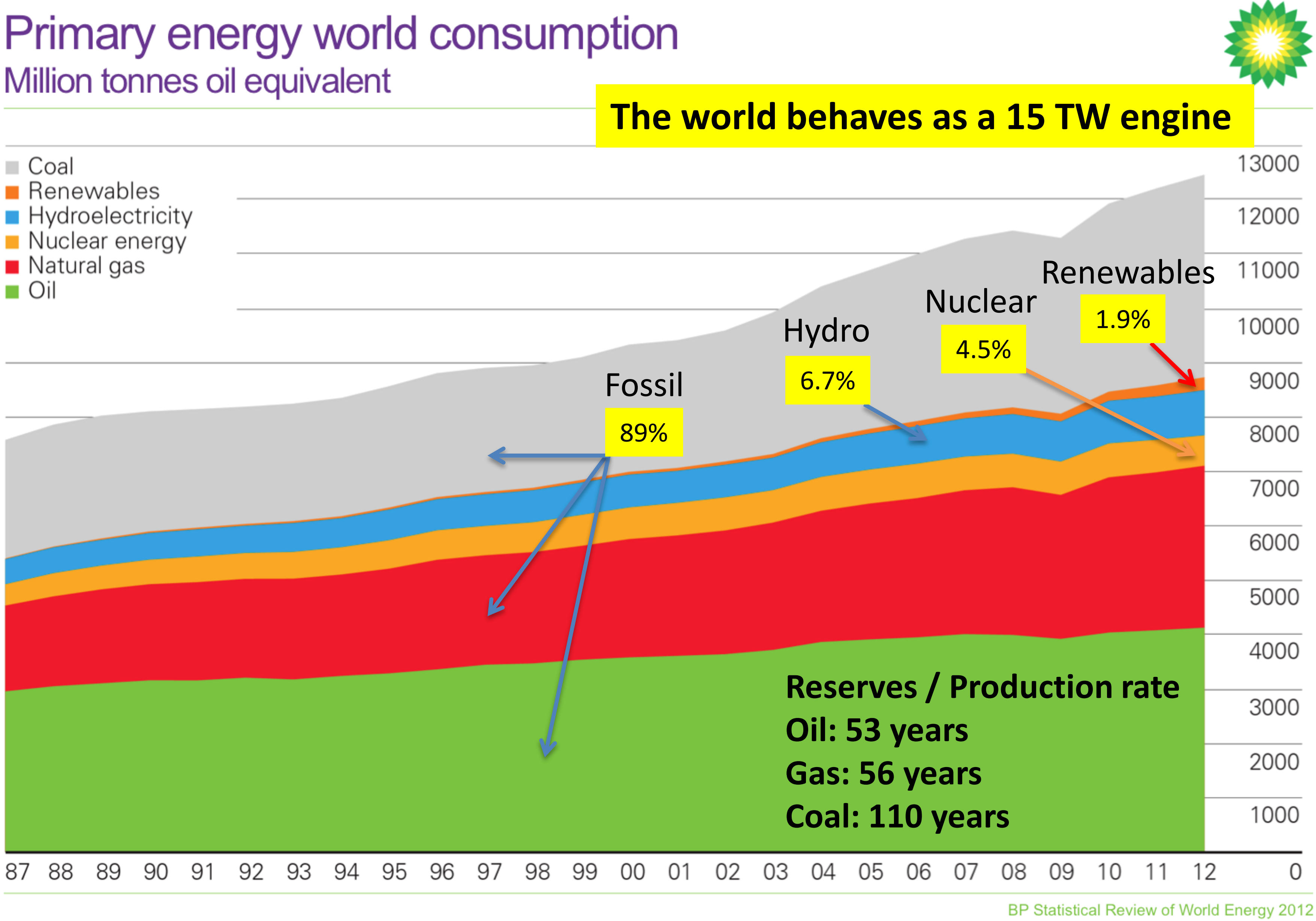
Why Accelerator-Driven Systems?

Eucard2-MAX
CERN, Geneva, Switzerland
March 20-21, 2014

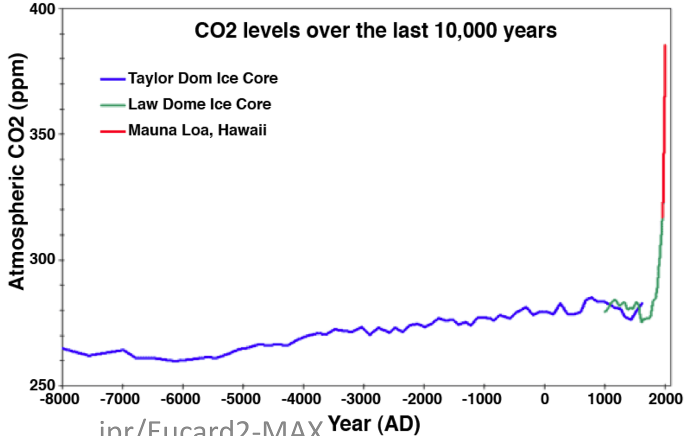
Jean-Pierre Revol
Centro Fermi, Roma
iThEC, Geneva



If by the end of this century, people in developing countries are allowed to live as well as we do in Europe today, the world power consumption will have to increase by a factor 3 or more

Burning fossil fuel till the end?

- **Global warming?** Not only is the atmospheric CO_2 level higher than ever in the past 15 million years, but it is also increasing faster than ever before (IPCC report March 2014)
- **Air pollution?**
  - Burning coal cost Europe alone 42.8 billion Euros in annual health care expenses (2013 report by the Health and Environment Alliance)
  - The ambient air pollution caused the premature deaths of 400,000 Chinese in 2013
- The current tendency is to increase the use of fossil fuel
- **Way out?** Develop renewable energies, save energy, improve energy efficiency and **innovate!**
- Innovation implies investment in a broad spectrum of R&D domains



Energy R&D

- Relying entirely on wind and solar energies would imply increasing their contribution to world energy by a factor 140 or more by the end of the century
(+ dispersed and intermittent)
- Energy R&D has to explore all possibilities, without prejudice:
  - Energy efficiency
  - Energy storage and transport
  - Wind
  - Solar Photovoltaic
  - Solar thermal
  - Biomass
  - Geothermal
  - Nuclear fusion
  - Nuclear fission
    - Generation IV
    - **Innovative nuclear systems based on thorium**

Thorium Energy Conference (ThEC13)

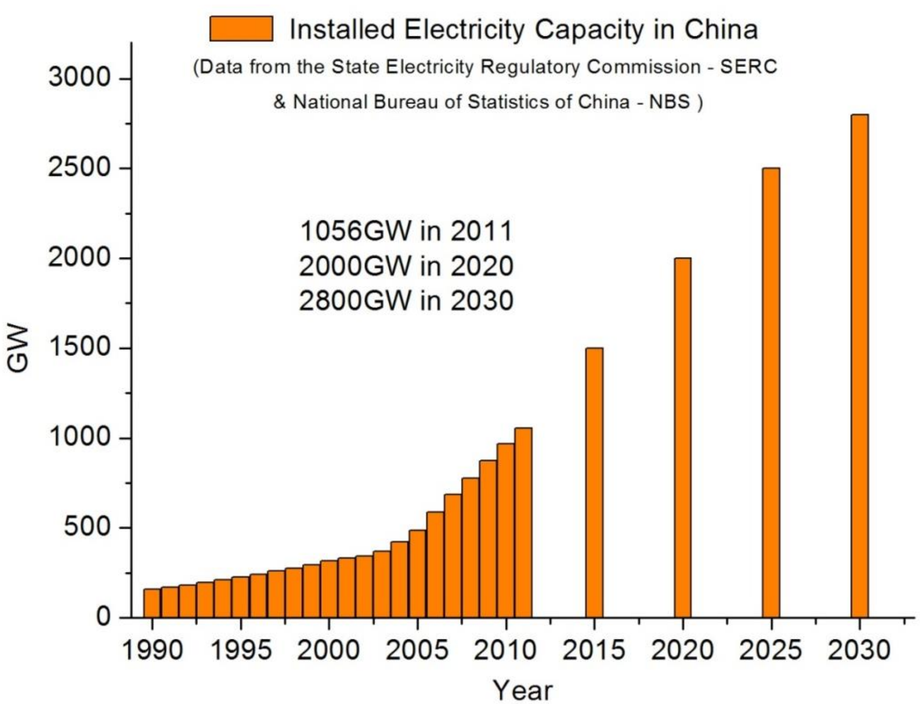
- Organized by the international Thorium Energy Committee (iThEC, http://www.ithec.org)
- Participants from 32 countries, 47 speakers, including some prestigious personalities.
- Representatives of both India and China cited energy issues as their prime concern and announced strong motivations to do R&D on thorium http://indico.cern.ch/event/thec13

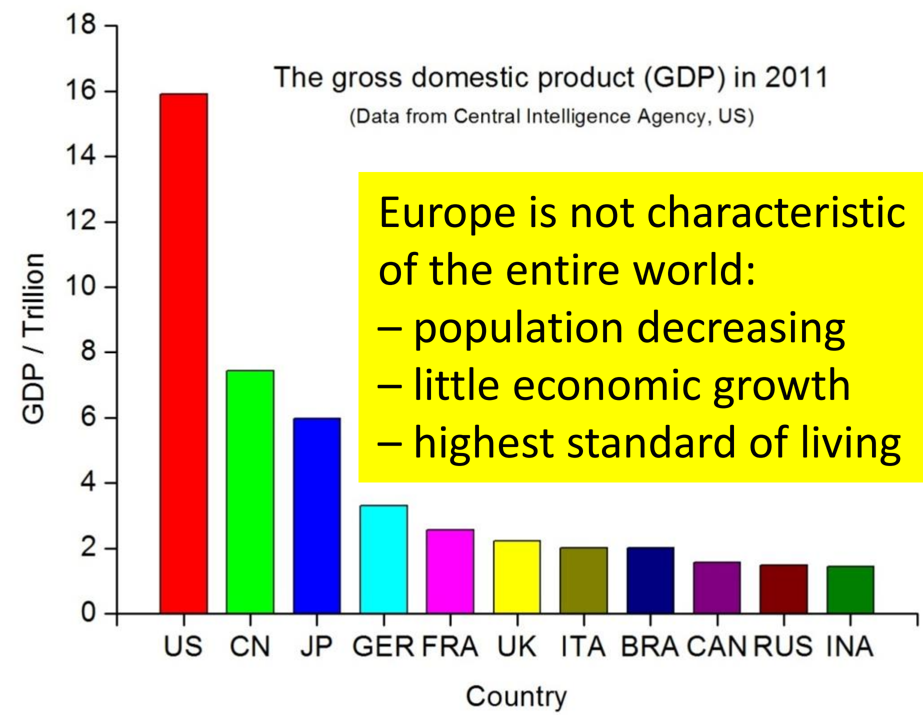
Foundation for the Economy and sustainable Development of the Regions of Europe

Xu Hongjie

China's Energy Challenge

- Analysis and forecast on national electric power in China: In 2030, the electricity demand of per person will be about 2KW, total generation capacity will reach about 3000GW, the MW -level power stations will need 3000.





The interest of industry

- Clear sign of an increasing worldwide interest in thorium, finally reaching nuclear industry. Present nuclear scheme not sustainable: go to fast critical breeders (GENERATION IV) or to thorium.
- For the first time, thorium officially mentioned by a French main nuclear actor. At ThEC13, AREVA and SOLVAY announced an agreement on thorium:

AREVA and SOLVAY join their know-how to add value to thorium's entire life cycle

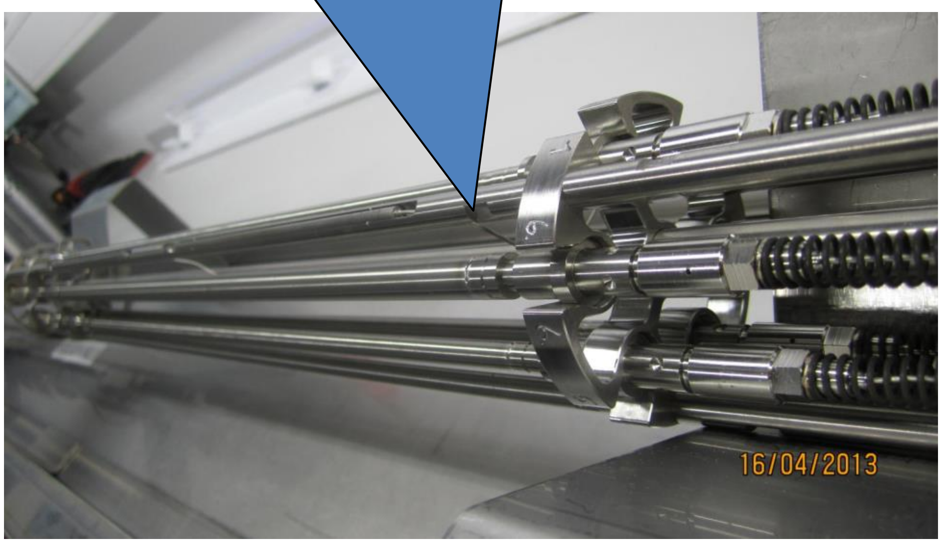
Luc van den Durpel
CERN, Oct. 29, 2013

- Industry is presently only considering an adiabatic transition from uranium to thorium, starting by inserting a few thorium fuel elements in a uranium reactor.

Thorium in Light Water Reactors

Thor Energy (The Norwegian Thorium Initiative) collaborates with Westinghouse to carry out **thorium fuel tests** in the Halden research reactor.

