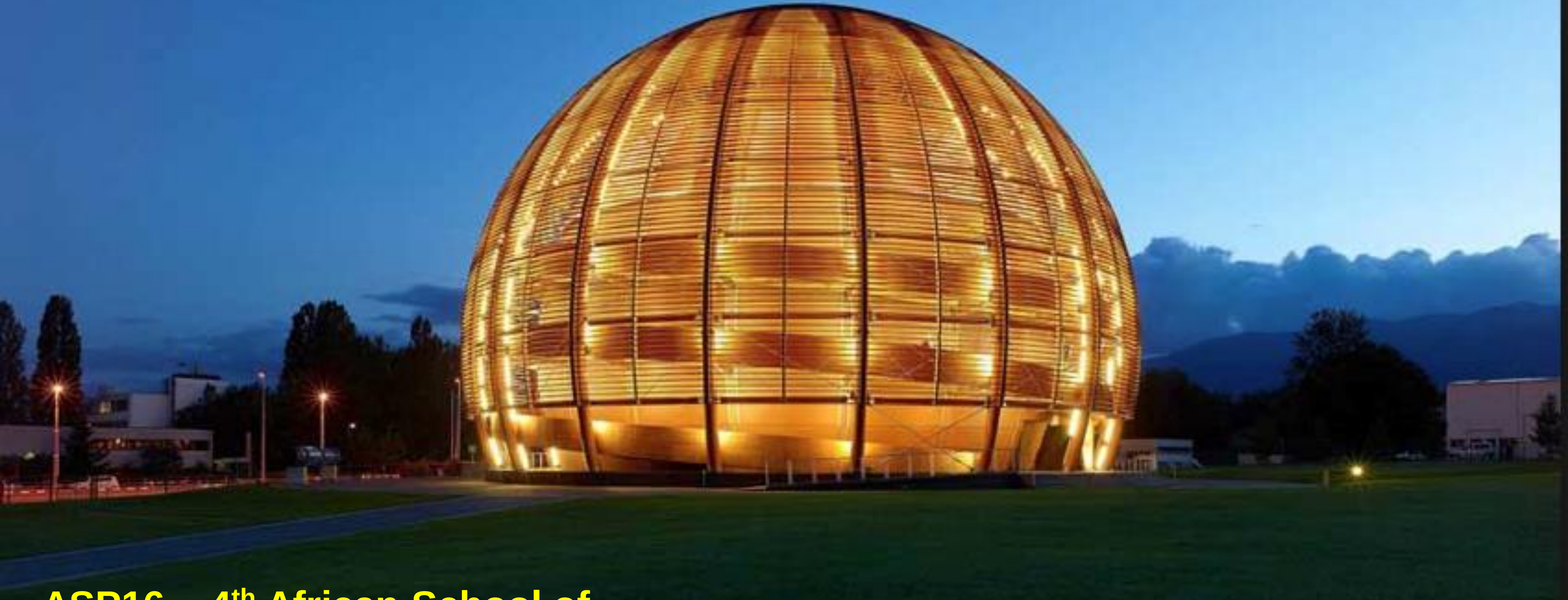
Application of Accelerators to Nuclear Energy



ASP16 – 4th African School of Fundamental Physics and Applications
University of Rwanda, Kigali, Rwanda
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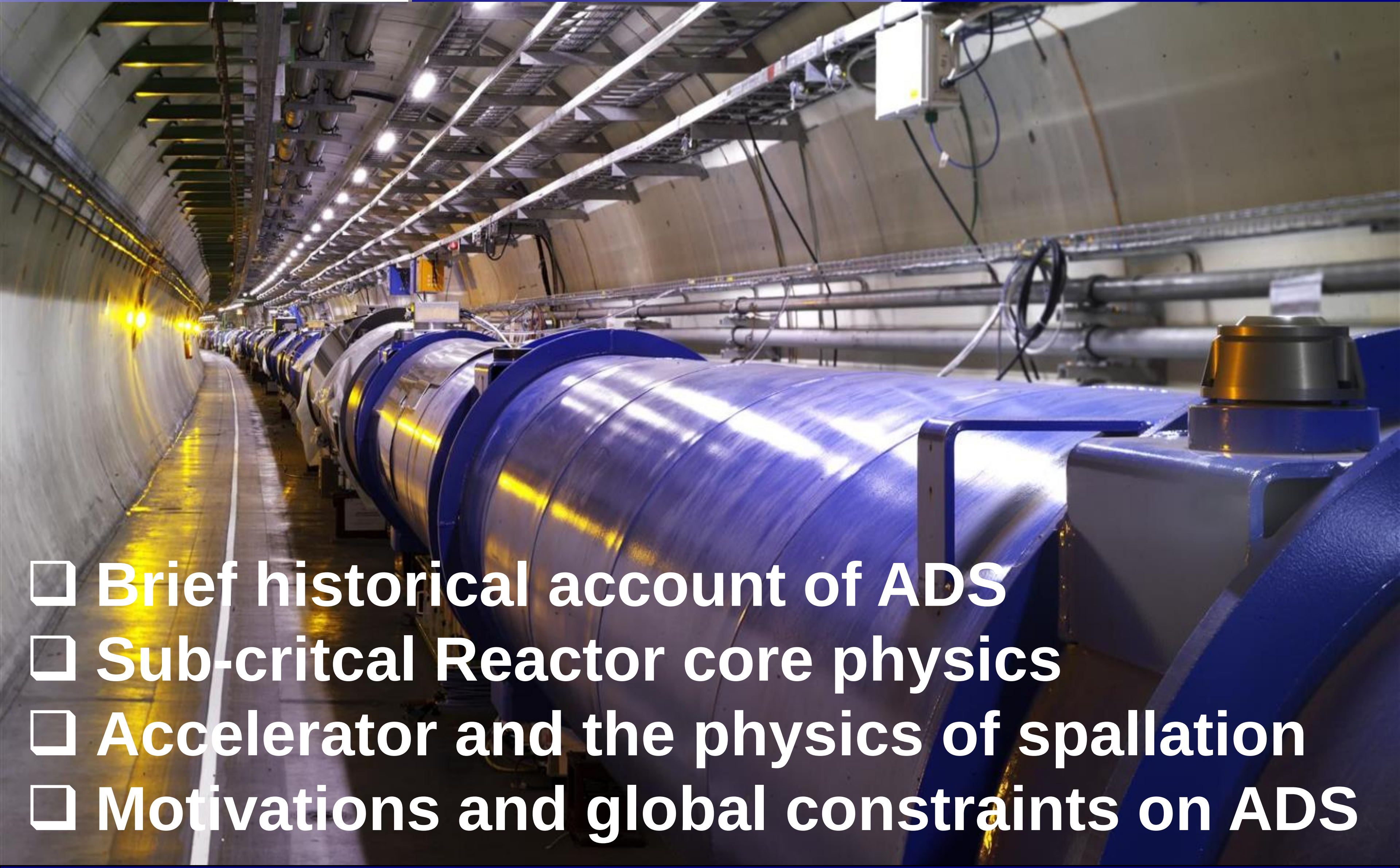
Outline



- ☐ Brief historical account of ADS
- ☐ Sub-critcal Reactor core physics
- ☐ Accelerator and the physics of spallation
- ☐ Motivations and global constraints on ADS

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 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)


Keystone

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~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

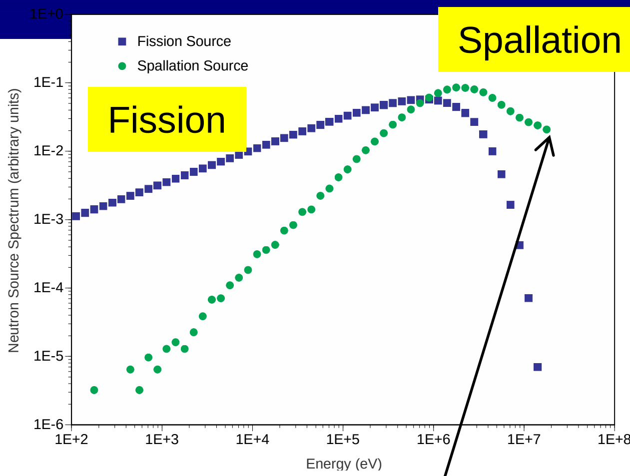
Followed by proposals for demonstrators

P. Stumpf/SIPA PRESS

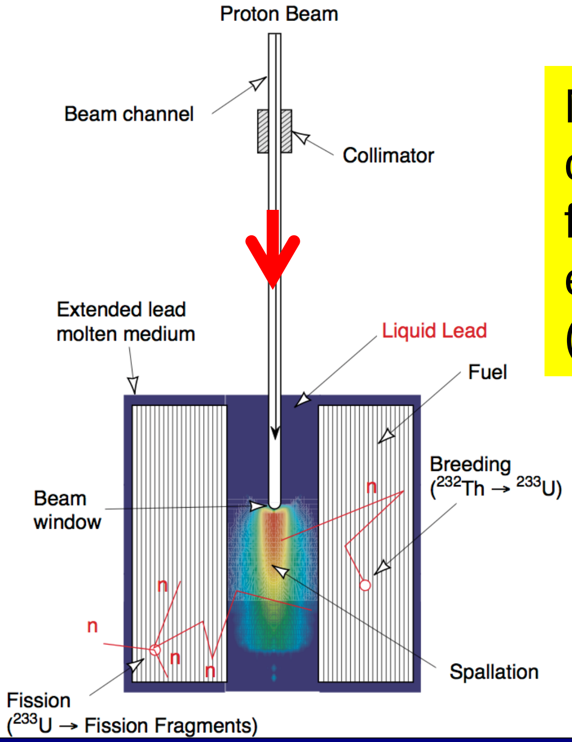
C. Rubbia triggered a major R&D effort on ADS worldwide

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)



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

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

- 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: $k_\infty \sim 1.2\text{-}1.3$)

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

- All modes are excited

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

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

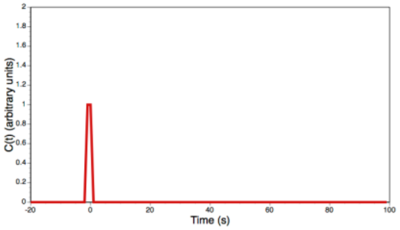
Time dependence

- ☐ Diffusion equation (with Φ = βn, 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 can be used for an ADS.

