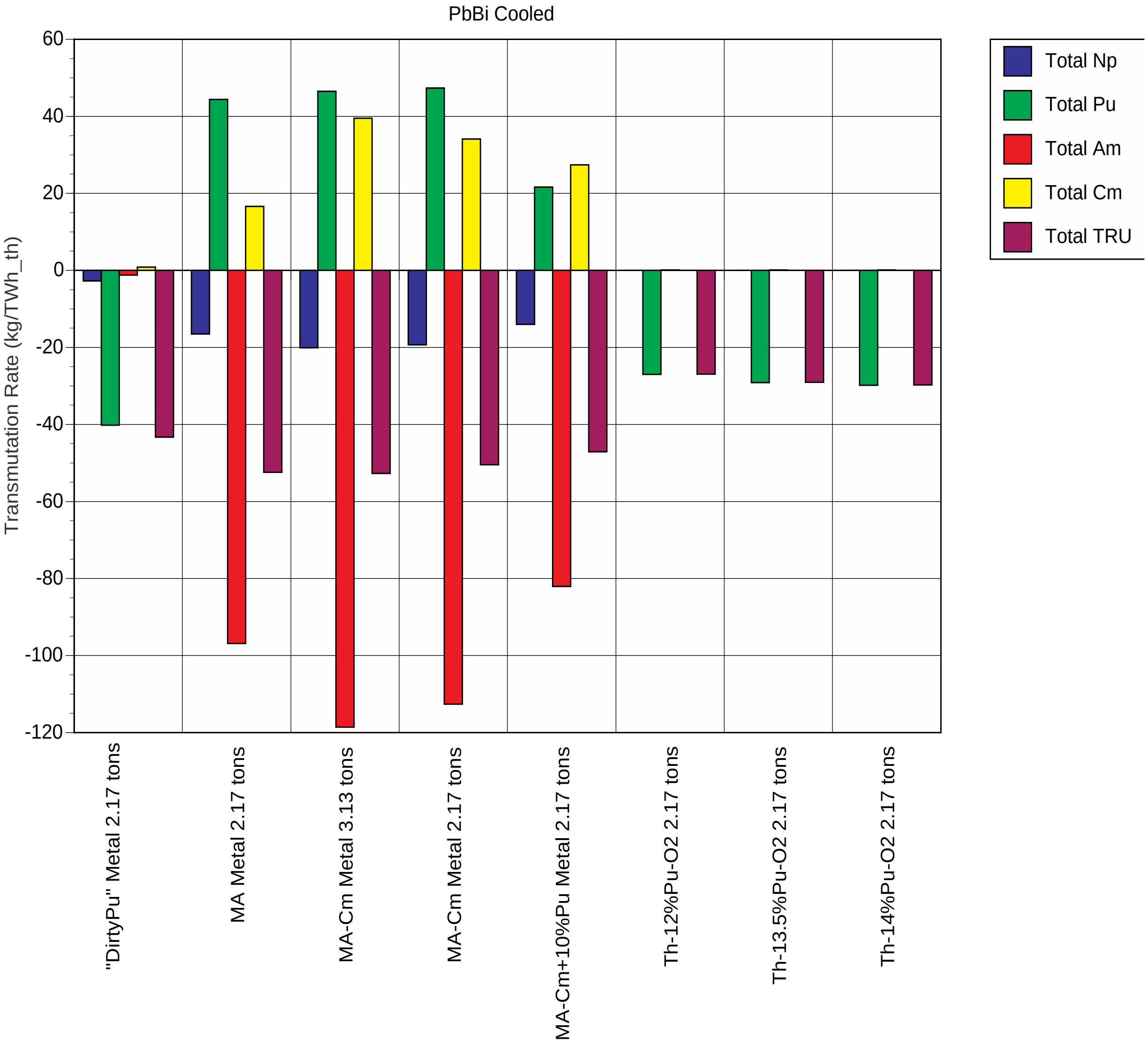




Transmutation of Nuclear Waste

Typical transmutation rates (~ 50 kg/TWh) using MA based fuels.