- 2 Rods 85%Th - 15%Pu pellets, ITU, Germany
- 2 Rods 7%Th – 93%UOX, IFE, Norway
- 1 Rod 65%Th – 35%UOX, IFE, Norway
- 1 UOX Reference rod



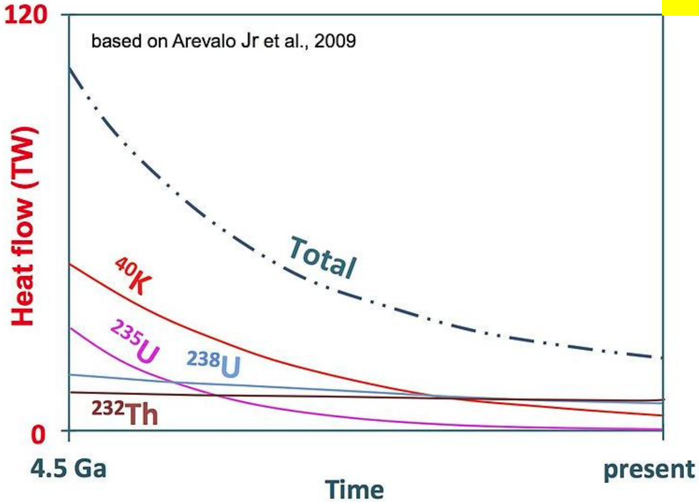
Halden Research Reactor
Institute for Energy Technology (IFE)

$^{232}Th_{90}$

- **Abundant**, as much as lead, and about three to four times more than uranium
- Main contributor to the 30 TW of Earth's internal thermal energy flow
- Known and estimated resources: 4.4×10^6 tons (> 700 years of world energy)
- "Thorium is essentially a sustainable source of energy on the human time scale"

C. Rubbia @ ThEC13

Monazite sample containing 2 to 3% of thorium mixed with rare earths (from the Steenkampskraal mine, South Africa)

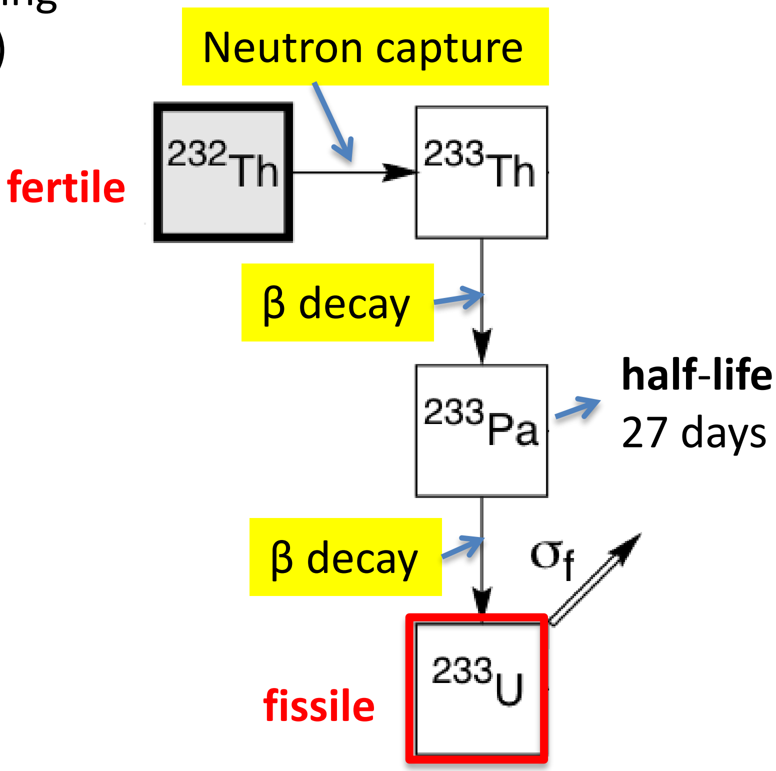


– Thorium occurs in several minerals including thorite ($ThSiO_4$), thorianite ($ThO_2 + UO_2$) and monazite. **Often a by-product of mining for rare earths** (lanthanides plus scandium and yttrium), tin, coal and uranium (tailings)

– α-decay with a half-life of 14 billion years

Fission energy from $^{232}Th_{90}$

- No CO_2, no NOx, etc. Fission energy well understood, the technology exists
- Thorium is **fertile**, not fissile, so **ONLY** in breeding mode, however, this gives a potential 140 factor gained compared to ^{235}U in PWR (in addition to the factor 3 to 4 in abundance)
  - ☞ Thorium dioxide (ThO_2) has the highest melting point (3300 °C compared to 2865 °C for UO_2) of all oxides and is one of the best refractory materials.



Thorium chain

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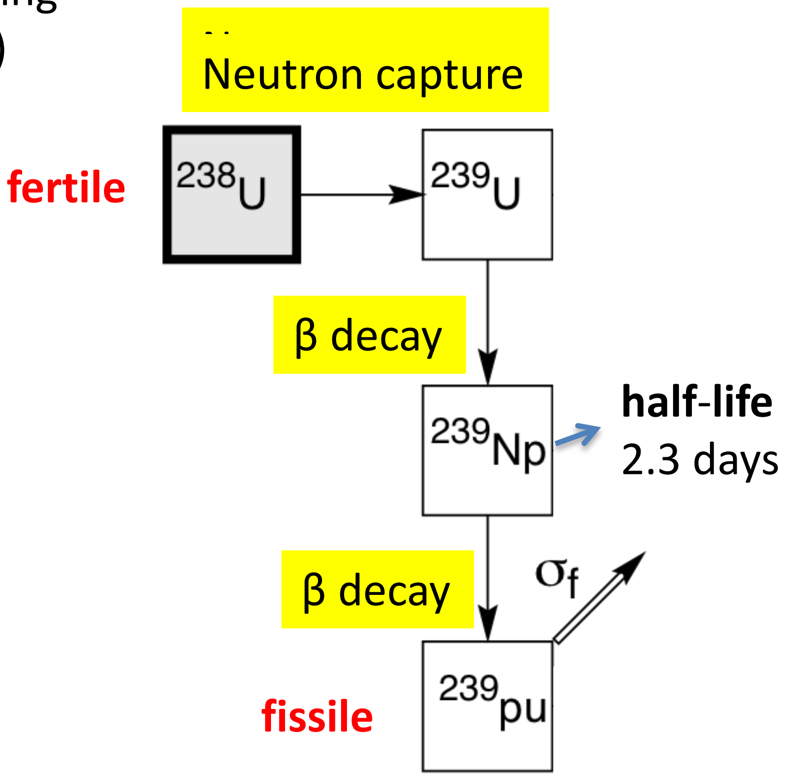
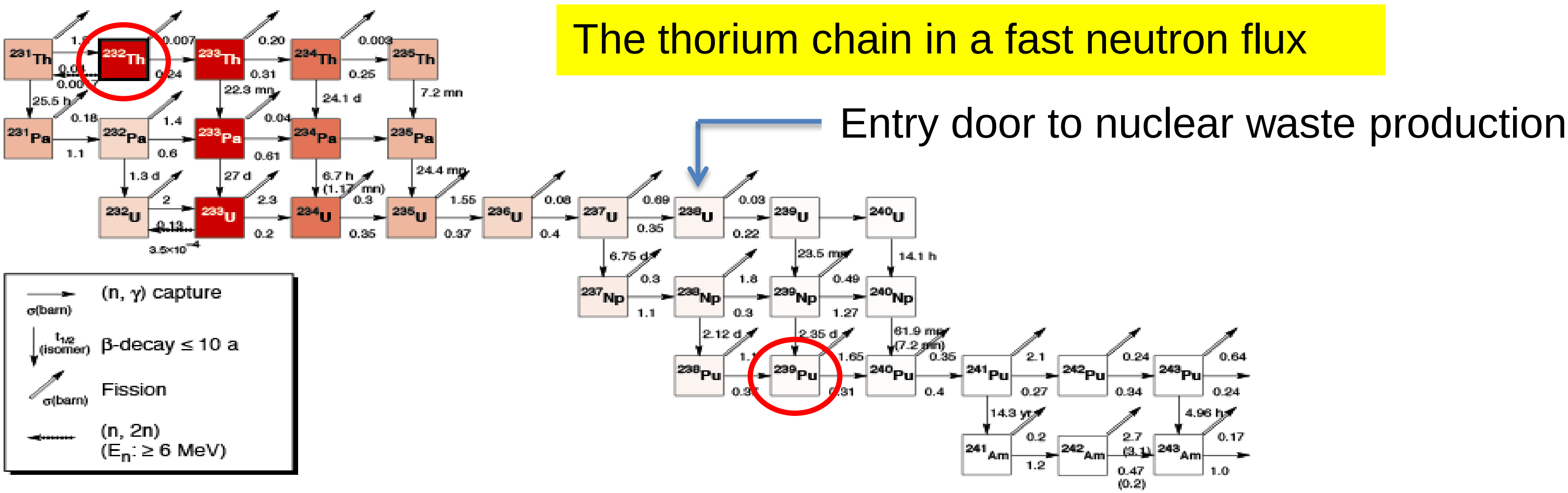


Uranium chain

Fission energy from thorium

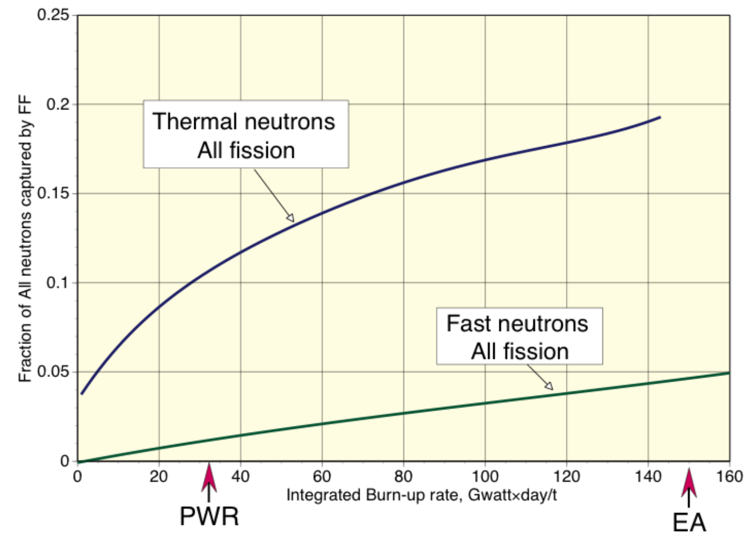
- Thorium minimizes nuclear waste production, because it is **7 neutron captures away from plutonium-239**

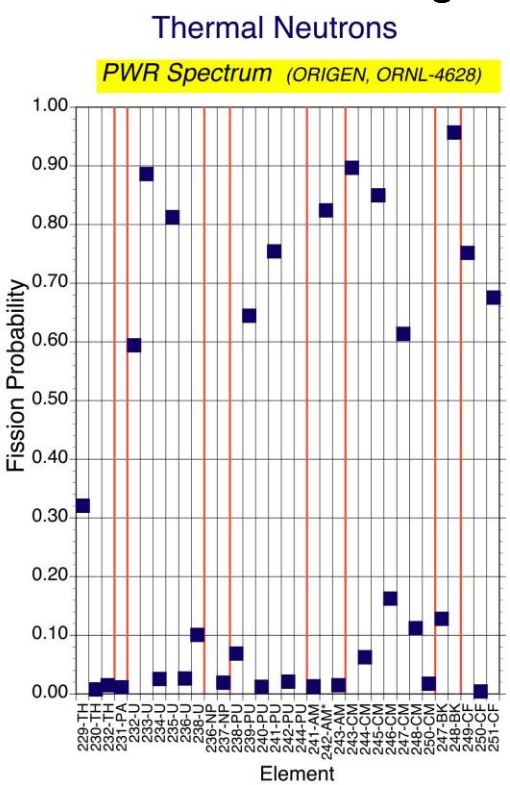


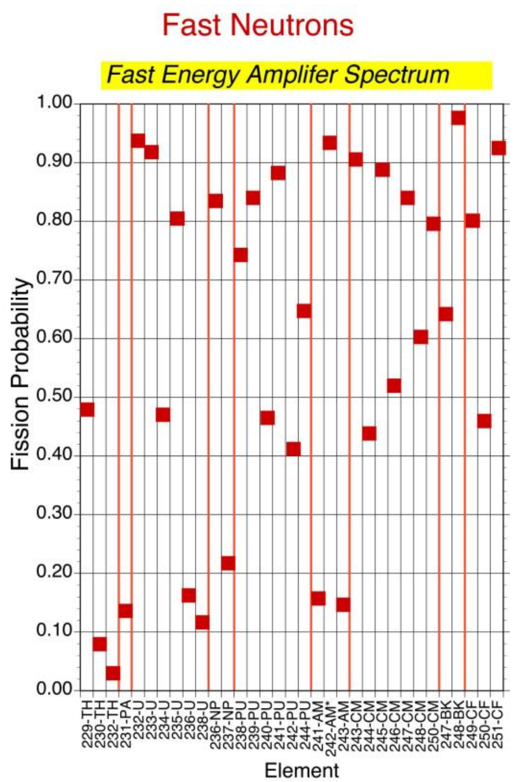
- Combining with a fast neutron flux, thorium represents a unique potential for nuclear waste elimination
- The thorium fuel cycle is non proliferating (very hard to make bombs)

Nuclear waste elimination

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







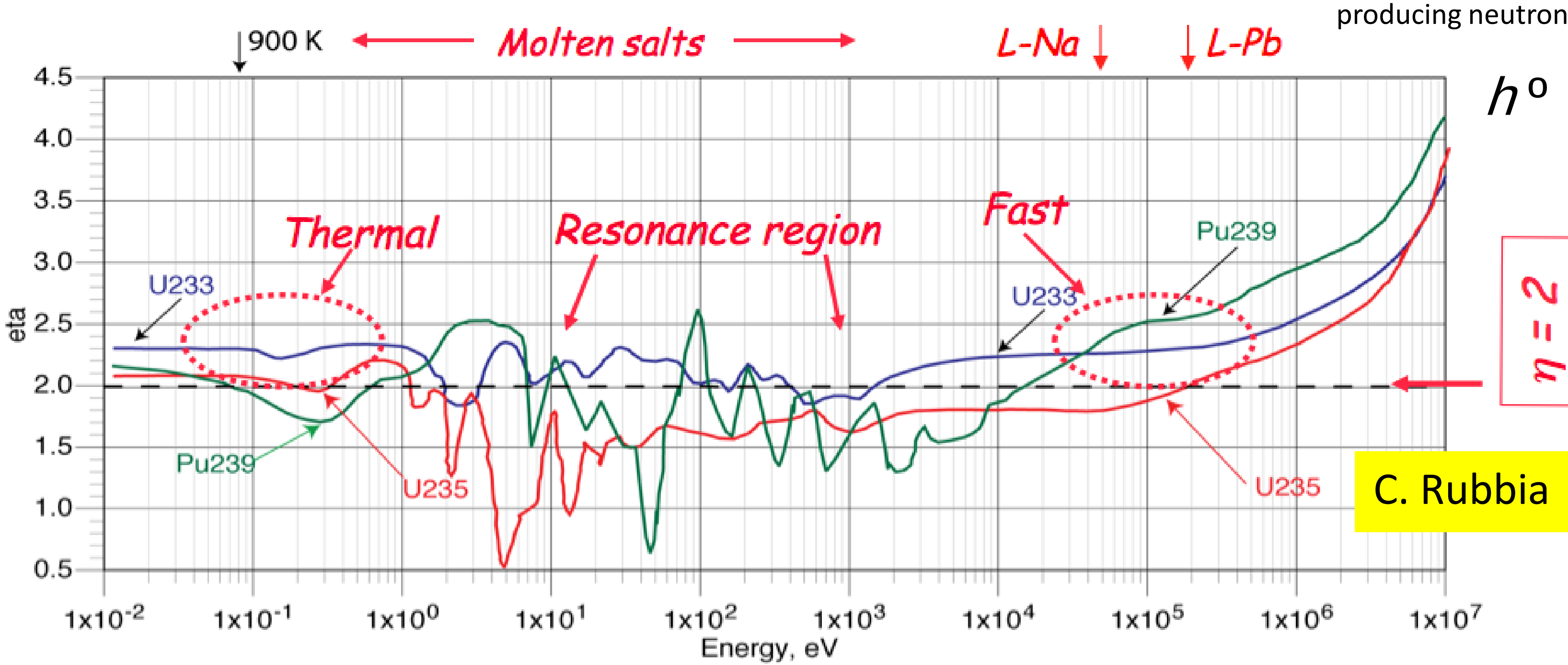
Thorium

- **Why is it challenging to use thorium?**
  - ^{233}U has to be produced from thorium (breeding)
  - Thorium + fissile element cannot be substituted simply to PWR fuel because of neutron inventory issues (large capture rate on thorium and long half-life of ^{233}Pa)
  - ^{233}U is generally better than ^{235}U and ^{239}Pu except in a fast neutron flux, where neutronics is less favourable than ^{239}Pu.