Neutron multiplication factor

- The neutron multiplication factor depends on the source:

Fission

Spallation

$$k_s \approx \frac{\nu \Sigma_f \Phi(\vec{r},t) + C(\vec{r},t)}{\Sigma_a \Phi(\vec{r},t) - D\nabla^2 \Phi(\vec{r},t)} > k_{eff}$$

Absorption

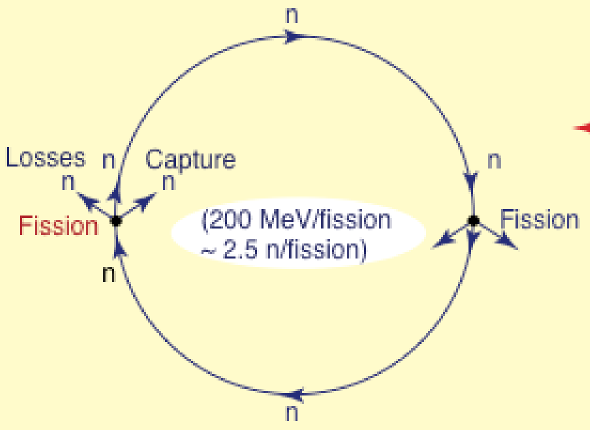
Leakage

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



Effective neutron multiplication factor

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

Self-sustained process:

$k = 1$

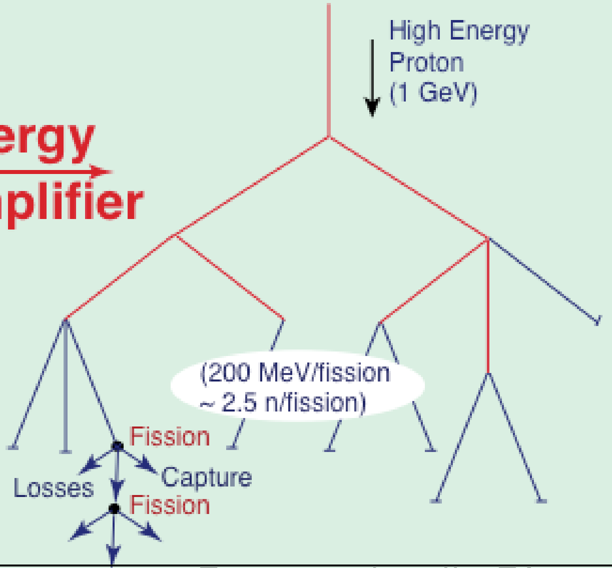
(if $k < 1$ the Reactor stops

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



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

Externally driven process:

$k < 1$ ($k = 0.98$)

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

Energy Produced   Beam Energy

⇒ Constant Energy Gain

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

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:

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

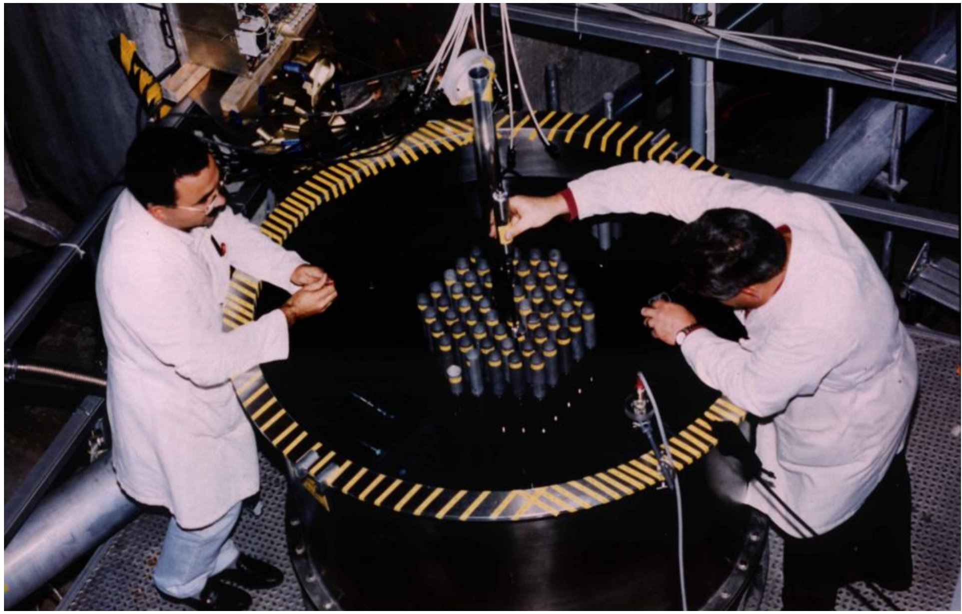
- The energy gain G is a characteristic of ADS:

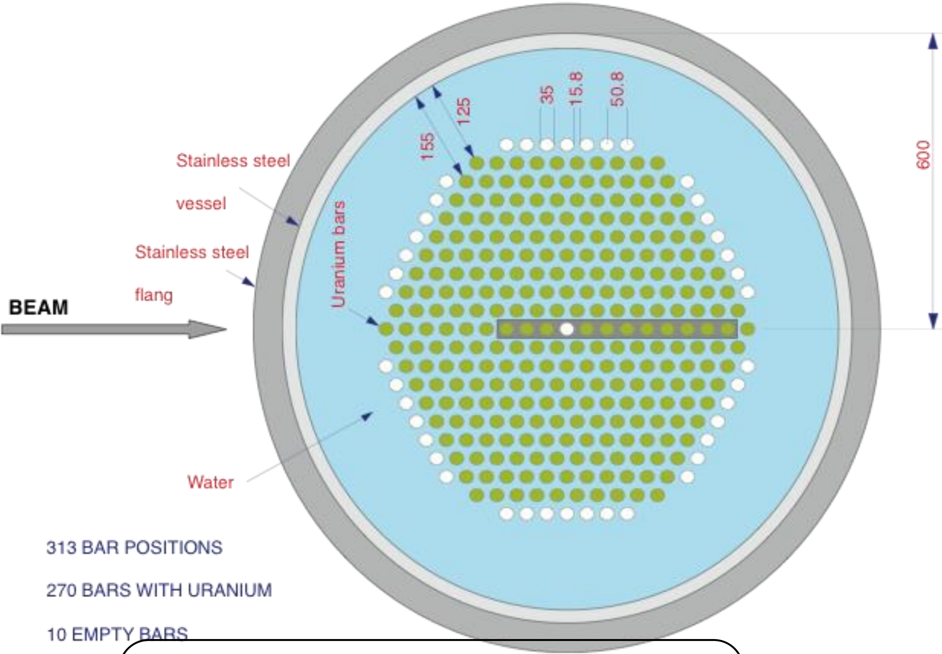
$$G\equiv\frac{\mathit{Energy\ produced\ in\ EA}}{\mathit{Energy\ injected\ by\ the\ beam}}=\frac{\overset{\text{Energy/fission}}{0.18}\,k_s\overset{\text{n/p}}{N_0}}{\underset{\text{n/fission}}{\nu}\left(1-k_s\right)\underset{\text{Beam energy}}{E_b}}=\frac{G_0k_s}{\left(1-k_s\right)}\approx\frac{G_0}{\left(1-k_s\right)}$$

- 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 **F**irst **E**nergy **A**mplifier **T**est (**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.