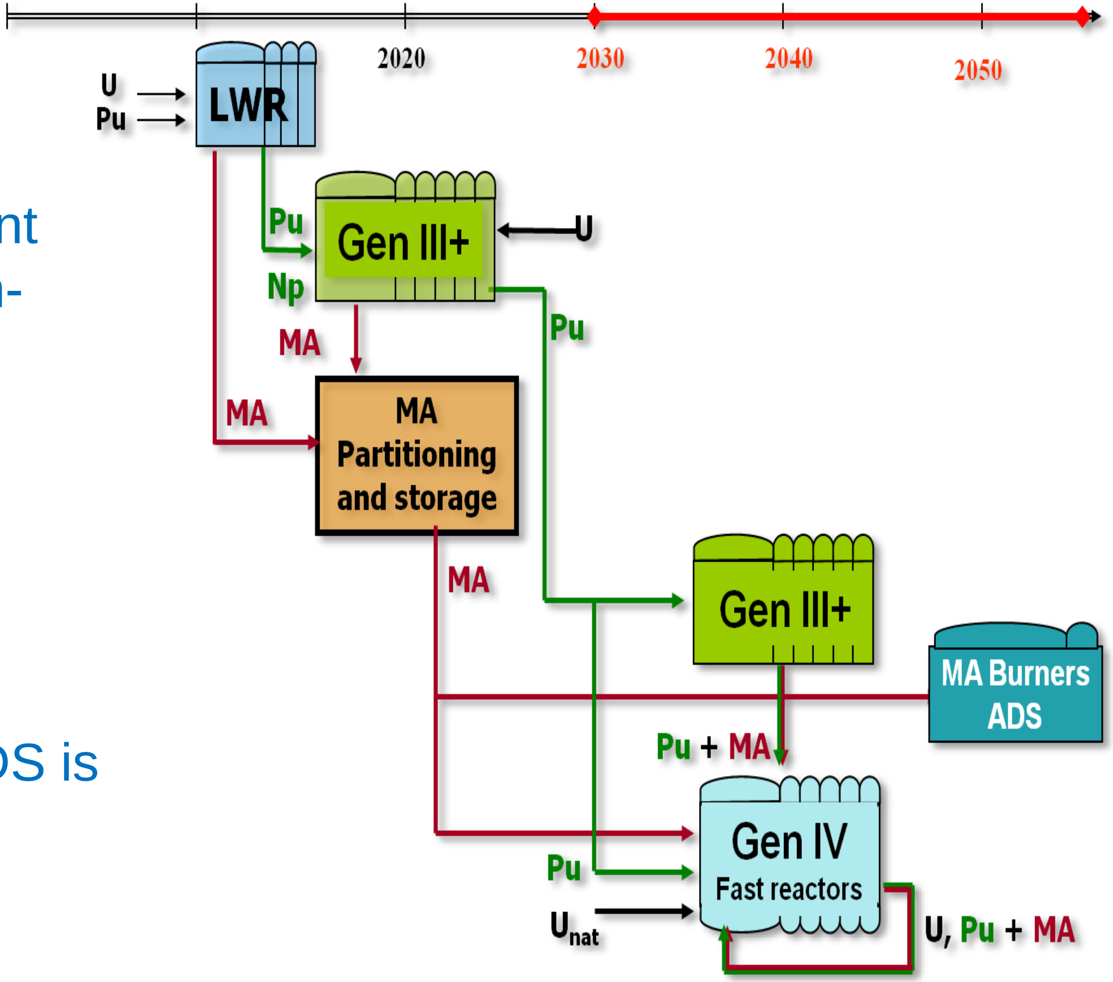
Doping with Pu will sensibly decrease the transmutation efficiency of such systems