Fraction of neutron absorptions producing neutrons

$$\eta \equiv \nu \frac{\sigma_f}{\sigma_f + \sigma_c}$$

Neutrons per fission



C. Rubbia

CERN_Oct_2013

Using thorium

- **What are the options?**
  - ☛ Use **thorium blankets** around reactors, to breed ^{233}U and introduce ^{233}U in fuel
    ($n + {}^{232}Th \rightarrow {}^{233}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$)
  - ☛ **Continuously move the fuel out**, such as to always have fresh fuel
    - Pebble bed reactors (once through)
    - Molten salt reactors (reprocessing on-line)
  - ☛ **Accelerator Driven Systems** (ADS), providing an external neutron source: this is the solution proposed by C. Rubbia at CERN and promoted by iThEC

Thorium blankets challenges

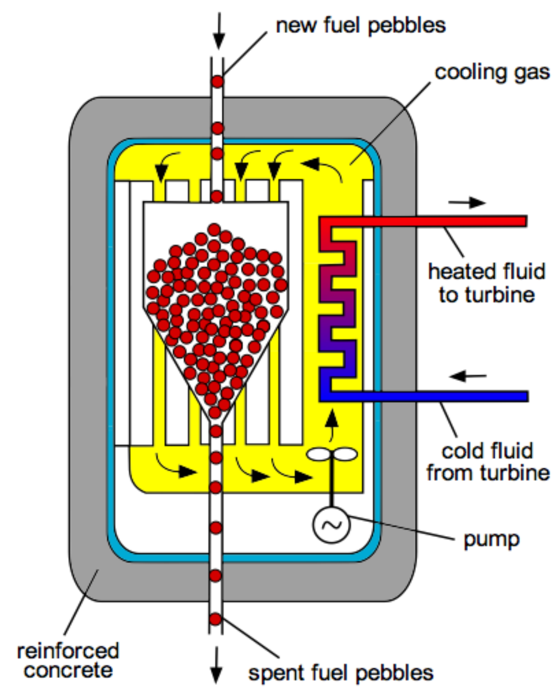
- India, with little uranium resources but a lot of thorium, has the most advanced practical scheme for using thorium, including front-end and back-end of the fuel cycle:
  - Use **heavy water reactors** (CANDU) or LWR to produce plutonium from their small uranium supply
  - Use **sodium cooled U-Pu fast reactors** with a thorium blanket to breed ^{233}U
  - Reprocess blankets and manufacture ^{233}U-Th fuel for **advanced fast reactors or thermal water reactors**

- The Indian scheme works. However, issues remain concerning the **complexity** (three technologies), the **sustainability** and it does not solve **nuclear waste management**.

Pebble bed critical reactors

- First proposed by Farrington Daniels at Oakridge, in the 1940s. Initial developments in Germany (AVR Jülich), followed by THTR-300. New developments in South Africa, the United States and Turkey:
  - Not discussed at ThEC13
- Several issues for pebble bed reactors:
  - No containment building if cooling by natural air convection
  - Uses of flammable graphite as moderator
  - Produces more high-level nuclear waste than current nuclear reactor designs
  - Relies heavily on nearly perfect fuel pebbles
  - Relies heavily upon fuel handling as the pebbles are cycled through the reactor. There was an accident at a pebble bed reactor in Germany due to fuel handling problems
  - Reprocessing virtually impossible

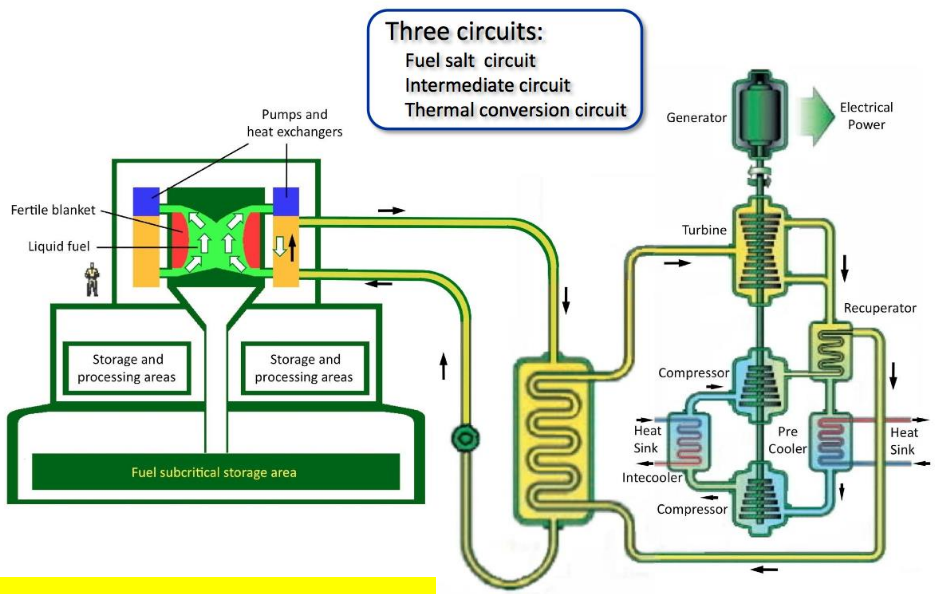
Pebble Bed Reactor scheme



Molten salt critical reactors

- This is clearly a technology that is concentrating interest (10 talks related to the subject at ThEC13)
- There is a particularly well focussed and most ambitious effort in China (Xu Hongjie, Shanghai, CAS Center)
- This is clearly a line of research where synergy should be improved, as there are a lot of developments to be made to demonstrate the practicality of the scheme.
- Presently not providing a fast neutron spectrum. R&D should be extended to other salts in view of minimizing waste
- Proliferating, breaking confinement principle, delayed neutrons emission, problem if the on-line chemistry loop is blocked, corrosion, licencing issues, etc.

Molten Salt Fast Reactor (MSFR)



Paul Madden (Oxford, UK)

ADS @ ThEC13

- Largest number of talks at ThEC13 (16 talks), very advanced conceptual studies (Carlo Rubbia's EA, MYRRHA)
- Status of readiness of technologies:
  - Accelerator(s) (cyclotrons, linacs, Fixed Field Alternating Gradient)
  - Spallation targets
  - Core designs
- Presentation of systems
  - MYRRHA
  - Troitsk (Russia) & CADS (China) for burning minor actinides, and a discussion in India to use ADS to simplify the present thorium utilization scheme
  - Molten salt ADS (C. Rubbia, Japan, Korea)
- Concrete tests
  - PSI beam (> 1MW proton beam)
  - MW spallation target (MEGAPIE@SINQ (Swiss Spallation Neutron Source), SNS (US Spallation Neutron Source), etc.)
  - Reactivity measurement by beam pulses (Cheol Ho Pyeon)
  - Corrosion, material compatibility, etc.

Advantages of ADS

- **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!
  - Operate system with passive safety elements to avoid core melting or limit its consequences, borrowing features from US advanced fast critical reactor designs;
  - Avoid dangerous coolants such as liquid sodium (use lead) Generation IV?
- **Waste management**:
  - Use (1) fast neutrons, (2) thorium fuel, and (3) recycle long-lived transuranic actinides (TRU) to minimize waste production or destroy existing waste
- **Military proliferation**:
  - Use thorium fuel (very small Pu prod., ^{233}U very difficult mixture)
  - Avoid Pu separation (Purex), use pyroelectro reprocessing instead (developed for uranium at Argone N.L.)

Accelerator Driven Systems

- The basic process in ADS is nuclear transmutation
  - 1919 Rutherford ($^{14}N_7 + {}^4He_2 \rightarrow {}^{17}O_8 + {}^1p_1$) **^{210}Po accelerator!**
  - 1940 E.O. Lawrence/USA and W.N. Semenov/USSR proposed to use a **particle accelerator as a neutron source**
  - 1941 G. Seaborg discovers **^{238}Pu** and then, in
  - 1942 produced the **first μg of ^{239}Pu** with the Berkeley 60 inch cyclotron
  - 1950 E.O. Lawrence proposed the **Materials Testing Accelerator (MTA)** at the Lawrence Livermore Radiation Lab, to produce ^{239}Pu from Oak Ridge depleted uranium
  - 1952 W.B. Lewis in Canada proposed to use an accelerator to produce **^{233}U from thorium** for CANDU reactors (electro-breeder concept)

Accelerator Driven Systems

- MTA and Lewis' projects dropped or slowed down when (a) rich uranium deposits were discovered in the USA, and (b) it was realized that it required several hundred mA of beam intensity, hundreds of MW to produce the beam! [*Pu, no amplification*] **today ≈ 10 MW beams seem sufficient**
- Renewed interest in ADS in the 1980's, when the USA decided to slow the development of fast critical reactors (Fast Flux Test Facility @ Argone National Lab.):
  - ☛ H. Takahashi at Brookhaven National Lab: several proposals of ADS systems (PHOENIX), including the **idea of burning minor actinides** (Fast neutrons – $k_s \approx 0.99$);
  - ☛ Ch. D. Bowman at Los Alamos: thermal neutron ADS (**ATW**) with thorium & chemistry on-line for FP and ^{233}Pa extraction;
  - ☛ Japan launches **Options for Making Extra Gains from Actinides** (OMEGA, now JPARC) at JAERI (now JAEA).

Accelerator Driven Systems

- In the 1990s, Carlo Rubbia gave a big push to the ADS, by launching a vigorous research programme at CERN based on:
  - development of **innovative simulation** of nuclear systems
  - specific **experiments to test basic concepts** (FEAT, TARC)
  - construction of an **advanced neutron Time of Flight facility** (n_TOF) to acquire neutron cross-section data, crucial to simulate reliably any configuration with new materials
  - Followed by several proposals for demonstrators

P. Stumpf/SIPA PRESS

C. Rubbia triggered a major R&D effort on ADS worldwide

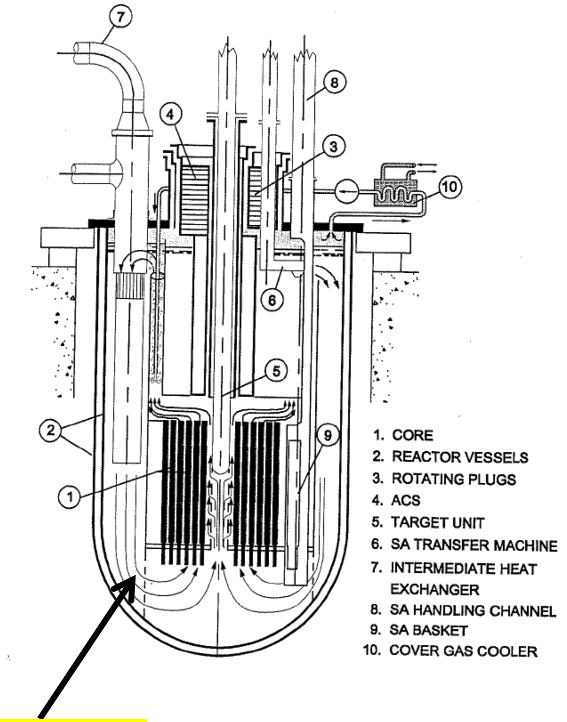
ADS

First proposal by C. Rubbia et al., in 1999
Ansaldo engineering design for the Energy Amplifier Demonstration Facility
EA B0.00 1 200 (Jan. 1999)

- The main issue for ADS today is the absence of a demonstrator. This is much more a political issue (funding) than a scientific one.

- **The technology for a demonstrator with power of ≈ 100 MWth is ready**.

- Fuel reprocessing technologies are being developed:
  - Pyro-electro reprocessing (Argone National Lab) to destroy existing waste
  - Extraction of uranium by fluorination for energy systems
  - A combination of both

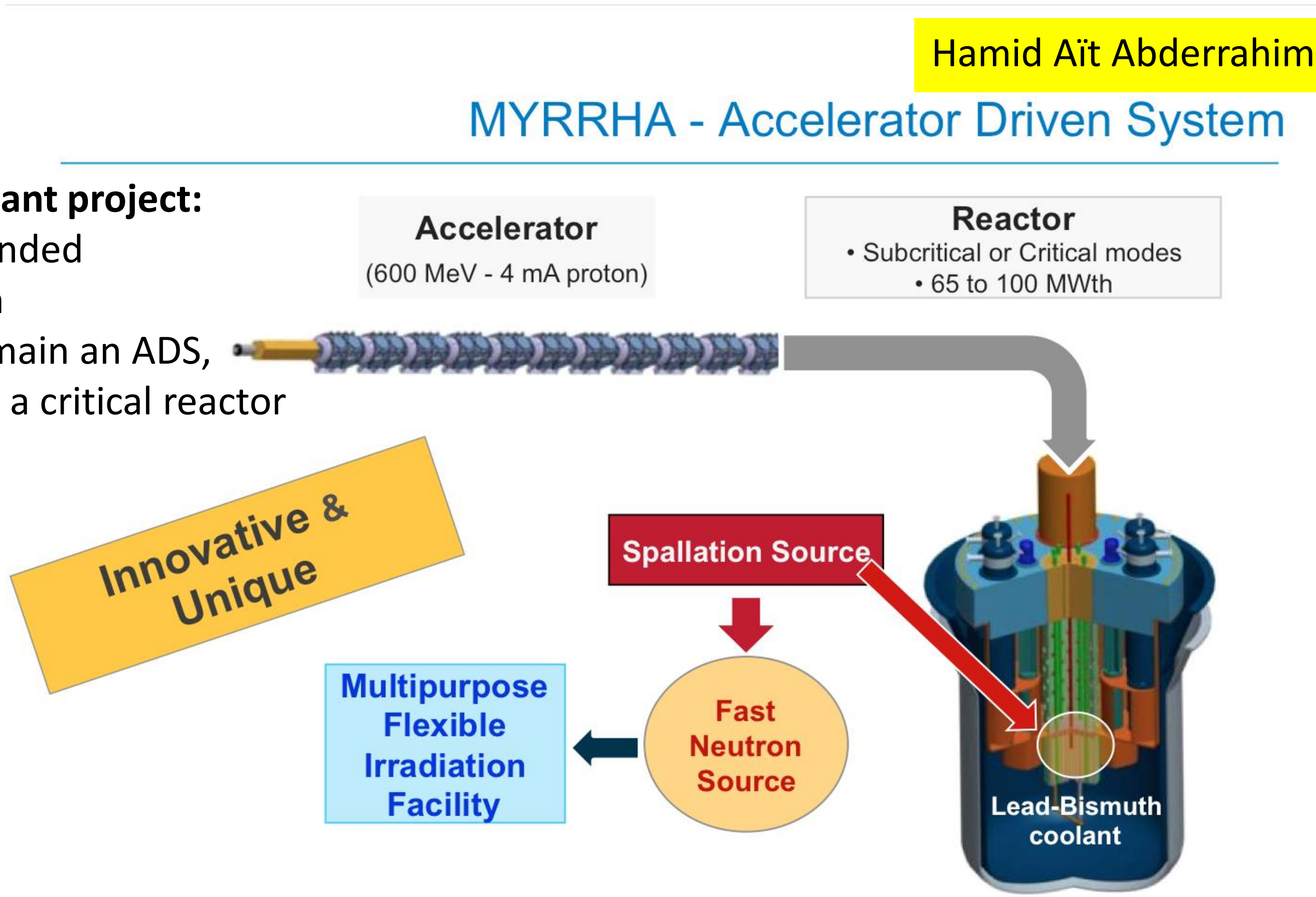


Forced convection

Accelerator Driven Systems

Hamid Aït Abderrahim

Most important project:
– partially funded
– no thorium
– will not remain an ADS,
will turn into a critical reactor