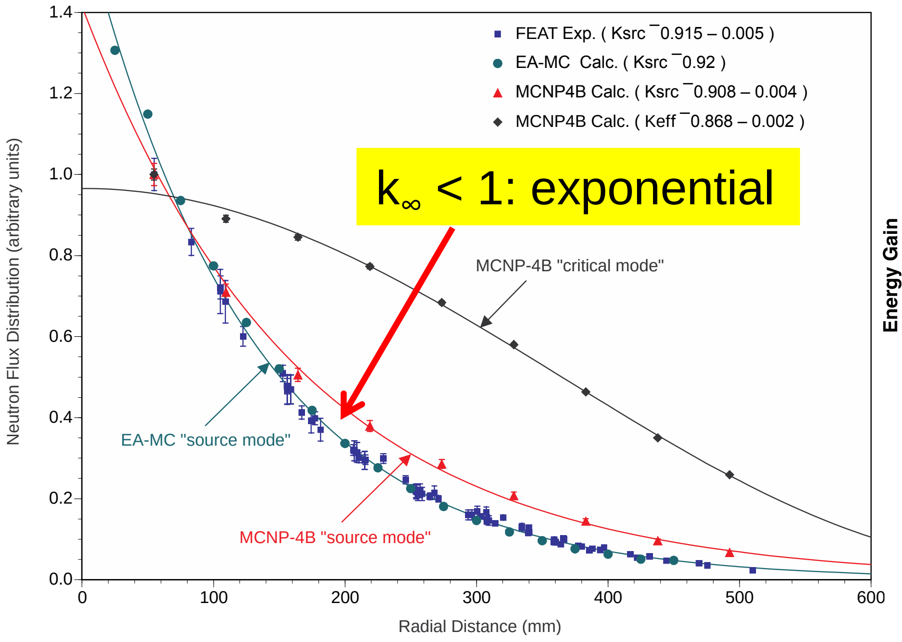




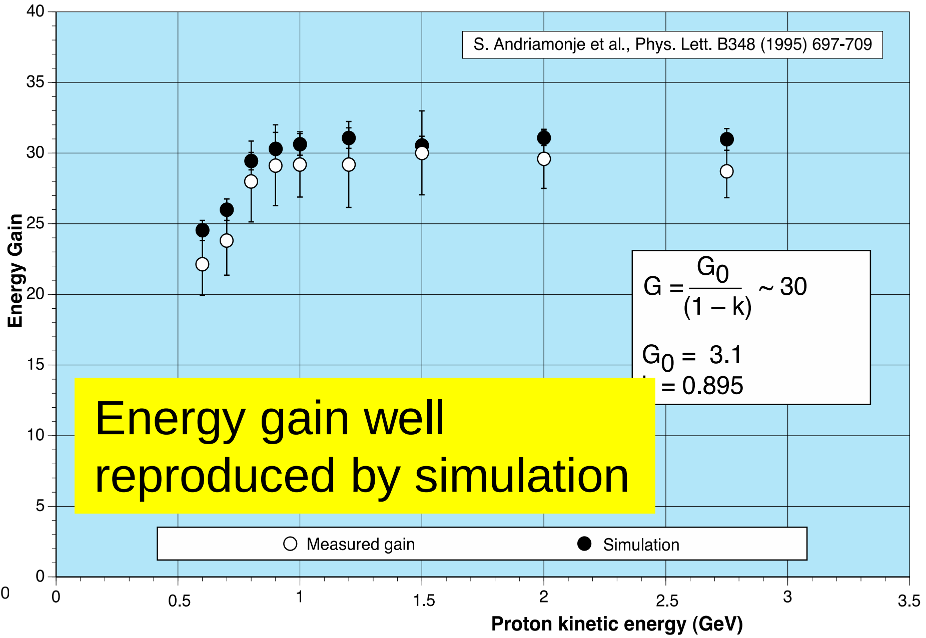
3.62 t of natural uranium; k_{eff} ~ 0.9

- Count fissions
- Measure temperature

Main results from FEAT



$k_\infty < 1$: exponential



$G = \frac{G_0}{(1 - k)} \sim 30$

$G_0 = 3.1$

$= 0.895$

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

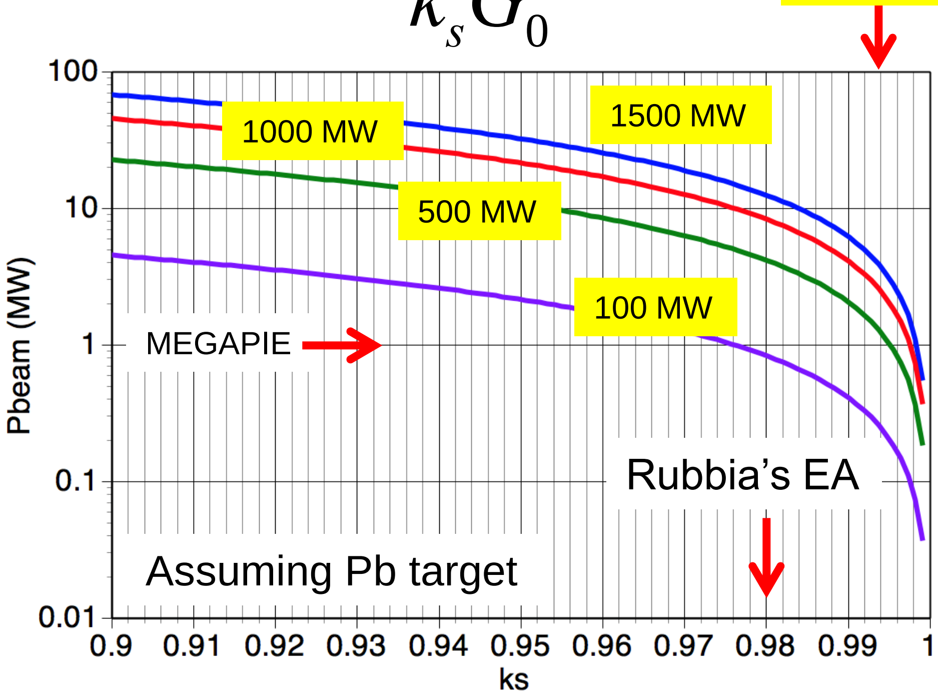
Energy gain in ADS systems

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

- 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

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

Margin of present PWR



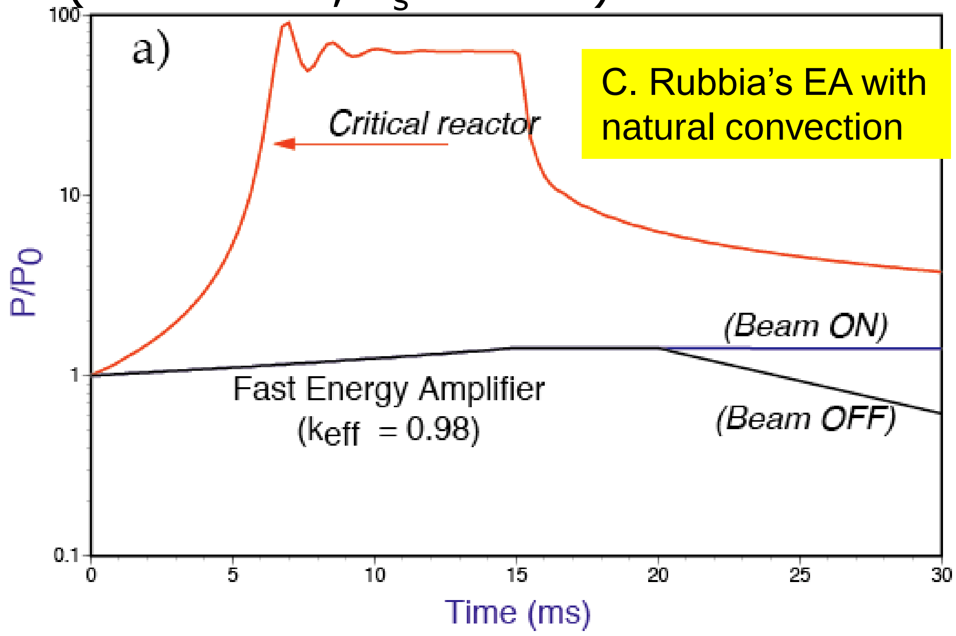
With PSI separate turns cyclotron (3 mA and 1.8 MW, with 0.59 GeV protons).
P_{ADS} = 243 MW_{th} with k = 0.98
P_{ADS} = 486 MW_{th} with k = 0.99.

Guidelines for ADS parameters choice

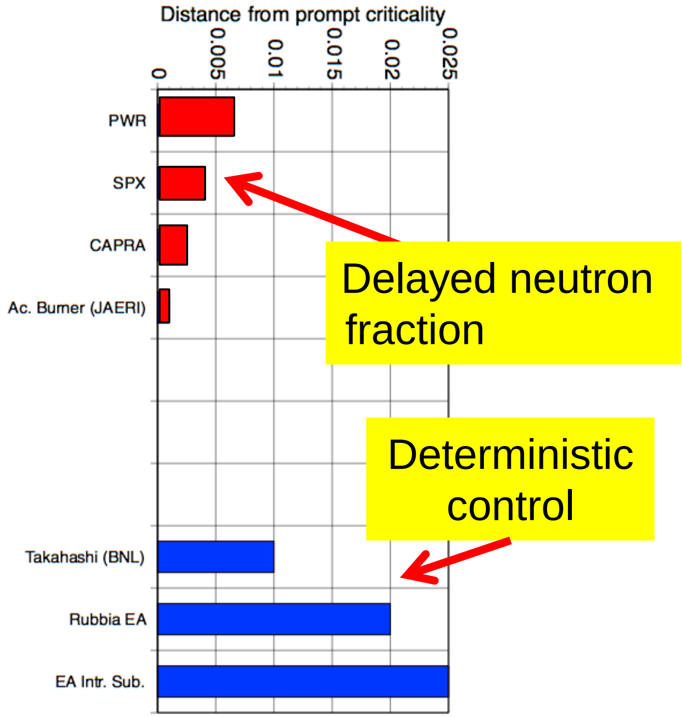
- ☐ **Safety**:
  - ☒ Eliminate criticality accidents by making the system subcritical (void coef., T coef., β_{eff} no longer "critical" parameters)
    This requires an external proton source!
  - ☒ Operate system with passive safety elements to avoid core melting or limit its consequences, borrowing 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.
- ☐ **Military proliferation**:
  - ☒ Use thorium fuel (small Pu prod., ^{233}U very difficult mixture)
  - ☒ Avoid Pu separation (Purex), use pyroelectro reprocessing instead (developed for uranium at Argone N.L.)