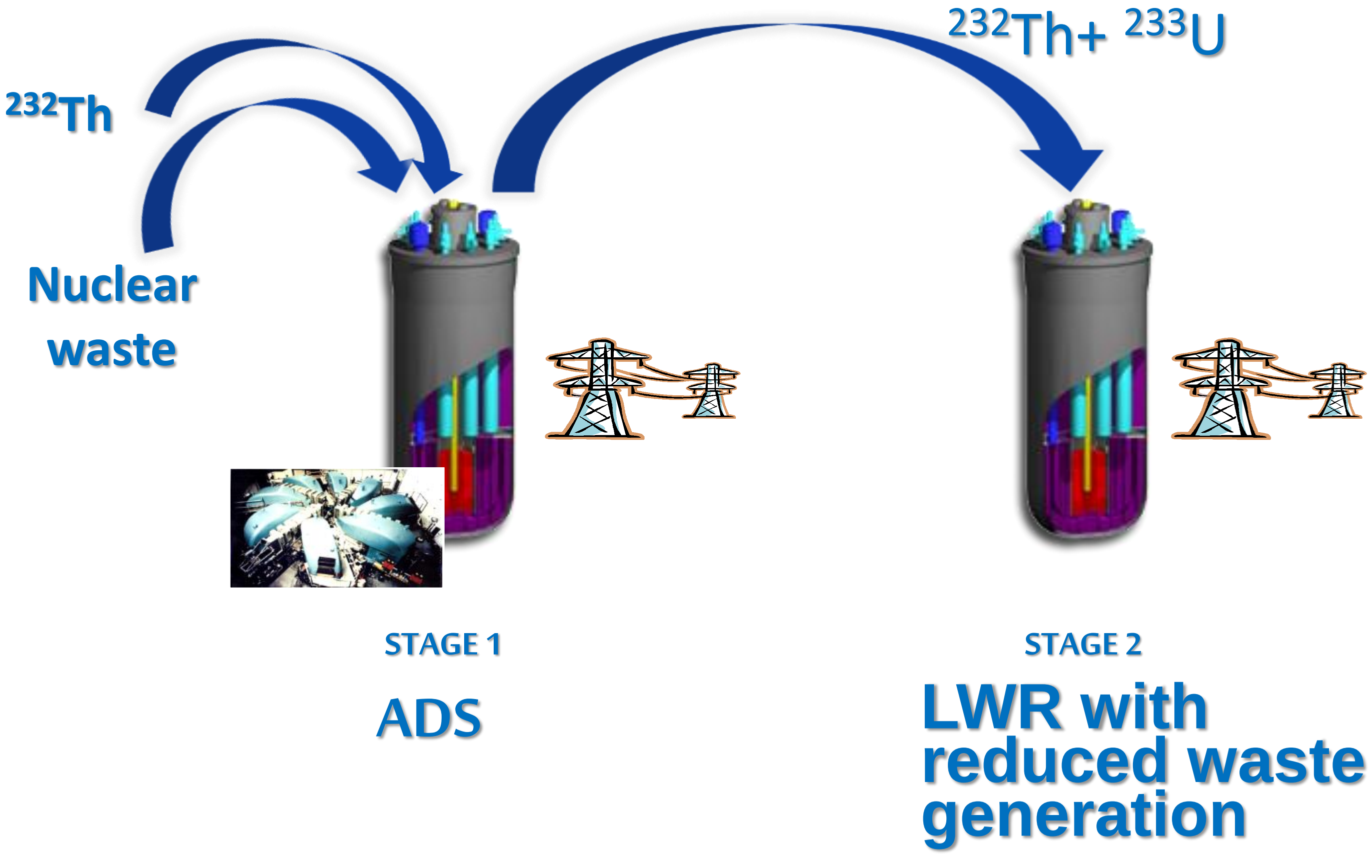
Transmutation of Nuclear Waste

- The objectives of GEN-IV include P/T (waste minimization), as consistent with sustainability and non-proliferation: it is the path towards “Advanced Fuel Cycles”.

- Implementation: currently related to Fast Reactor deployment. However, ADS is the only option for Minor Actinide elimination