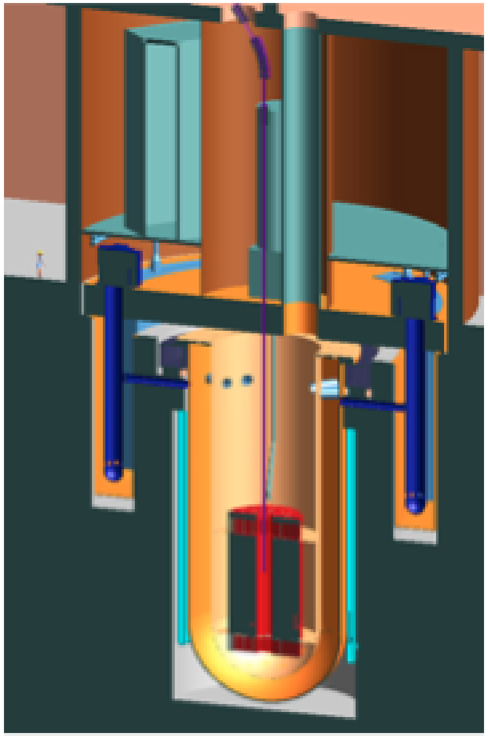
Industrialized ADS

EA Feasibility Study: Aker ASA and Aker Solutions ASA (2010)

AkerSolutions

- 1500MWTh/600MWe
- Sub-critical core
- Thorium oxide fuel
- Accelerator driven via central beam tube
- Molten lead coolant
- Coolant temp 400-540°C
- 2 Axial flow pumps
- 4 Annular heat exchangers
- Direct lead/water heat exchange

- *It may be modified to a Minor Actinide burner (ADS)*



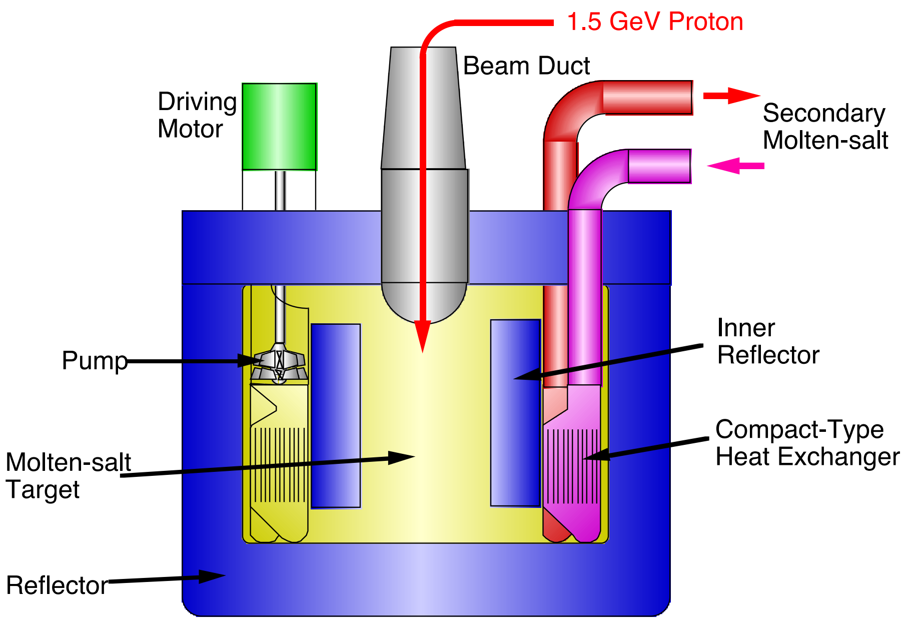
A Thorium fuelled reactor for power generation

Carlo Rubbia

CERN_Oct_2013 Slide# : 23

Molten salt ADS

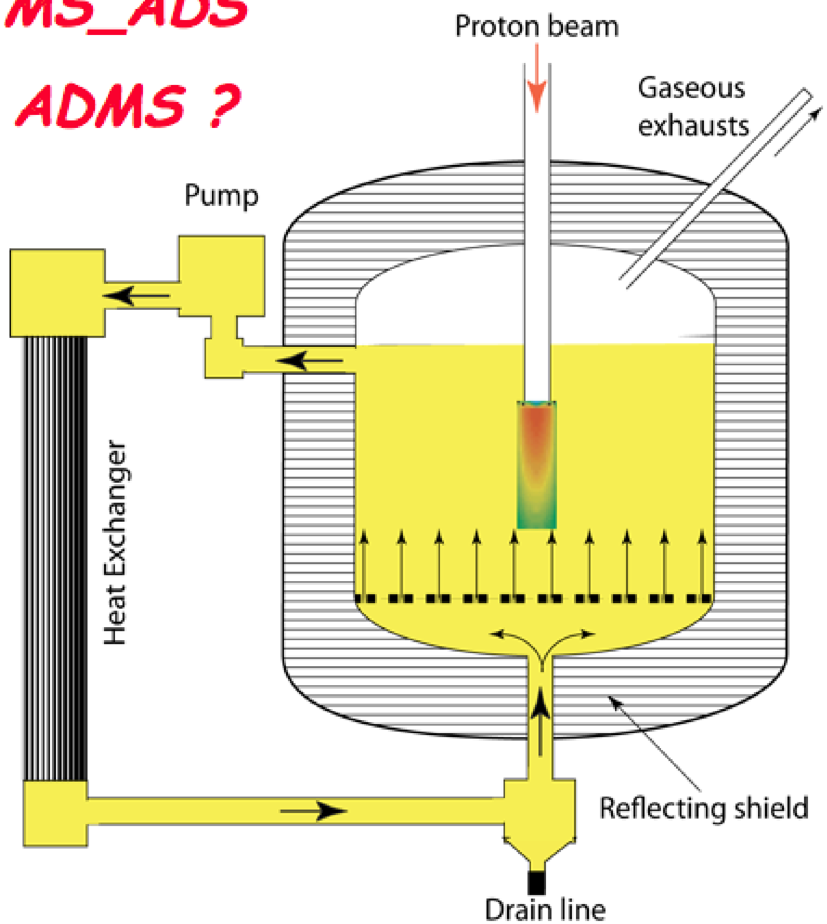
- Several **Molten Salt ADS concepts** were discussed: Carlo Rubbia, Toshinobu Sasa and Laszlo Sajo-Bohus.



Toshinobu Sasa

MS_ADS

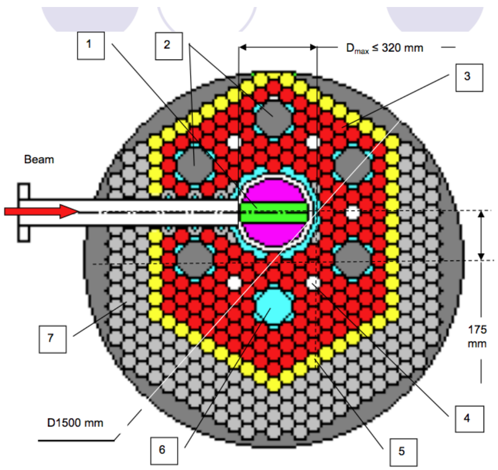
ADMS ?



Carlo Rubbia

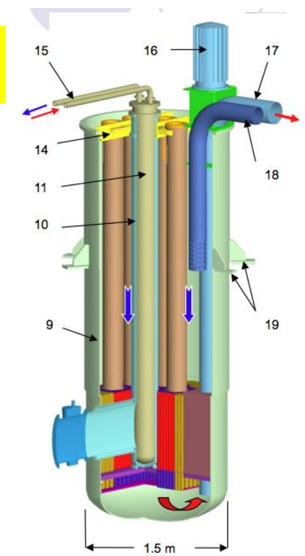
Other ADS projects

- China, Japan, Korea, Russia, USA, Venezuela and Ukraine
- 200 kW uranium-based ADS prototype, driven by an electron beam, due for completion in 2014 at the Karkhov Institute of Physics and Technology (**KIPT**)
- 10 MW **TROISKS** ADS, 300 kW proton beam, rearranging existing elements (accelerator, neutron source, etc.)
- Virginia Nuclear Energy Consortium Authority associated to Jefferson Lab, in the USA, with a view to create a "Science & Technology Center (STC) for the Application of High-Power Accelerators for the Advancement of Innovative Multidisciplinary Science"



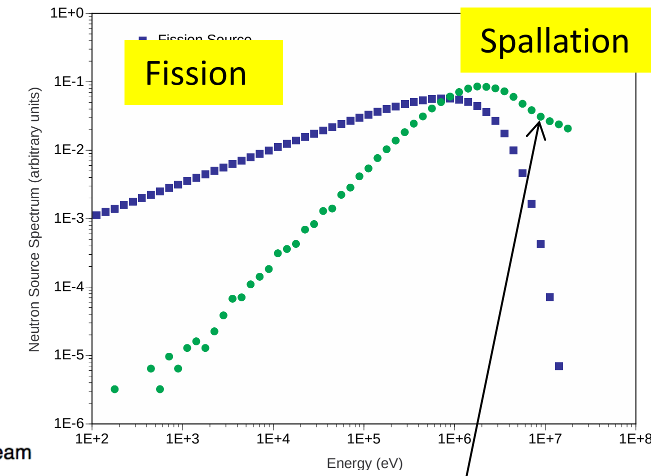
1 –target module;
2 – hermetical PbBi capsules with high enriched fuel and minor actinides;
3 – the cassettes of the water-cooled part of blanket with MOX fuel (~ 25% enr.);
4 – the module of controlled systems;
5 – decoupler (if it is required);
6 – traps of thermal neutrons (moderator) can construct in any place ;
7 – reflector.

S.Sidorkin

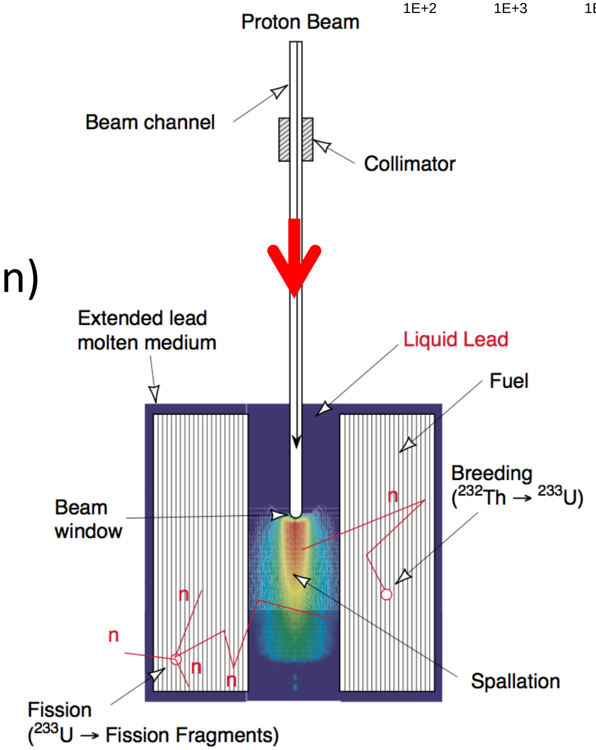


Basic elements of an ADS system

- A particle **accelerator**, to provide a **neutron source**
- A **core** in which both source neutrons and fission neutrons are at work – restricted here to the case of a **moderator** allowing for a fast neutron spectrum
- **Two main areas of physics:**
  - Neutron production by spallation from the beam
  - Neutron transport and interaction in the core
- **Physics also drives other ADS elements:**
  - Cooling (possibility of natural convection)
  - Electric power production efficiency (go to highest possible temperature)



Non negligible contribution from the high energy tail (n,xn) reactions on Pb. See later the effect on k_S



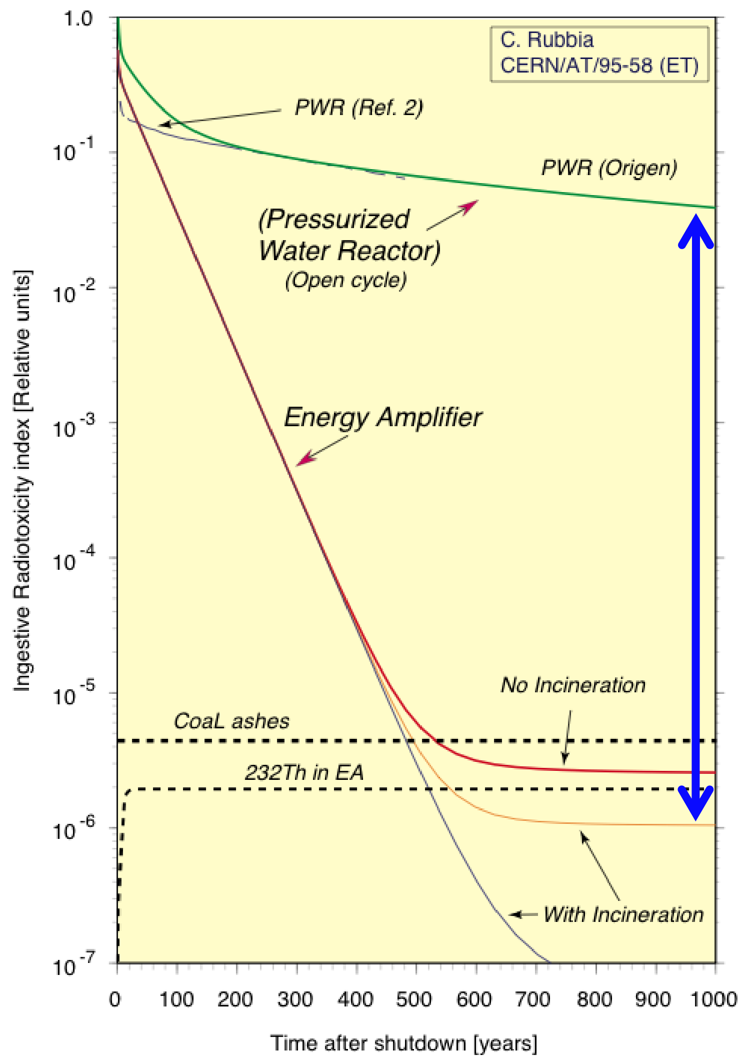
Transmutation performance of ADS

- **Destroy** 36 kg of TRU/TW_{th}.h
  (A PWR **produces** 14 kg of TRU/TW_{th}.h)