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 = 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)



C. Rubbia's EA with natural convection



Delayed neutron fraction

Deterministic control

Guidelines for ADS parameters choice

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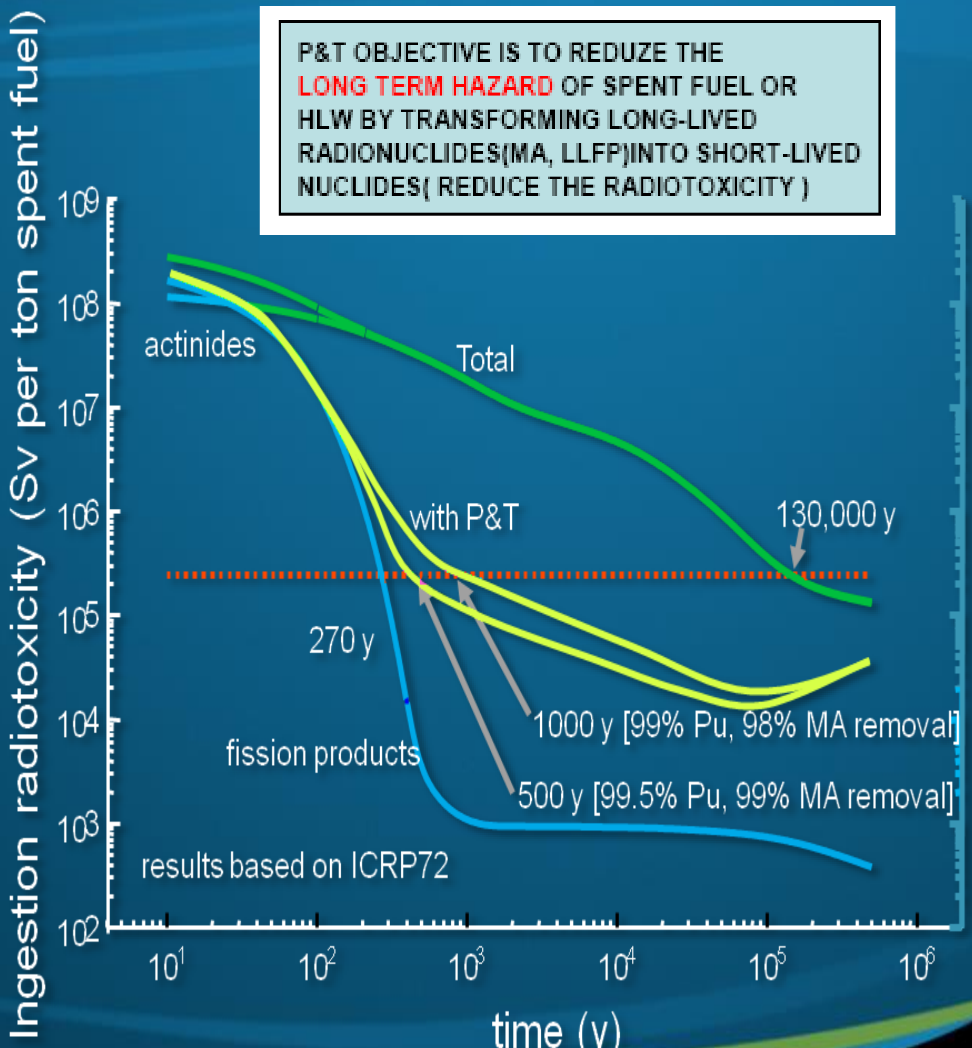
Partitioning &Transmutation

- 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.

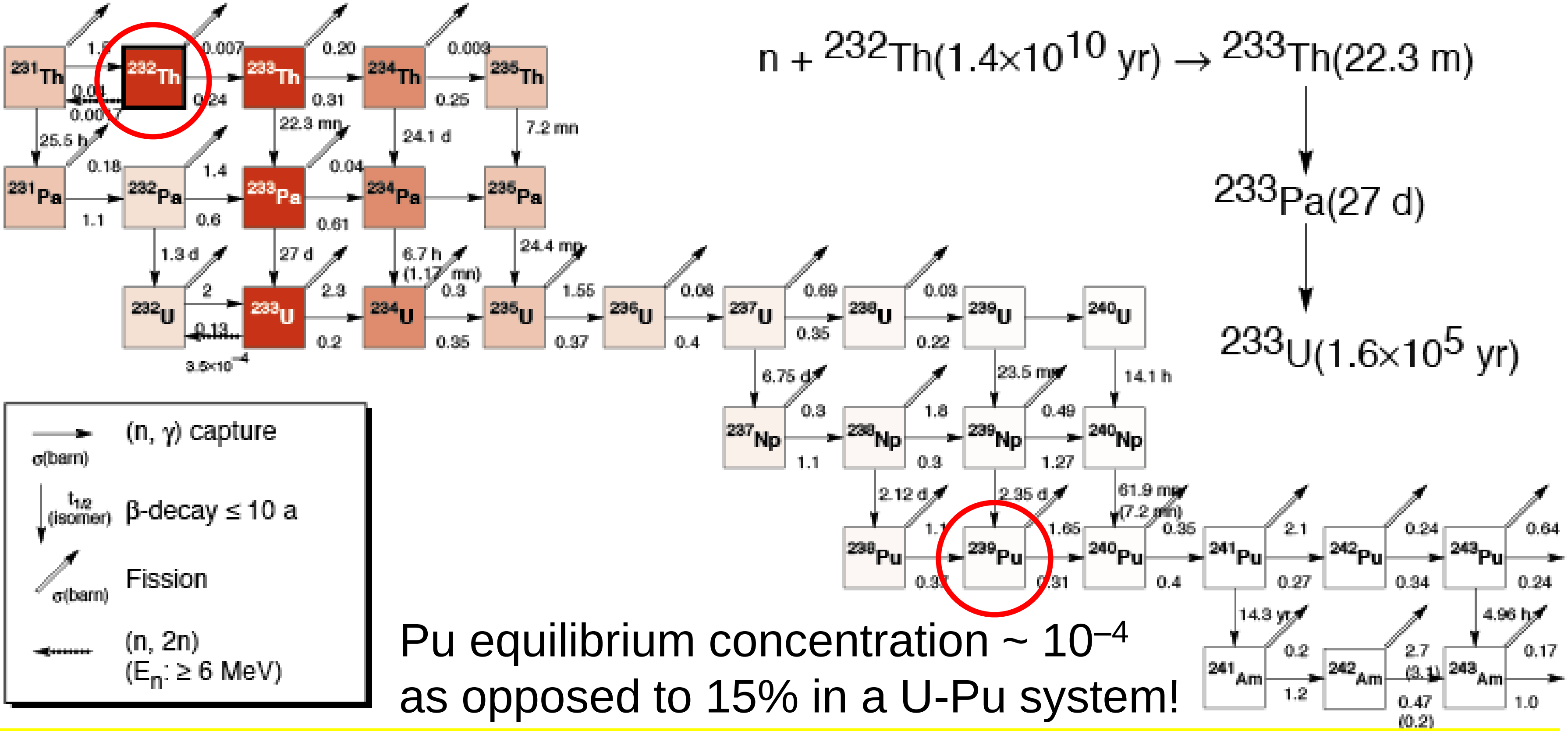


P&T OBJECTIVE IS TO REDUZE THE LONG TERM HAZARD OF SPENT FUEL OR HLW BY TRANSFORMING LONG-LIVED RADIONUCLIDES(MA, LLFP)INTO SHORT-LIVED NUCLIDES(REDUCE THE RADIOTOXICITY)

Physics of a thorium core

❑ **Thorium in a fast neutron flux**:

- ☒ It takes 7 neutron captures to go from ^{232}Th to ^{239}Pu!
- ☒ ^{233}Pa decay 10 times slower than ^{239}Np



$$n + {}^{232}\mathrm{Th}(1.4\times10^{10}\ \mathrm{yr}) \rightarrow {}^{233}\mathrm{Th}(22.3\ \mathrm{m})$$

$$\downarrow$$

$$^{233}\mathrm{Pa}(27\ \mathrm{d})$$

$$\downarrow$$

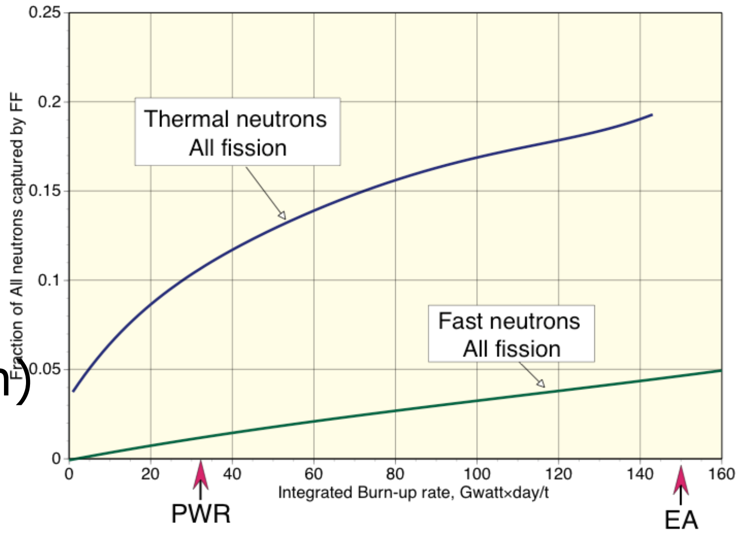
$$^{233}\mathrm{U}(1.6\times10^{5}\ \mathrm{yr})$$

Pu equilibrium concentration ~ 10^{-4}
as opposed to 15% in a U-Pu system!