Alternative Deployment of ADS



^{232}Th

Nuclear waste

^{232}Th+ ^{233}U

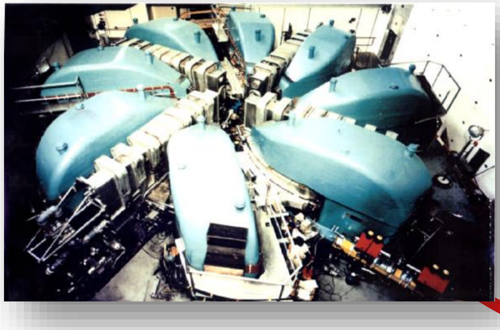
STAGE 1

ADS

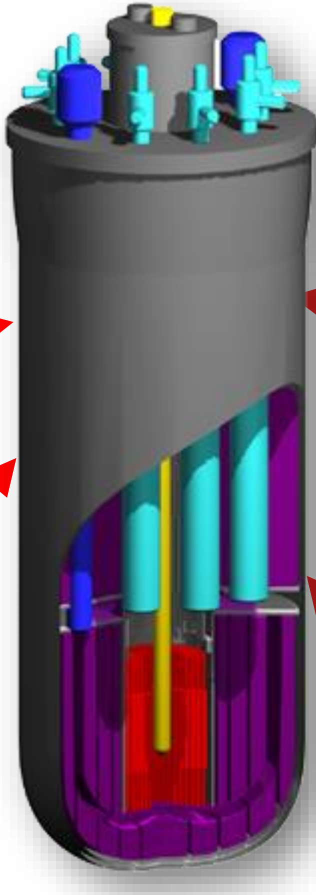
STAGE 2

LWR with reduced waste generation

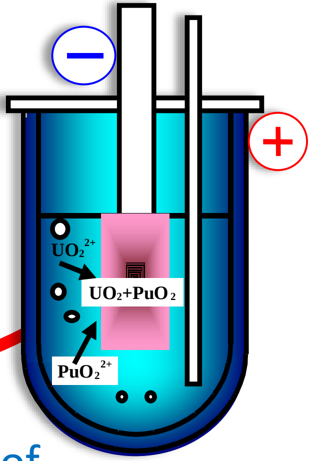
Status of ADS Technology



High power accelerators technology

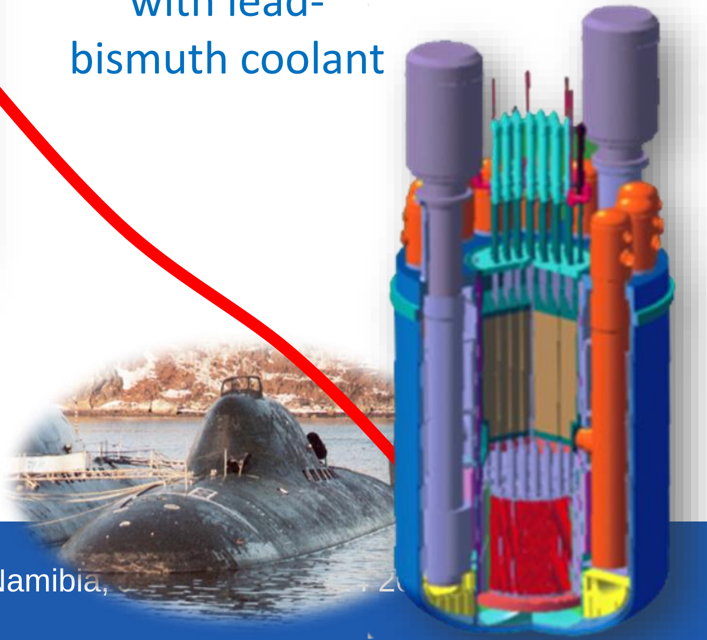


Technology of pyrochemical reprocessing of fuel



Technologies of fast reactors with lead-bismuth coolant

Liquid metal targets technology



Europe’s ADS Project: MYRRHA

In principle MYRRHA should be the flagship of ADS projects.

Strong support from the Belgian government, however:

– several challenges faced at the same time: the accelerator, the subcritical core and their coupling