Transmutation rates (kg/TW_{th}h) of plutonium and minor actinides and LLFPs

Nuclides	EADF (ThPuO2) ENDF/B-VI	EADF (UPuO2) ENDF/B-VI	EADF (UPuO2) JENDL-3.2	PWR (UO2)
^{233}U	+ 31.0			
Pu	– 42.8	– 7.39	– 5.55	+ 11.0
Np	+ 0.03	+ 0.25	+ 0.24	+ 0.57
Am	+ 0.24	+ 0.17	+ 0.14	+ 0.54
Cm	+ 0.007	+ 0.017	+ 0.020	+ 0.044
^{99}Tc prod	+ 0.99	+ 1.07	+1.22	+ 0.99
^{99}Tc trans	– 3.77	– 3.77		
^{129}I prod	+ 0.30	+ 0.31		+ 0.17
^{129}I trans	– 3.01	– 3.01		

Yacine Kadi



Simplified model of subcritical systems

- **Theory of subcritical systems** interesting in itself, to get insights into the physics. Properties are quite different from those of critical systems. (*C. Rubbia, CERN/AT/ET/Internal Note 94-036*)
- Neutron flux geometry important to determine the generated power distribution and the uniformity of fuel burnup
- Some simplifying assumptions (uniform material and mono-energetic neutrons, small absorption) to get a basic equation similar to that of a critical reactor, but with an **external neutron source term** in addition:

$$\frac{\partial n(\vec{r},t)}{\partial t} = \underbrace{\nu \Sigma_f \Phi(\vec{r},t)}_{\text{Fission}} + \underbrace{\boxed{C(\vec{r},t)}}_{\textbf{Spallation}} - \underbrace{\Sigma_a \Phi(\vec{r},t)}_{\text{Absorption}} + \underbrace{D \nabla^2 \Phi(\vec{r},t)}_{\text{Leakage}}$$

Simplified model of subcritical systems

- Example of finite system at equilibrium:

Diffusion length

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

- 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

Important theorem: $\forall\, i,\ k_i < k_1$

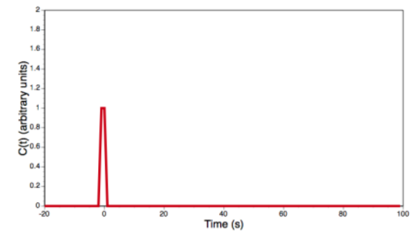
$$k_{l,m,n} \equiv k_\infty - L_c^2 B_{l,m,n}^2$$

Time dependence

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

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

- 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

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

- 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 is well suited for ADS.

Neutron multiplication factor

- The neutron multiplication factor depends on the source:

Fission

$$k_{eff} \gg \frac{n S_f}{S_a + DB^2}$$

Absorption

Leakage

Non-fission multiplication: For fast neutron systems, (n,xn) reactions on Pb are not negligible, in particular for the source neutrons

Source

$$k_s \approx \frac{n' S_f F(\vec{r},t) + C(\vec{r},t)}{S_a F(\vec{r},t) - D\nabla^2 F(\vec{r},t)} > k_{eff}$$

Change of flux distribution and multiplication in the source

- 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}.

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:

$$N_0\left(1+k_s+k_s^2+k_s^3+k_s^4+\ldots+k_s^n\right)=N_0M=N_0\frac{k_s^{n+1}-1}{k_s-1}\approx\frac{N_0}{\left(1-k_s\right)}$$

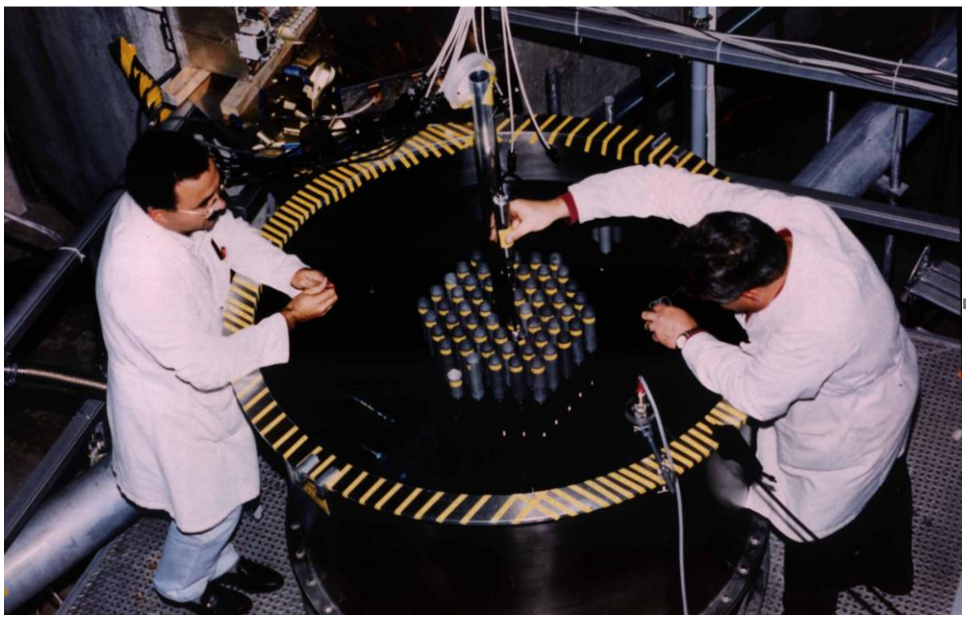
- The energy gain G is a characteristic of ADS:

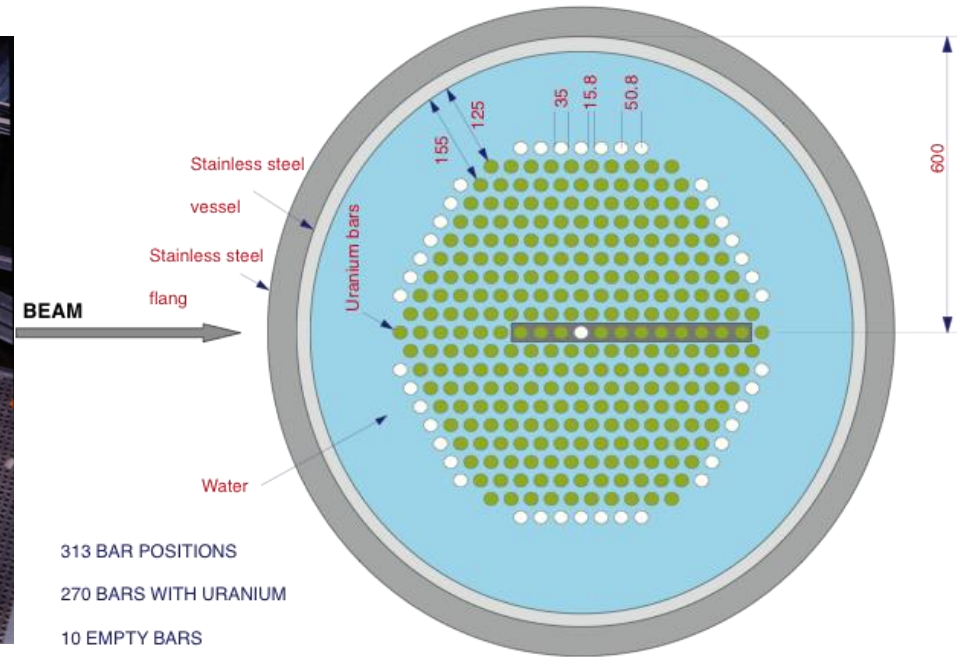
$$G\equiv\frac{Energy\ produced\ in\ EA}{Energy\ injected\ by\ the\ beam}=\frac{\overbrace{0.18}^{\text{Energy/fission}}k_s\overbrace{N_0}^{\text{n/p}}}{\underbrace{\nu}_{\text{n/fission}}\left(1-k_s\right)\underbrace{E_b}_{\text{Beam energy}}}=\frac{G_0k_s}{\left(1-k_s\right)}\approx\frac{G_0}{\left(1-k_s\right)}$$

- 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 **First Energy Amplifier Test (FEAT)** at the CERN PS was to check the **basic concept of energy gain**, and **validate the innovative simulation** developed by C. Rubbia and his group.

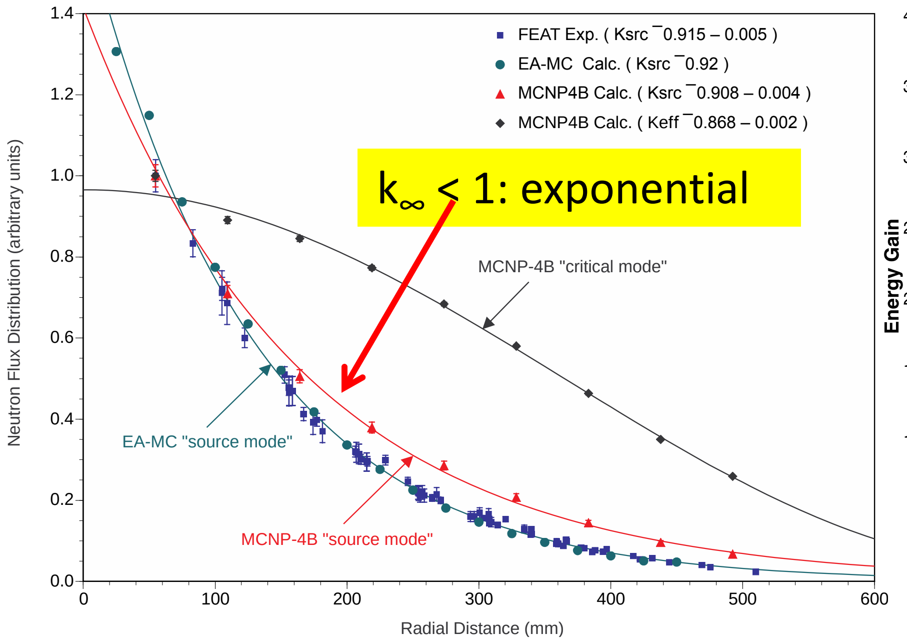


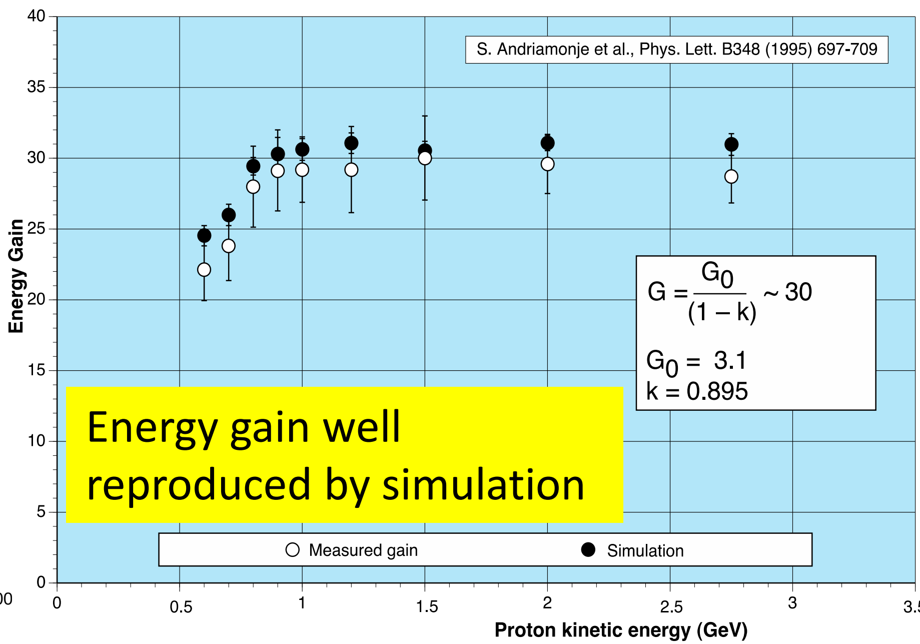


3.62 t of natural uranium; k_{eff} ~ 0.9

- Count fissions
- Measure temperature

Main results from FEAT





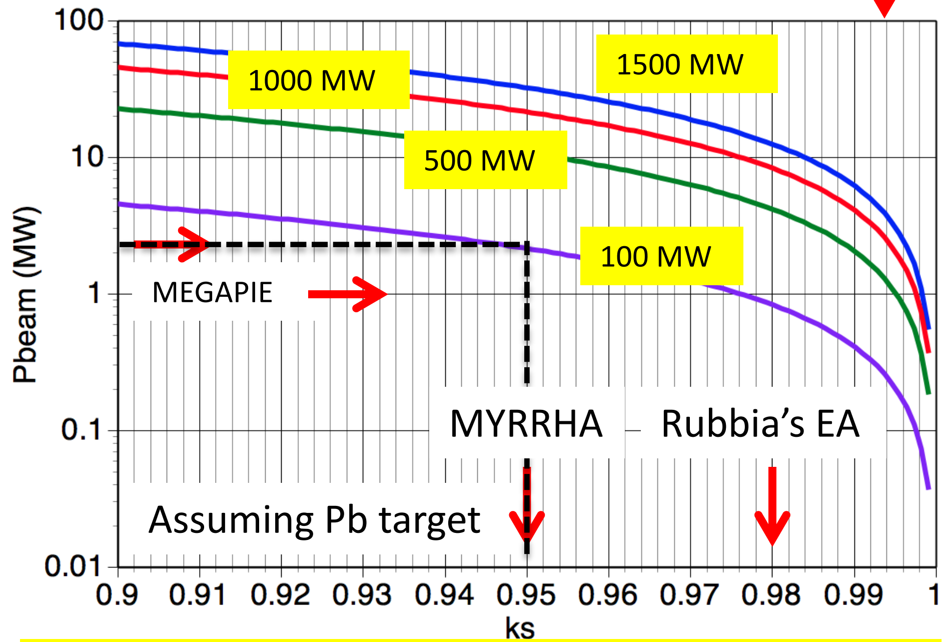
- Two important results from FEAT:
  - ☛ **Optimum beam energy reached at 800-900 MeV** (ionization vs nuclear cascade production), with slow decrease at higher energies. Above 900 MeV, the neutron yield scales with proton energy. At much higher energies, the gain drops because of pion production.
  - ☛ **Simulation validated** from spallation to energy production