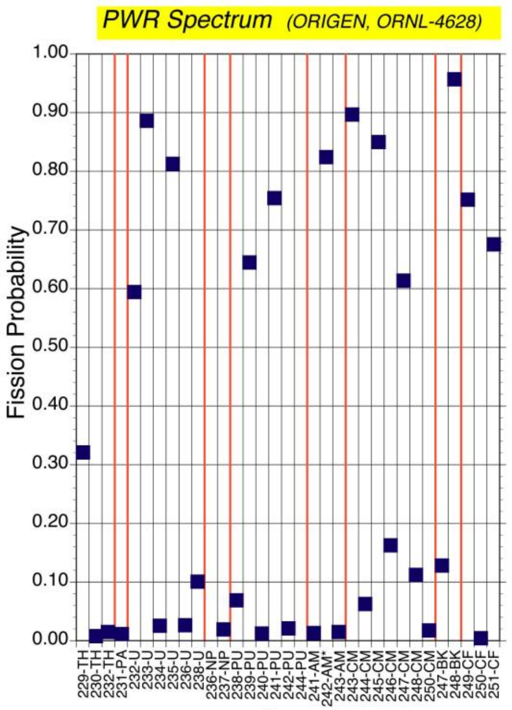
Thorium is a major asset to minimize waste production or to destroy waste

Why fast neutrons

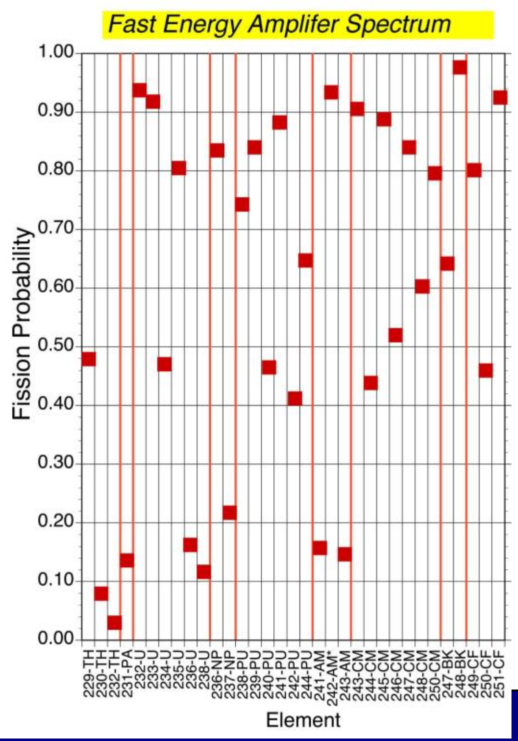
- **Use fast neutrons**:
  - ☒ Enhances TRU fission probability
  - ☒ No need to separate out Pu! (**Pyro-Electro reprocessing**)
  - ☒ Reduces captures on FF, extends burnup (120 GW.day/t achieved in fast electro-breeder at Argonne N.L., in EA simulation)

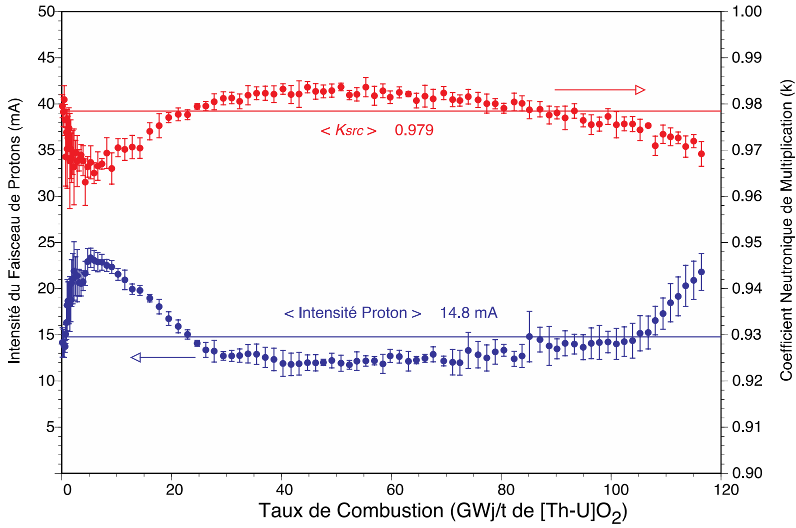


Thermal Neutrons



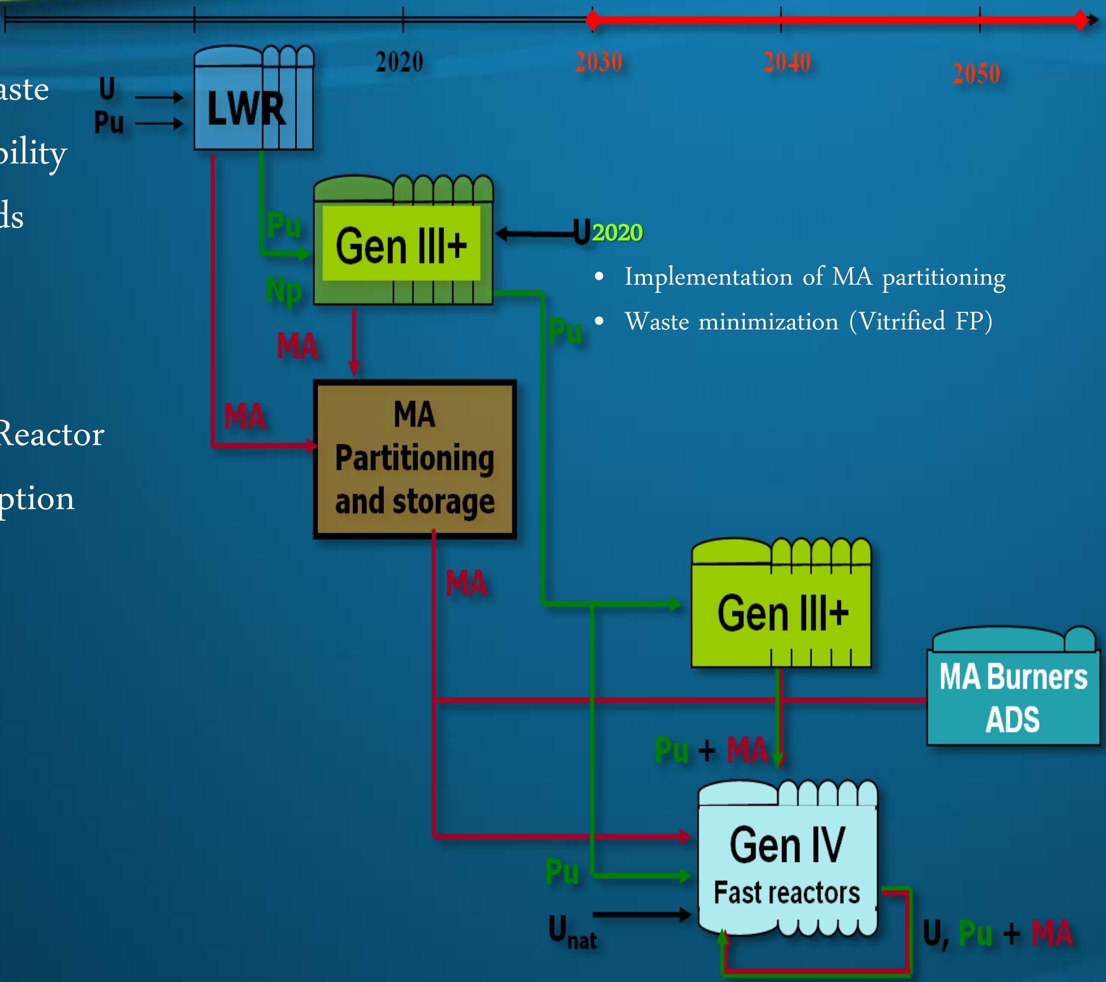
Fast Neutrons





Common Deployment Scenario

- 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

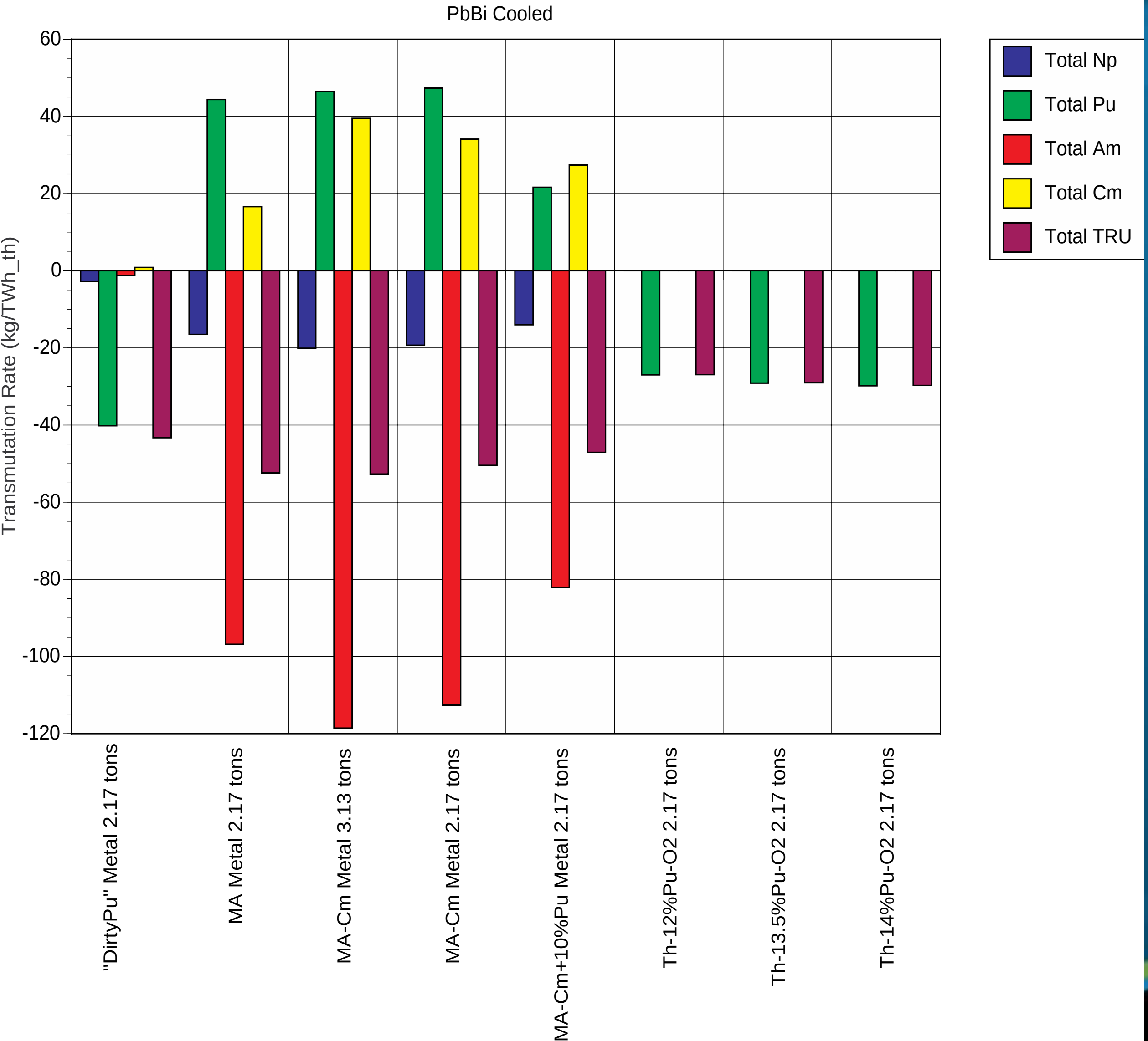


- Implementation of MA partitioning
- Waste minimization (Vitrified FP)