– no thorium in the plans

– only partially funded

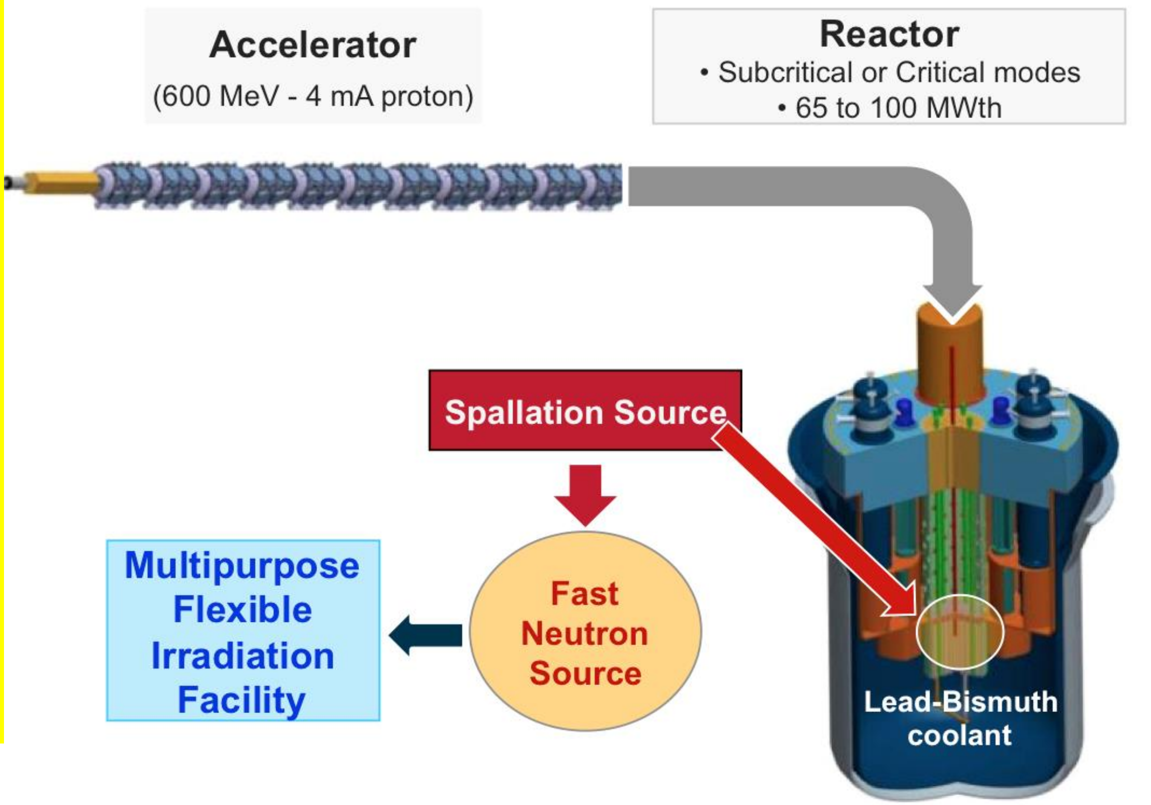
– not before 2025?

– will not remain an ADS, and will be turneds into a critical reactor

Hamid Aït Abderrahim

SCK•CEN, Boeretang 200, 2400 Mol, Belgium

MYRRHA - Accelerator Driven System



Accelerator

(600 MeV - 4 mA proton)

Reactor

- Subcritical or Critical modes
- 65 to 100 MWth

Spallation Source

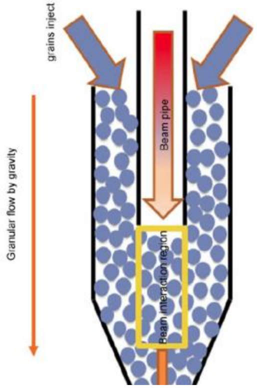
Fast Neutron Source

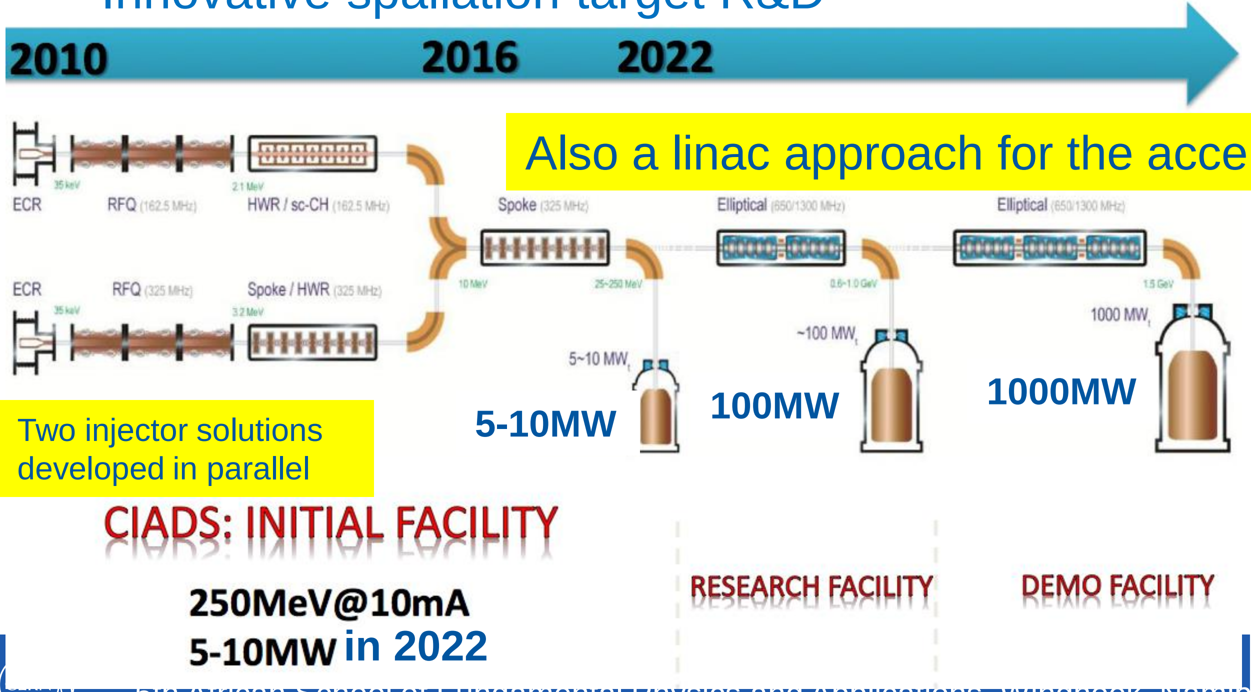
Multipurpose Flexible Irradiation Facility