Energy gain in ADS systems

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

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

Margin of present PWR



- 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)
- **Neutronics with thorium very favourable compared to uranium** $t_{1/2}$ (^{233}Pa) ~ 27d; $t_{1/2}$ (^{239}Np) ~ 2.3d! What was a problem in the use of thorium in critical reactors becomes an advantage in the case of ADS

PSI separate turns cyclotron
(3 mA and 1.8 MW, with 0.59 GeV protons).
P_{ADS} = 243 MW_{th} with k = 0.98
MYRRHA LINAC
(2.5-4 mA and ≤ 2.4 MW, with 0.6 GeV protons)
P_{ADS} = 50-100 MW_{th} with k = 0.95

Accelerator requirements

- In principle, it does not matter how the external neutron source is provided. In practice, for industrial applications, there are a number of well-defined requirements for the accelerator.
  - **Beam particle: protons** [electrons (low spallation neutron yield), deuterons (neutron background)];
  - **Beam power**: **a few to 10-15 MW** depending of choice of ks value, and desired unit power output;
  - **Beam Energy**: $\mathbf{E_{beam} \geq 800\text{-}900\ MeV}$
  - **Beam spot size (footprint):** large on impact on window, but perhaps some limitation due to beam transport issues (studies at JAEA: ≤ 0.1-0.2 mA/cm^2 ?), MYRRHA has 0.07mA/cm^2;
  - **Beam losses**: minimize irradiation of the accelerator and of the environment; impact on the maintenance and repair (main issue for any high power beam, not only for ADS);

Accelerator requirements

- **Reliability**, minimize beam trips (have multiple sources); the limitation comes mainly from thermal stress in fuel structure. For instance, for MYRRHA (F. Bouly, J.-L. Biarrotte @ ThEC13)
  - Trip < 0.1 s no limit
  - 0.1 s < Trip < 3 s not more than 100 per day
  - Trip > 3 s 10 in three months
  - Administrative limit if SCRAM event

  However these may evolve with time, with the development of new materials
- **Beam power stability and control**: 1% fluctuation on beam intensity is 1% fluctuation on the thermal power;
- **Large operational range of beam intensity**: to follow demand; factor 10?
- **Energy efficiency**: maximize fraction of electric grid power stored in the beam. Relevant to overall energy efficiency of system
- **Size of accelerator**: for waste elimination, people might want to fit it on the site o a standard nuclear power plant
- **Cost:** This is very important. One main criticism of ADS is that “the accelerator does not exist and will be too expensive”

- In the end, the solution chosen among LINAC, Cyclotron or FFAG will be the one best fulfilling all these requirements

Conclusion

- The energy problem is a huge challenge for Society.
- When taking into account the need for safety, waste management and non-proliferation, thorium in a fast neutron ADS represents a realistic energy option, along the lines developed by Carlo Rubbia and his team here at CERN.
- **The physics of ADS is well known.**
- It is a challenging innovation but there is no show stopper. Europe cannot afford not to built a “demonstrator” of significant power (MYRRHA?) in order to validate technological solutions.
- The accelerator community must take up the challenge of providing the required accelerator, at an affordable price. This would be one additional, very important, contribution of particle physics to Society.
- This workshop is a significant step in that direction.

RESERVE

Abstract

- ***Title***: **Why Accelerator-Driven Systems?**

- ***Abstract***: To meet the tremendous world energy needs, systematic R&D has to be pursued to replace fossil fuels. The ThEC13 conference organized by iThEC at CERN last October has shown that thorium is seriously considered by developing countries as a key element of their energy strategy. Developed countries are also starting to move in the same direction. Thorium can be used both to produce energy and to destroy nuclear waste. As thorium is not fissile, one elegant option is to use an accelerator, in so-called “Accelerator Driven Systems (ADS)”, as suggested by Carlo Rubbia. After presenting a brief history of ADS, requirements and challenges for an ADS accelerator will be discussed.

Outline

- **Energy** issues
- Why **thorium**?
- Why **ADS**?
  - ☛ Use thorium efficiently to produce clean energy
  - ☛ Destroy nuclear waste
- A brief history of ADS
- ADS **accelerator** requirements and challenges

Choice of the accelerator type: Linac versus cyclotron

In principle both accelerator types can deliver the required proton beam for ADS applications. However, the nature of each — one compact unit for an isochronous cyclotron, a sequential modular structure for the linac — brings both advantages and disadvantages.

Due to its recirculation nature, a cyclotron is compact and cost effective. However, it lacks every form of redundancy which is crucial for fault tolerance. Hence, a cyclotron will not reach the wanted level of availability, and furthermore an upgrade of its beam energy is not a realistic option.

Linacs on the other hand, can be built as a sequence of many independent accelerating structures (RF cavities), which is a highly modular situation. It is this modularity that makes such a linac particularly well suited to tackle the availability issue. In case of failure of a single accelerating module, independently controlling the RF amplitude and phase of the adjacent modules creates the conceptual possibility of recovering the beam within a short time. Furthermore, increasing the final beam energy is obtained by merely adding accelerating modules.

For these reasons **MYRRHA favours the linac option**.

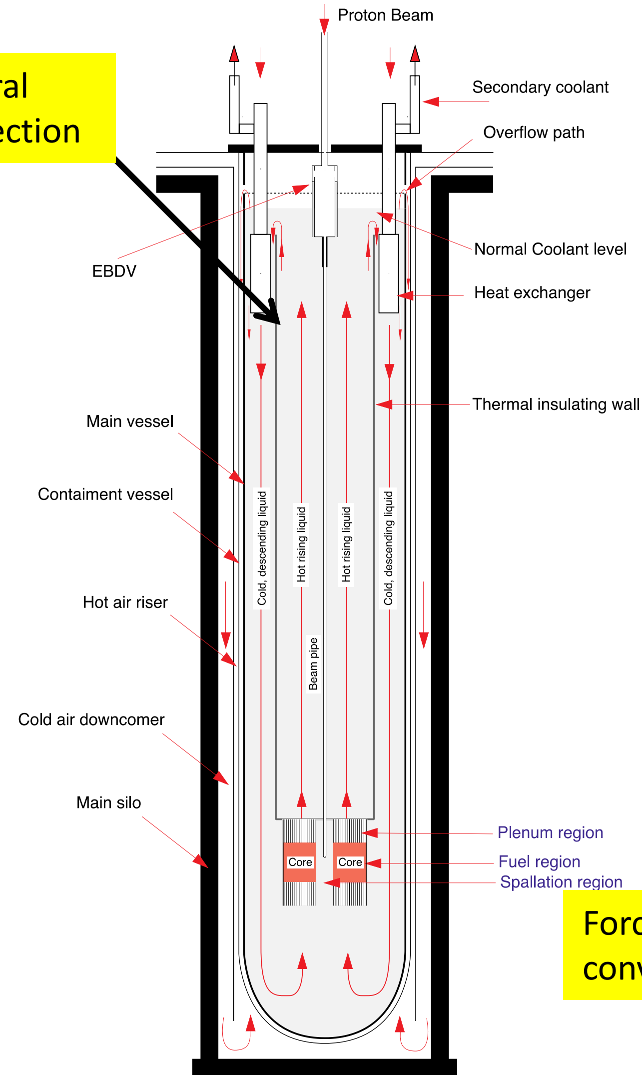
Linac versus cyclotron

LINAC	CYCLOTRON
Large space requirement (few hundred m long) but light	**Compact but heavy**
Expensive	**Cheaper in construction**
Less efficient power conversion	**More efficient power conversion**
Modularity provides redundancy	**No intrinsic redundancy**
Upgradable in energy	Difficult to upgrade in energy
Straightforward beam extraction	Difficult extraction and related beam losses
Capable of high beam current (100 mA)	Modest beam current capability (5 mA)

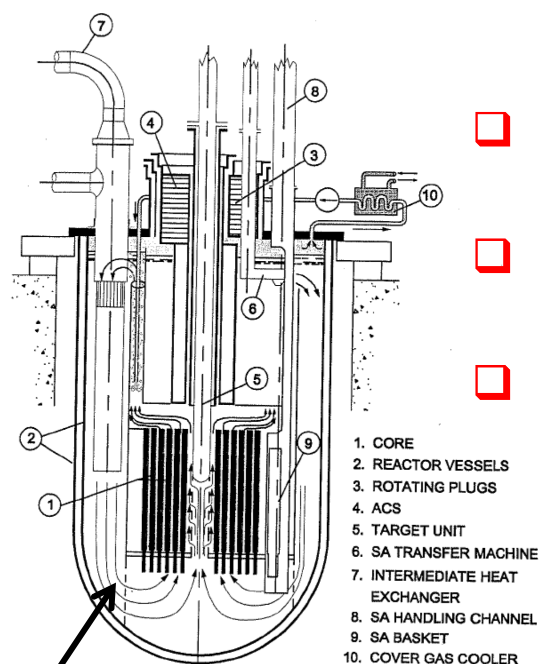
Realistic ADS system

Energy Amplifier Conceptual Design
C. Rubbia, et al., CERN/AT/95-44 (ET)

Natural convection



Ansaldo Engineering design
for the Energy Amplifier
Demonstration Facility
EA B0.00 1 200 (Jan. 1999)



Forced convection

- Today one can simulate in great detail any realistic system of this type (LHC experiments have up to 30 million volume elements in their simulation)
- The physics is extremely well known!
- Use passive safety – physics does not fail!
- Neutron data are improving

Simulation never better than
the quality of input data :
Strategic importance of n_TOF at CERN!

Energy and pollution in China

- Even though coal accounts for 70% of China's total energy consumption, China is doing better than most European countries, in terms of CO_2 emissions: no point telling China to stop burning coal …

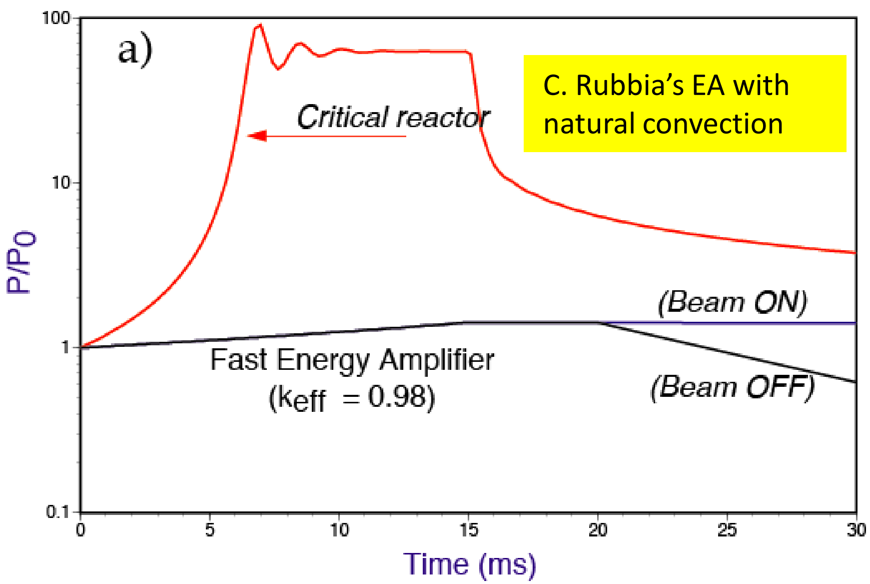
Country	ton of CO_2 per capita
China	5.92
Denmark	7.48
France	5.04
Germany	9.14
USA	16.94
World	**4.50**

Source:
IEA 2013
Key World
Energy Statistics

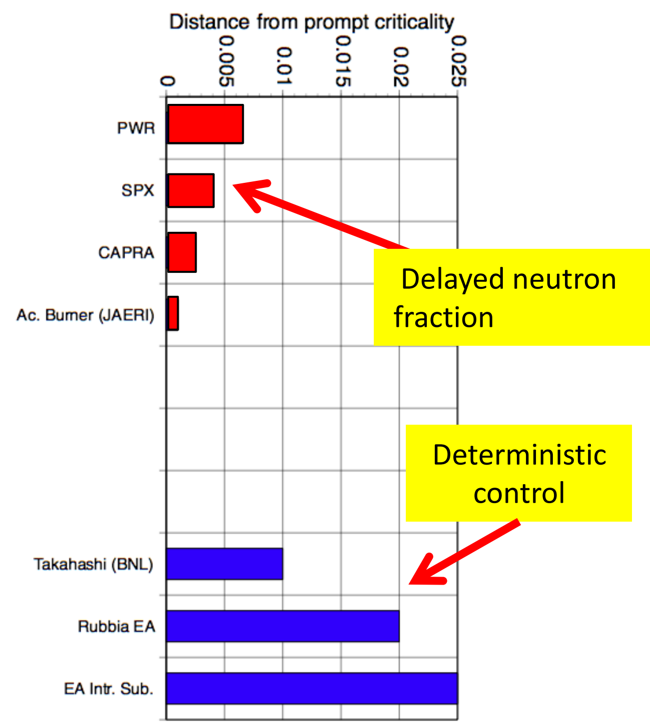
- The best strategy is to collaborate fully with China and with all developing countries to face this global challenge

Physics 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!
- $k_s \approx 0.975$ 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)

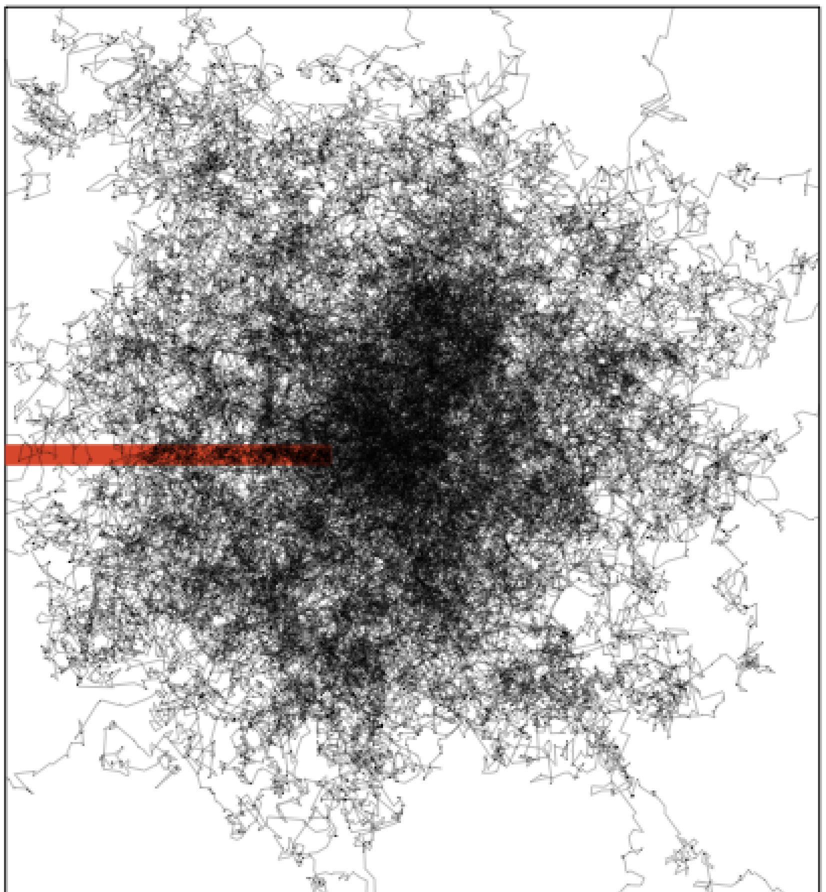


The CERN LHC beam can be switched off in 270μs, the CERN SPS in 46 μs, and a smaller accelerator for ADS, even much faster. So the reaction time will not be limited by the accelerator. The typically response time of a critical system to reactivity insertion is of the order of 5 ms.