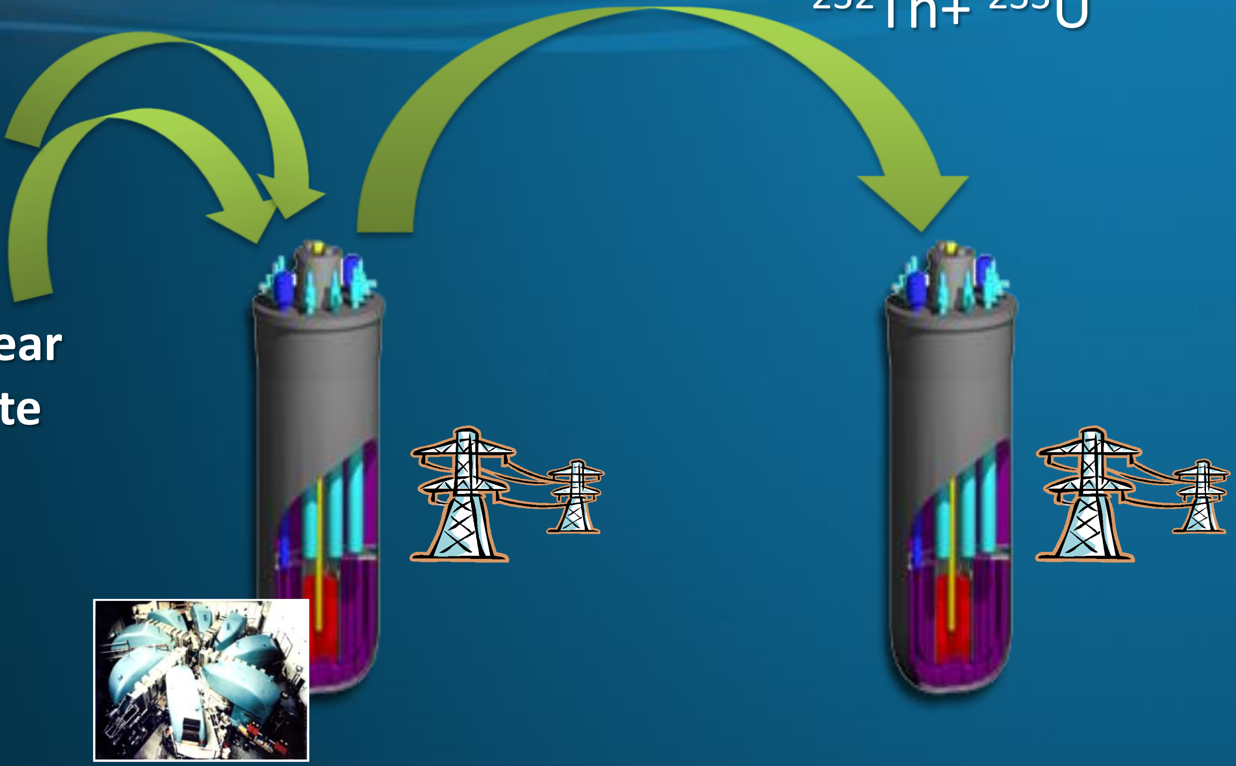
MA Transmutation

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

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



Alternative Deployment Scenario



^{232}Th

Nuclear waste

^{232}Th+ ^{233}U

STAGE 1

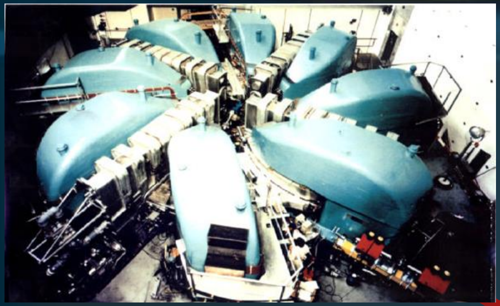
ADS

STAGE 2

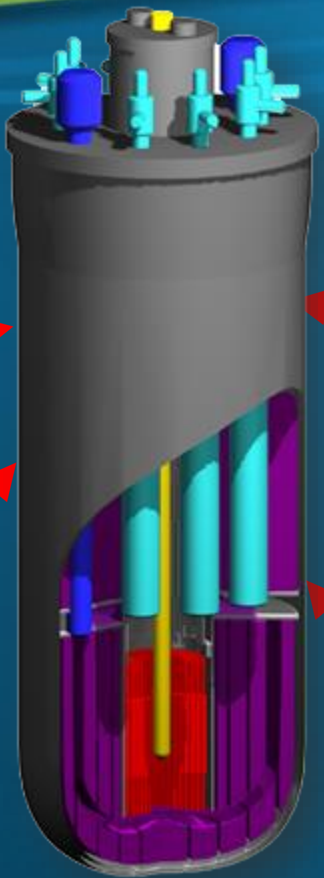
LWR with reduced waste generation

Fast track by Integration of Consolidated Technologies … by 2030 !

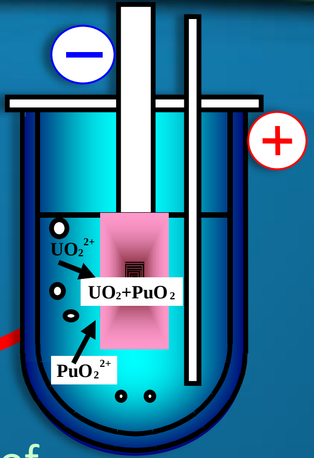
iThEC
INTERNATIONAL THORIUM ENERGY COMMITTEE



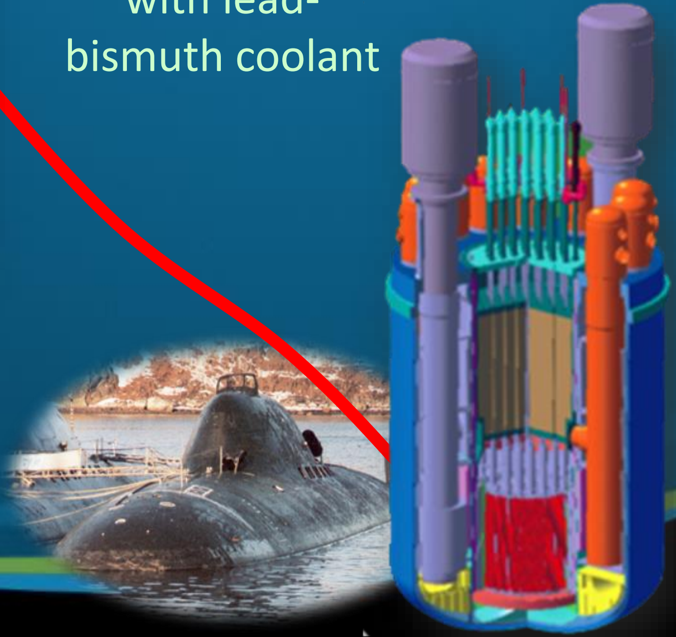
High power accelerators technology



Technology of pyrochemical reprocessing of fuel



Technologies of fast reactors with lead-bismuth coolant



Liquid metal targets technology

Europe ADS: MYRRHA

In principle MYRRHA should be the flagship of ADS projects.

Strong support from the Belgian government, however:

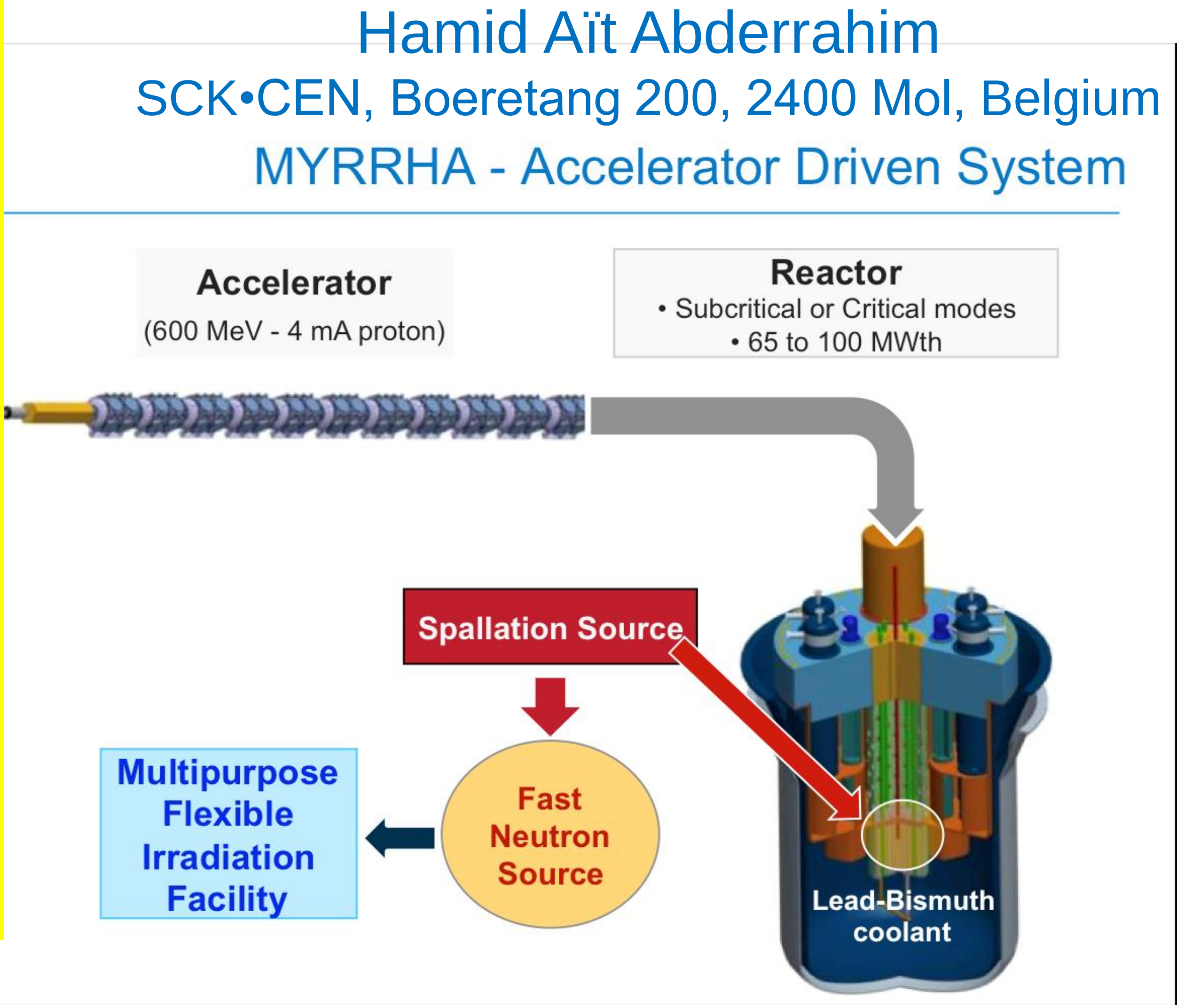
– several challenges faced at the same time: the accelerator, the subcritical core and their coupling

– 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

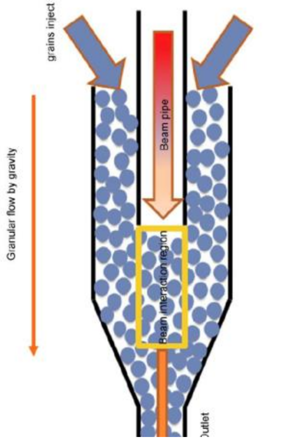
Fast Neutron Source

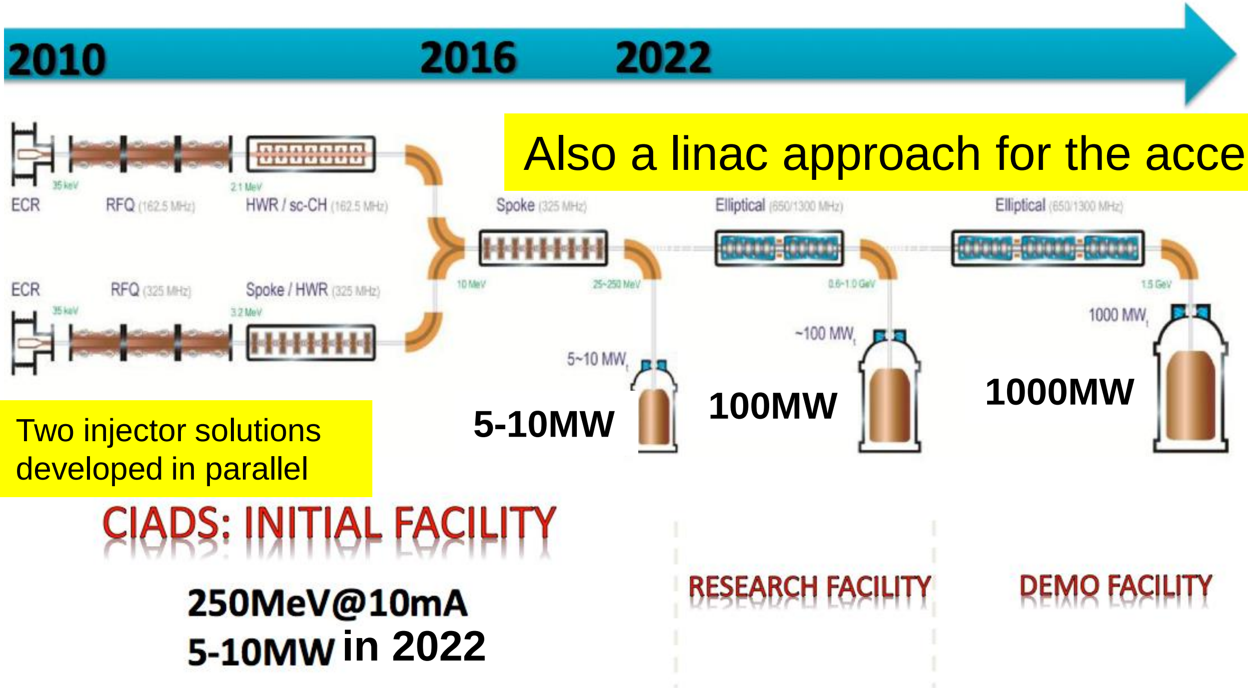
Multipurpose Flexible Irradiation Facility

Lead-Bismuth coolant

China ADS: 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

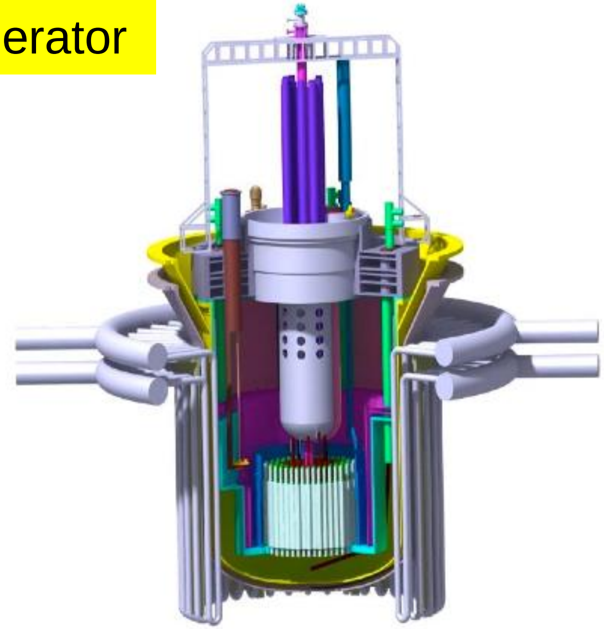
Two injector solutions developed in parallel

CIADS: INITIAL FACILITY

250MeV@10mA
5-10MW in 2022

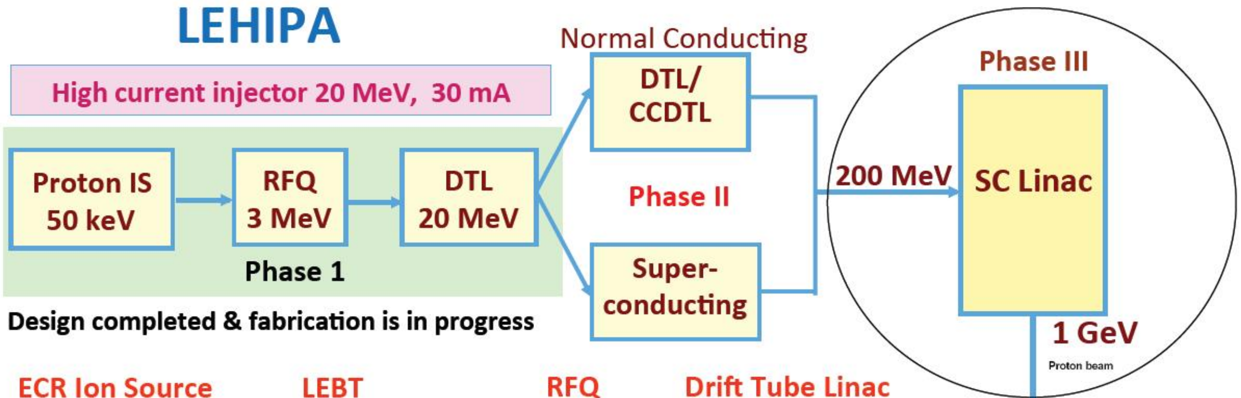
RESEARCH FACILITY

DEMO FACILITY



India ADS at BARC

Shashikant Degweker



LEHIPA

High current injector 20 MeV, 30 mA

Proton IS 50 keV → RFQ 3 MeV → DTL 20 MeV

Phase 1

Design completed & fabrication is in progress

Normal Conducting

DTL/ CCDTL

Phase II

Super-conducting

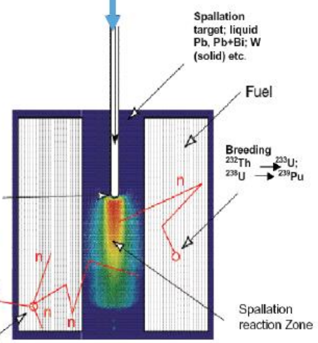
200 MeV

Phase III

SC Linac

1 GeV

Proton beam



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 (Aker Solutions with C. Rubbia) – 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**