Lead-Bismuth coolant

China’s ADS Project: ADANES

- The Chinese Accelerator-Driven System (CADS) project includes the accelerator, the target and the blanket. Accelerator-Driven Advanced Nuclear Energy System (ADANES) proposed as a complete energy system, integrating nuclear waste transmutation, nuclear fuel multiplication and energy production, aiming at 1000 MWe.
- ADANES has the potential to reach the requirements of sustainable development, safety, economic competitiveness, and nuclear weapon non-proliferation.
- Innovative spallation target R&D





Also a linac approach for the accelerator

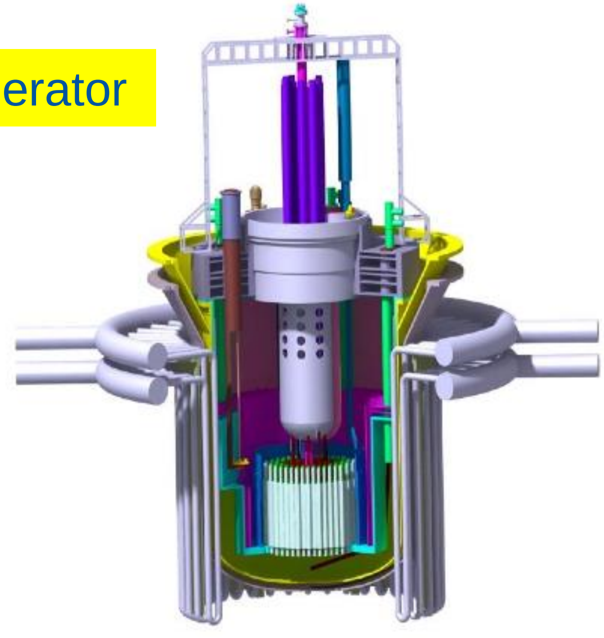
Two injector solutions developed in parallel