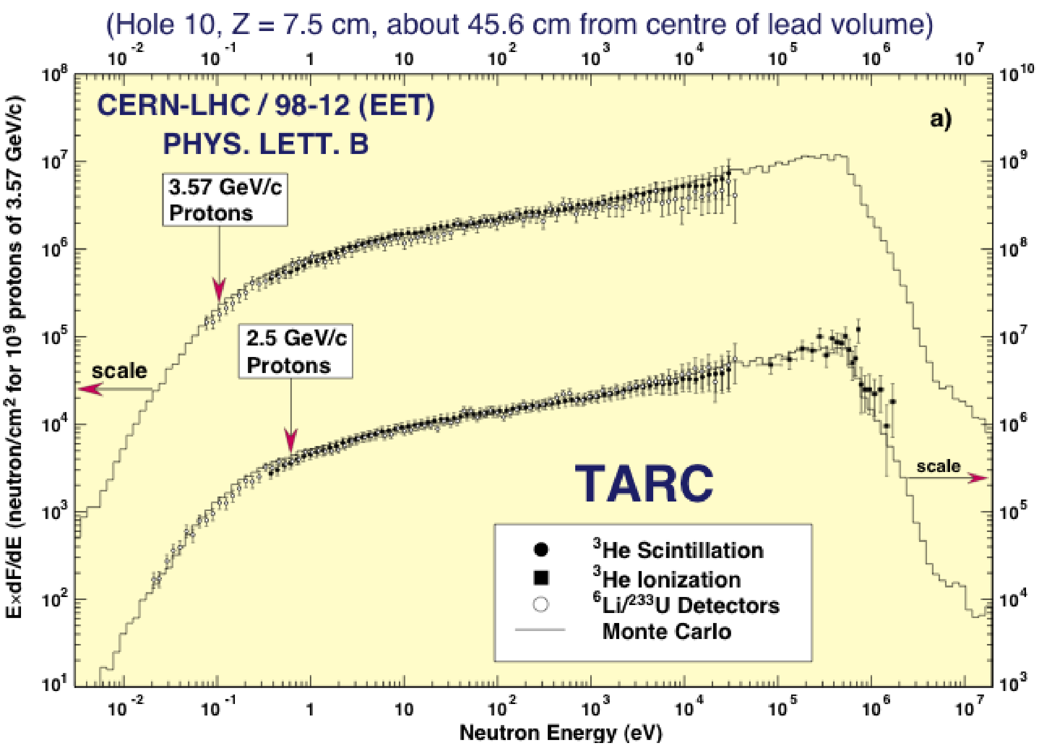


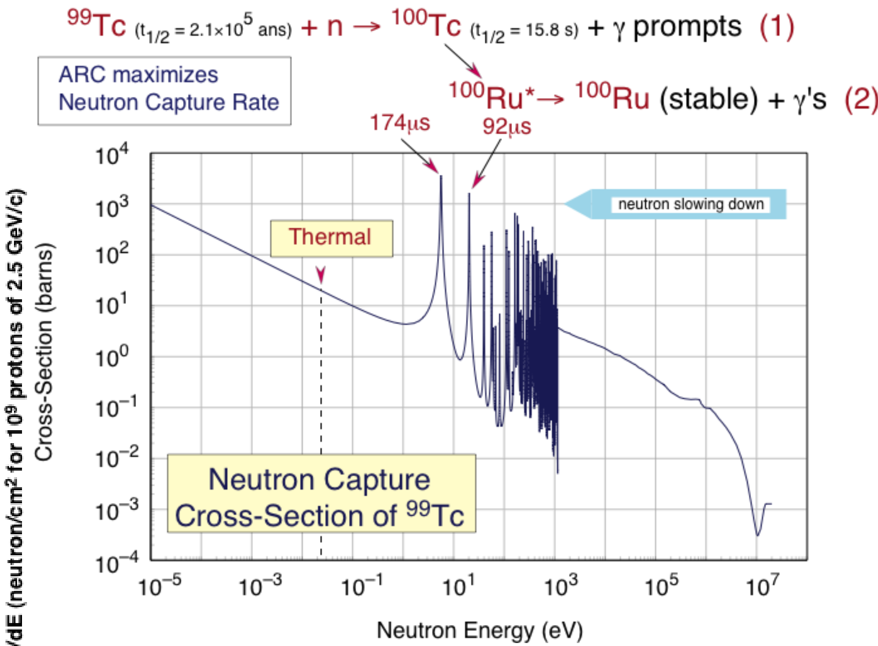
TARC at the CERN PS

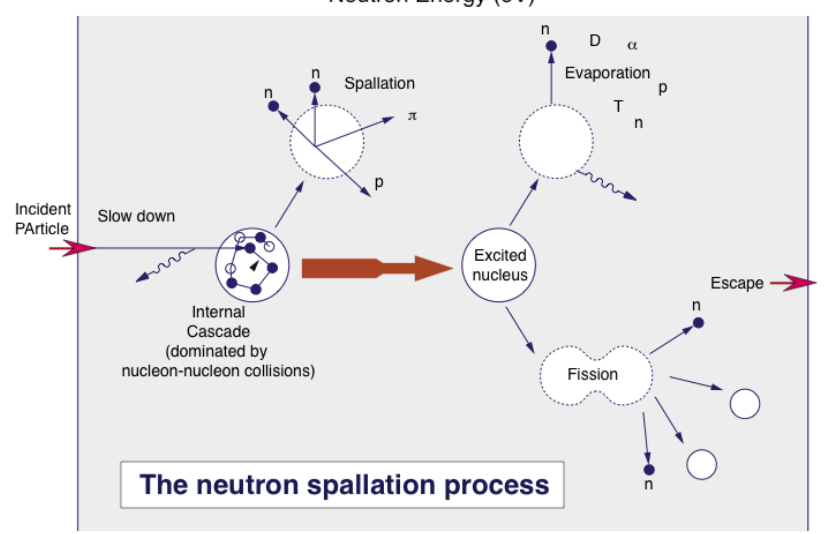
- Neutron phenomenology studied in great details in the TARC experiment at the CERN PS (1996-1997).
- Testing both the spallation process and the transport in lead



Results from TARC



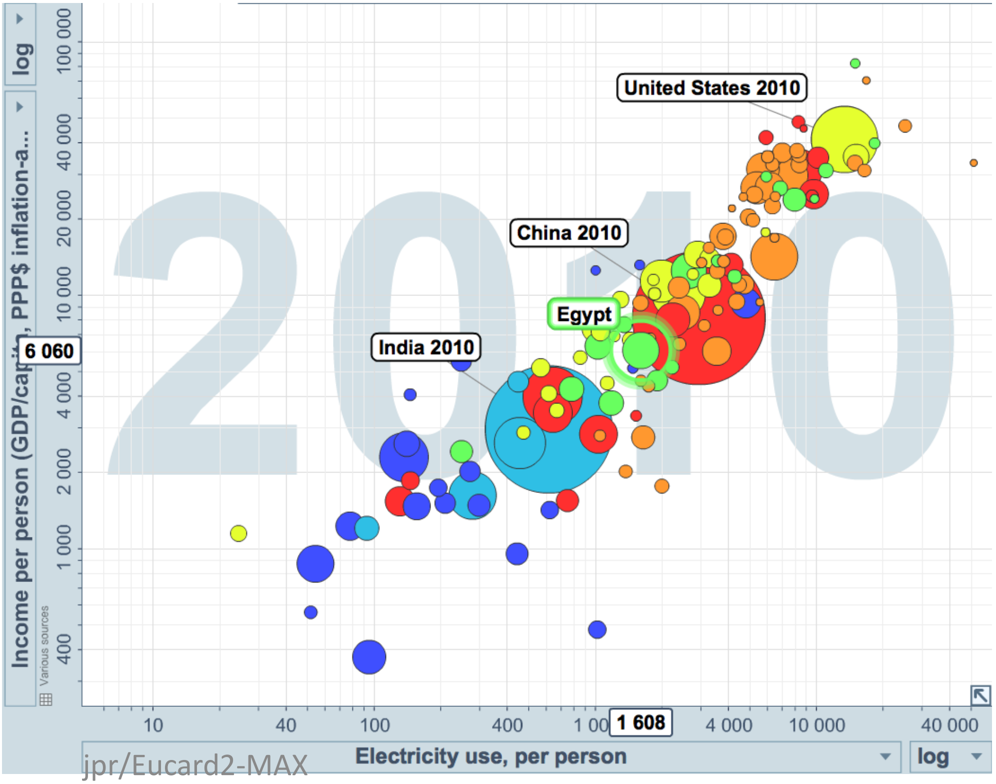


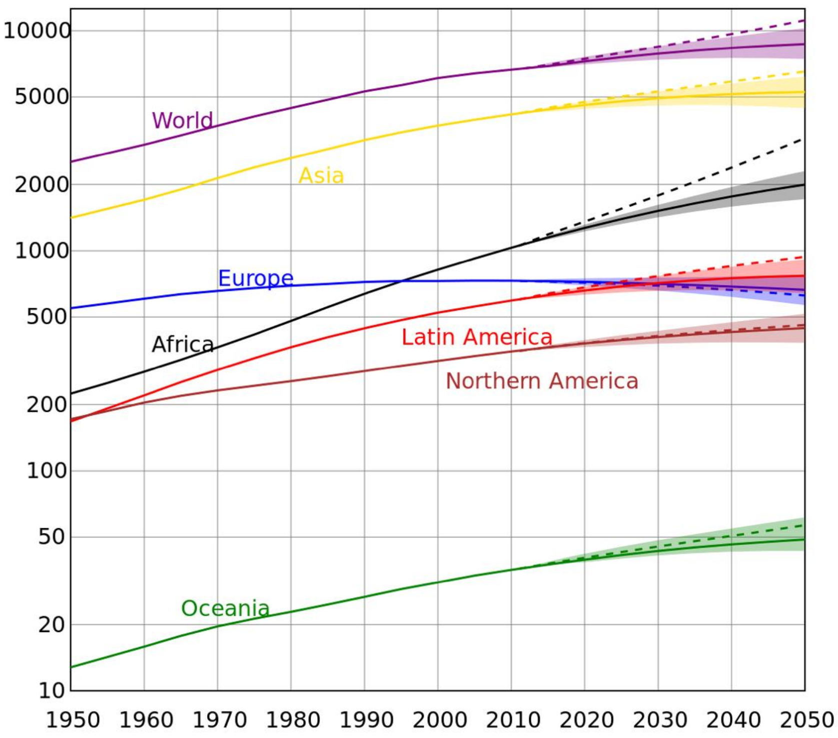


- Demonstrated **Adiabatic Resonance Crossing** for the elimination of long-lived fission fragments, an idea also proposed by C. Rubbia.

The energy problem

- If the rest of the world is allowed to live as well as we do in Europe today, then the energy production of the world will have to be increased by a factor of 3 or more, by the end of this century, when the world population will likely approach 11 billon individuals (from 15 TW to ≥ 50 TW). Most of the population increase is expected in developing countries. **Europe is not representative of the world!**



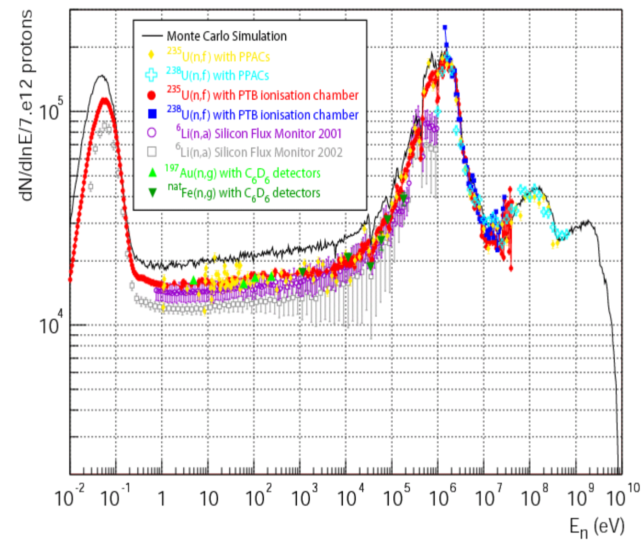


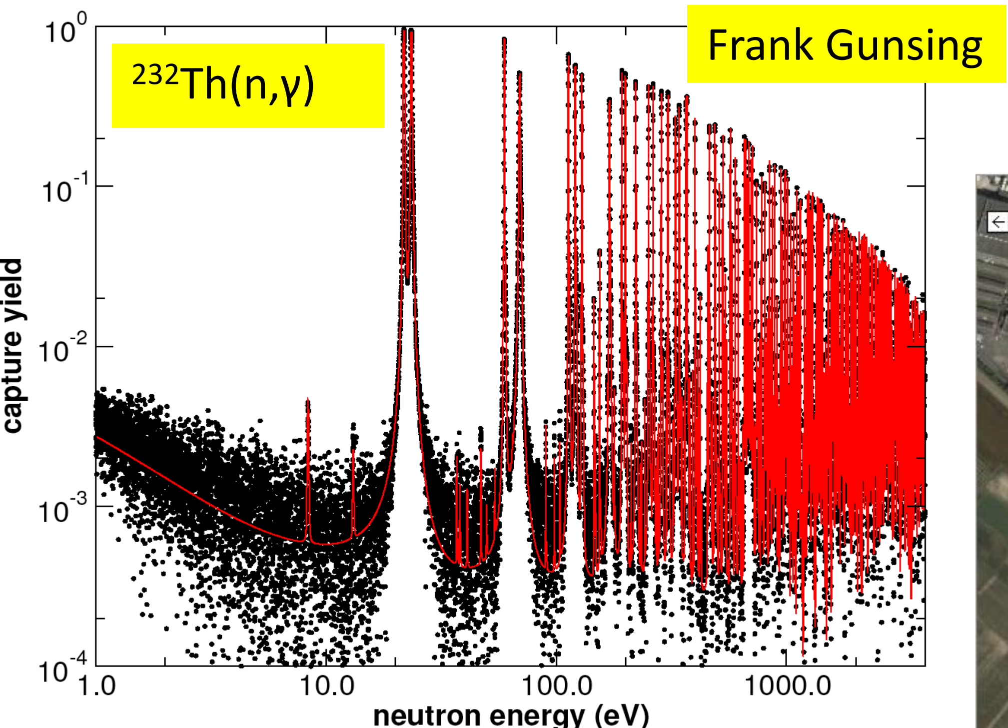
jpr/Eucard2-MAX

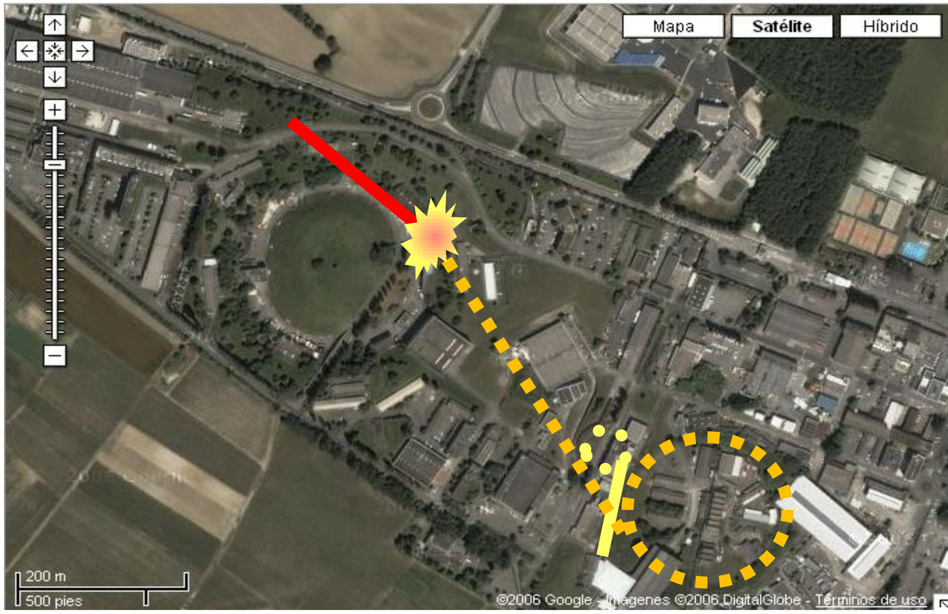
“Visualization from **Gapminder World**, powered by Trendalyzer from www.gapminder.org.“