Accelerator requirements

- Choices for an industrial system will rely on specifications in terms of:
  - ☒ **Beam power**: 1-10 MW depending of choice of k value, and desired unit power; $E_{beam} \geq 900$ MeV
  - ☒ **Beam losses**: minimize irradiation of the accelerator and of the environment; impact on the maintenance (minimize and localize beam losses)
  - ☒ **Reliability**, minimize beam trips (have multiple sources); ease of maintenance
  - ☒ **Beam stability and control**: 1% fluctuation on beam intensity is 1% fluctuation on the thermal power; beam intensity to be varied by a factor ≥ ?2
  - ☒ **Energy efficiency**: maximize fraction of electric grid power stored into the beam) Improves with increasing beam power.
  - ☒ **Size, cost**

iThEC
INTERNATIONAL THORIUM ENERGY COMMITTEE

Development is Time-Consuming

Generation I

Early Prototype Reactors

- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors

- LWR-PWR, BWR
- CANDU
- AGR

Generation III

Advanced LWRs

- ABWR
- System 80+
- AP600
- EPR

Generation III +

Evolutionary Designs Offering Improved Economics for Near-Term Employment

Generation IV

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

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

iThEC aims to promote the deployment of these technologies

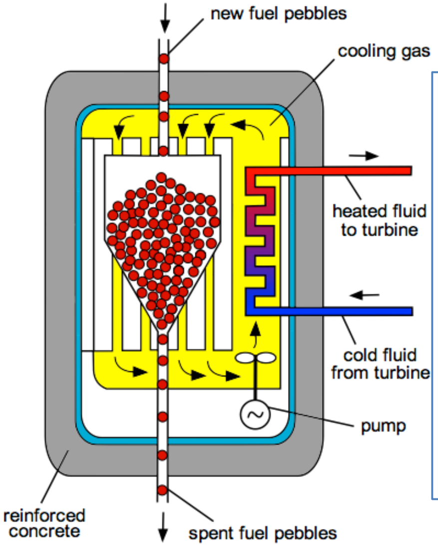
Click to edit Master

Thank You

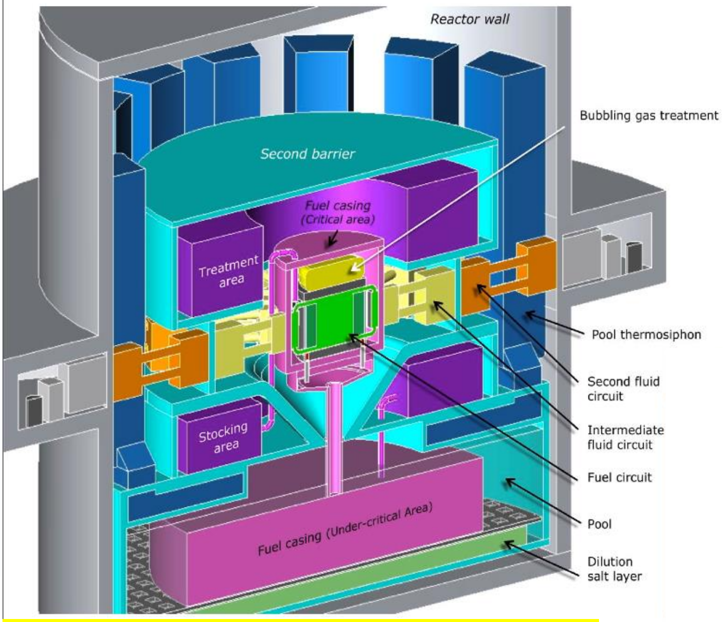
How to use thorium in practice?

- **Thorium blankets around fast critical reactors to breed ^{233}U**: the Indian approach, at the cost of maintaining three different nuclear reactor technologies
- **Continuously circulating fuel to always have fresh fuel in the core**
  Pebble bed or molten salt critical reactors (MSR) or Traveling wave reactors?
- **Provide extra neutrons with an accelerator: ADS**

Pebble bed Scheme



Pebble-bed and Molten salt reactors have both severe issues to be resolved, mainly in terms of safety, in addition to the fact that **they do not provide (so far) a fast neutron flux**



Molten Salt Reactor Scheme

Thorium blanket: Indian strategy

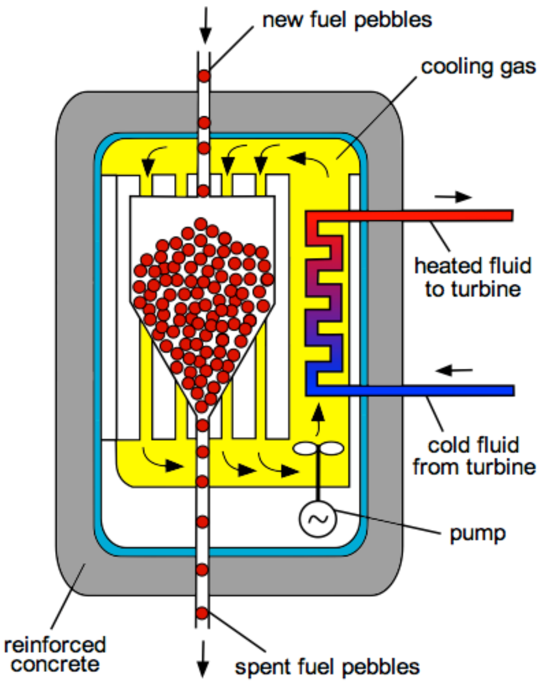
- India, with little uranium resources but a lot of thorium, has the most advanced practical scheme for using thorium (including front-end and back-end of the fuel cycle):
  - Use **heavy water reactors** (CANDU) or LWR to produce **plutonium**
  - Use **sodium cooled U-Pu fast reactors** with a thorium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

- The Indian scheme works. However, several issues remain concerning the **complexity** (three technologies), the **sustainability** and **nuclear waste management**.

Pebble bed critical reactors

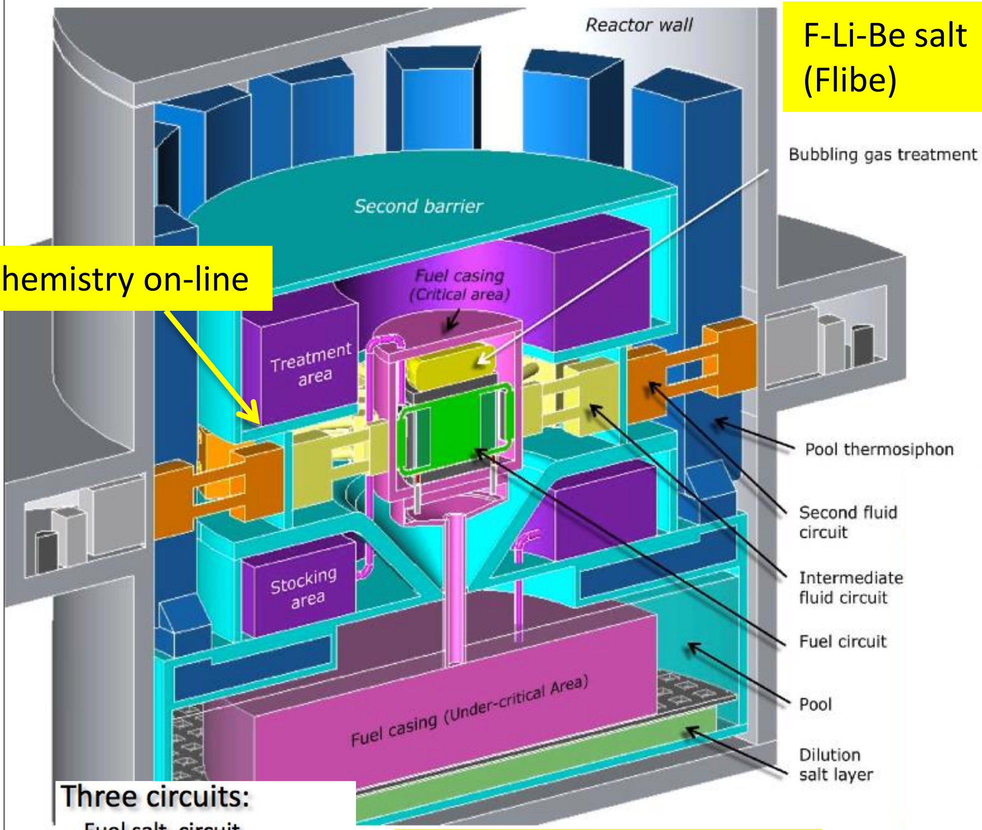
- Proposed by Farrington Daniels at Oakridge, in the 1940s. Initial developments in Germany (AVR Jülich), followed by THTR-300MW (1983-1989). New developments in South Africa, now in the United States and Turkey.
  - Presented as passively safe, as high temperature systems can be cooled by natural air convection
- Several severe issues to be resolved:
  - No containment building if cooling by natural air convection
  - Uses flammable graphite as moderator
  - Produces more high-level nuclear waste than current nuclear reactor designs
  - Relies heavily on pebble integrity and fuel handling (pebble accident in THTR-300)
  - Water ingress, reprocessing virtually impossible, etc.

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): China, India, UK, USA, Czech Republic, France, Switzerland
- Pioneered at Oakridge in 1960 (Molten Salt Reactor Experiment, UF4, 7.4MWth)
- Advantages:
  - Liquid fuel allows extending burnup indefinitely, because of reprocessing on-line
  - High temperature (500˚C – 600˚C), heat produced directly in heat transfer fluid
  - Passive cooling for decay heat removal
- **Several severe issues**: neutrons emission, on-line chemistry failure, corrosion, licencing issues, etc.
- Presently not using a fast neutron spectrum (R&D should be extended to other salts – $PbCl_3$, to minimize waste)
- There is a particularly well focussed and ambitious effort in China (Xu Hongjie, Shanghai Institute of Applied Physics)



F-Li-Be salt (Flibe)

Chemistry on-line

Three circuits:
Fuel salt circuit
Intermediate circuit
Thermal conversion circuit

Elsa Merle-Lucotte @ ThEC13