5-10MW

100MW

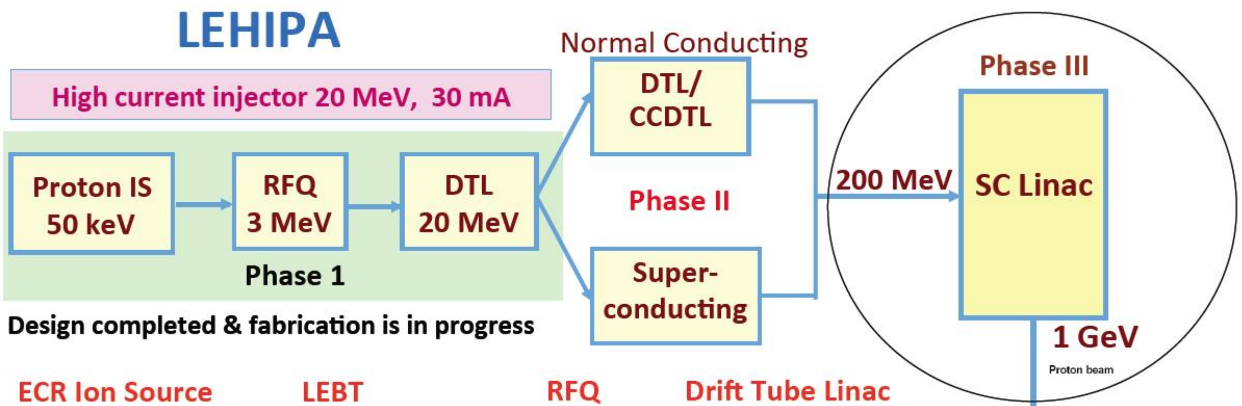
1000MW

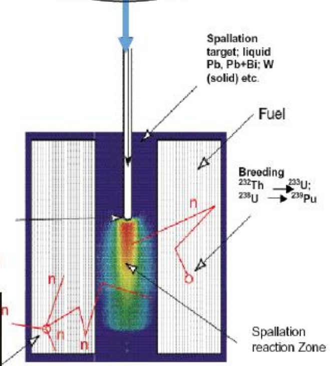
in 2022



India’s ADS Project:

Shashikant Degweker

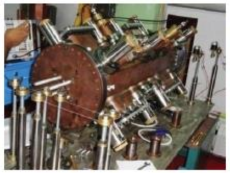




ECR Ion Source

LEBT

RFQ



Drift Tube Linac

50 kW RF Coupler

60 kW RF System

1.3 MW Klystron

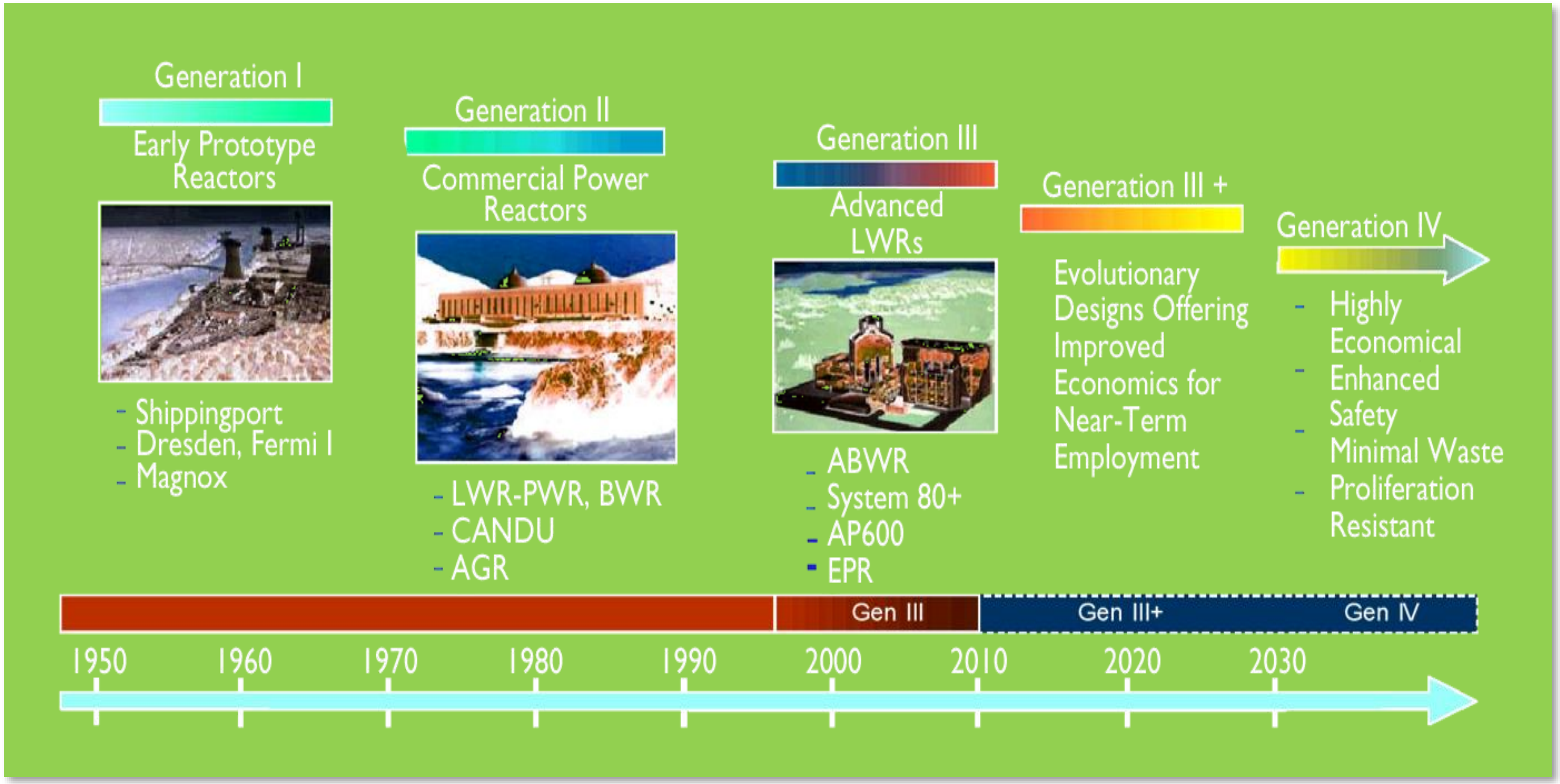
- India is mostly concentrating on the accelerator at this time
- Study of a high-current, high-energy proton accelerator (1 GeV and 30 mA), in collaboration with the USA (Old Fermilab Project X).
- **First phase**: development of a 30 mA, 20 MeV linac injector (LEHIPA).
- **Second phase**: accelerating the beam to an energy of 1 GeV by way of a superconducting linac.