Neutron cross section data

- **Develop precise and predictive simulation, requires precise input data**:
  - ☛ n_TOF facility at CERN

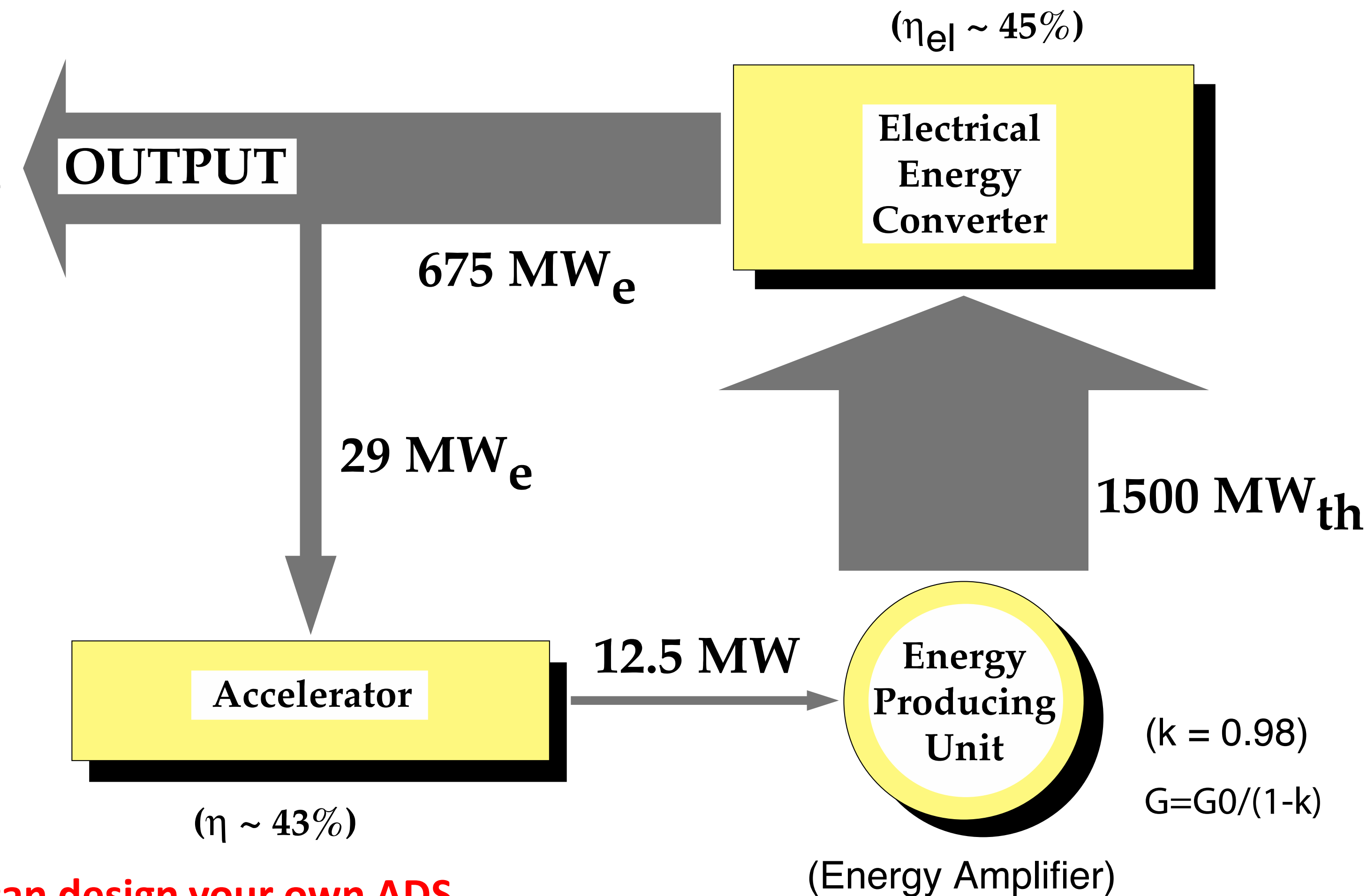






Architecture of an ADS system

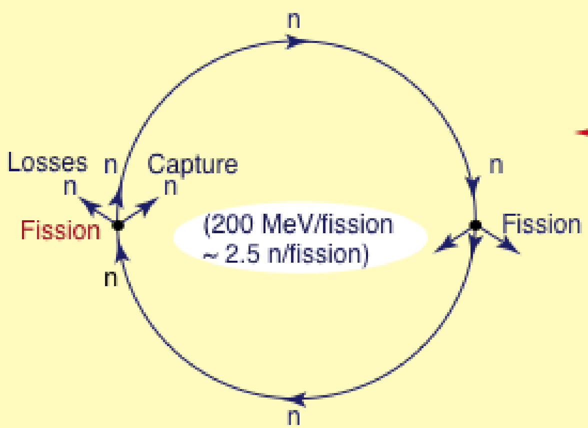
- Example of the generic 1500 MW_{Th} system (Energy Amplifier), designed and simulated by C. Rubbia (CERN/AT/95-44 (ET))



With this input you can design your own ADS

Critical versus Subcritical Systems

Chain Reaction



Effective neutron multiplication factor

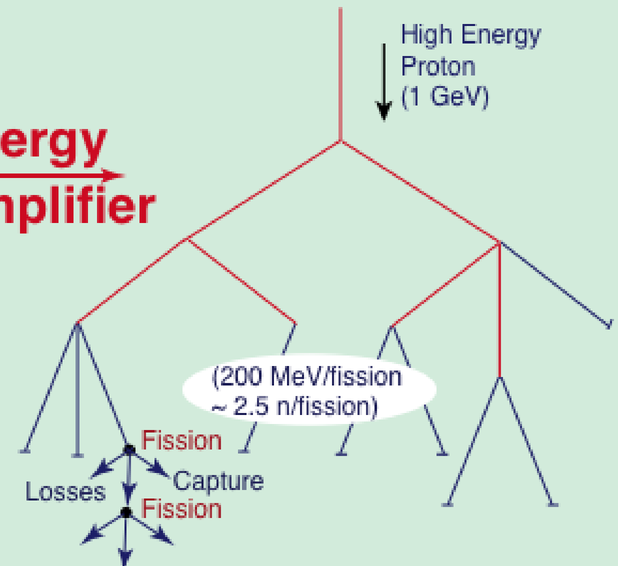
$$\boxed{k = \frac{\text{Production}}{\text{Absorption + Losses}}}$$

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

Critical Reactor ← → **Energy Amplifier**

Nuclear Cascade



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

Externally driven process:
k < 1 (k = 0.98)

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

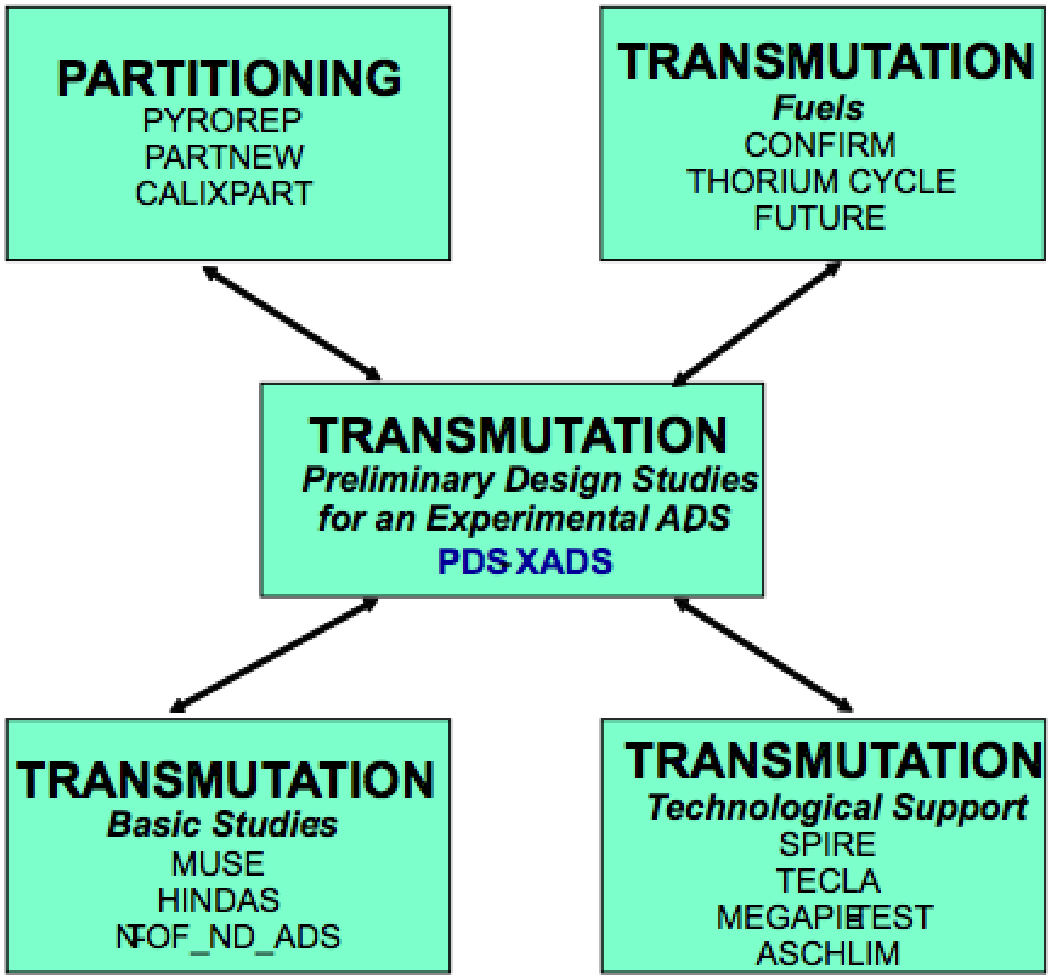
Energy Produced   Beam Energy

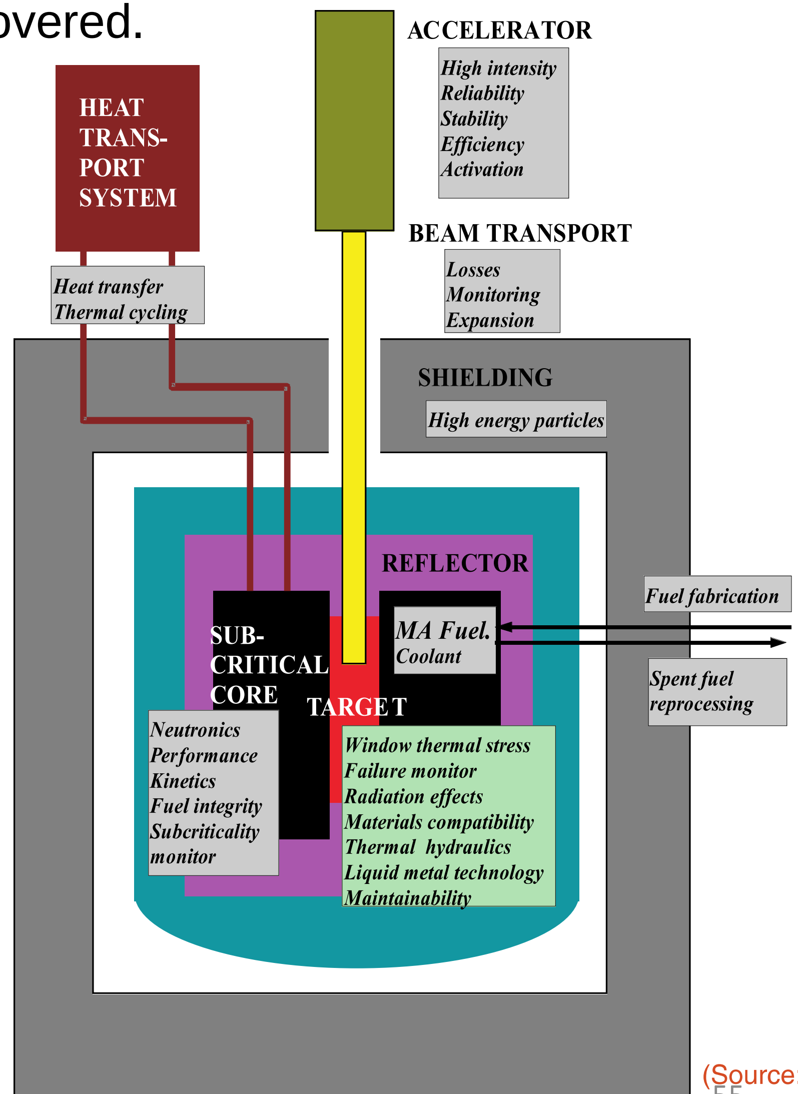
⇒ Constant Energy Gain

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

R&D in Europe

Many projects carried out since the EU FP5 and FP6 (Eurotrans) in the field of partitioning and transmutation. All aspects covered.





(Source:PSI)