Other AD R&D activities in may countries such as Venezuela, Turkey, Korea, Japan, Ukraine, UK – Many activities in the world but a lack of cooperation

A brief history of ADS projects

Project	Neutron Source	Core	Purpose
FEAT (CERN)	Proton (0.6 to 2.75 GeV) (~10^{10}p/s)	Thermal (≈ 1 W)	Reactor physics of thermal subcritical system (k≈0.9) with spallation source - **done**
TARC (CERN)	Proton (0.6 to 3.5 GeV) (~10^{10}p/s)	Fast (≈ 1 W)	Lead slowing down spectrometry and transmutation of LLFP - **done**
MUSE (France)	DT (~10^{10}n/s)	Fast (< 1 kW)	Reactor physics of fast subcritical system - **done**
YALINA (Belorus)	DT (~10^{10}n/s)	Fast (< 1 kW)	Reactor physics of thermal & fast subcritical system - **done**
MEGAPIE (Switzerland)	Proton (600 Me) + Pb-Bi (1MW)	-----	Demonstration of 1MW target for short period - **done**
TRADE (Italy)	Proton (140 MeV) + Ta (40 kW)	Thermal (200 kW)	Demonstration of ADS with thermal feedback - **cancelled**
TEF-P (Japan)	Proton (600 MeV) + Pb-Bi (10W, ~10^{12}n/s)	Fast (< 1 kW)	Coupling of fast subcritical system with spallation source including MA fuelled configuration – **reactivated**
SAD (Russia)	Proton (660 MeV) + Pb-Bi (1 kW)	Fast (20 kW)	Coupling of fast subcritical system with spallation source - **cancelled**
TEF-T (Japan)	Proton (600 MeV) + Pb-Bi (200 kW)	-----	Dedicated facility for demonstration and accumulation of material data base for long term – **reactivated**
MYRRHA (Belgium)	Proton (600 MeV) + Pb-Bi (1.8 MW)	Fast (60 MW)	Experimental ADS – **under design, not fully funded, 2025?**
CADS (China)	Protons (0.6 – 1.5 GeV)	Fast (100– >1000MW)	**Four phase project: 2011 – 2032**
U-ADS (Ukraine)	Electrons (100 MeV)	100 kW	Uranium-based ADS prototype (KIPT) **Status??**
ADS (Russia)	Protons (250-500 MeV)	1-5 MW	**Using an existing facility at Troitsk – under consideration promoted by iThEC**

Development is Time-Consuming



Concluding remarks

- Accelerator-driven systems offers a unique level of safety, which give operational flexibility to future systems for safe and clean energy production and waste transmutation
- Present accelerator technology offers the possibility of closing the thorium fuel cycle. The Energy Amplifier is one of the examples with high potential

Thank You