INTERNATIONAL THORIUM ENERGY COMMITTEE
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Sustainable Thorium Energy for the World

Nuclear energy based on thorium and controlled by a proton accelerator instead of uranium in a critical reactor

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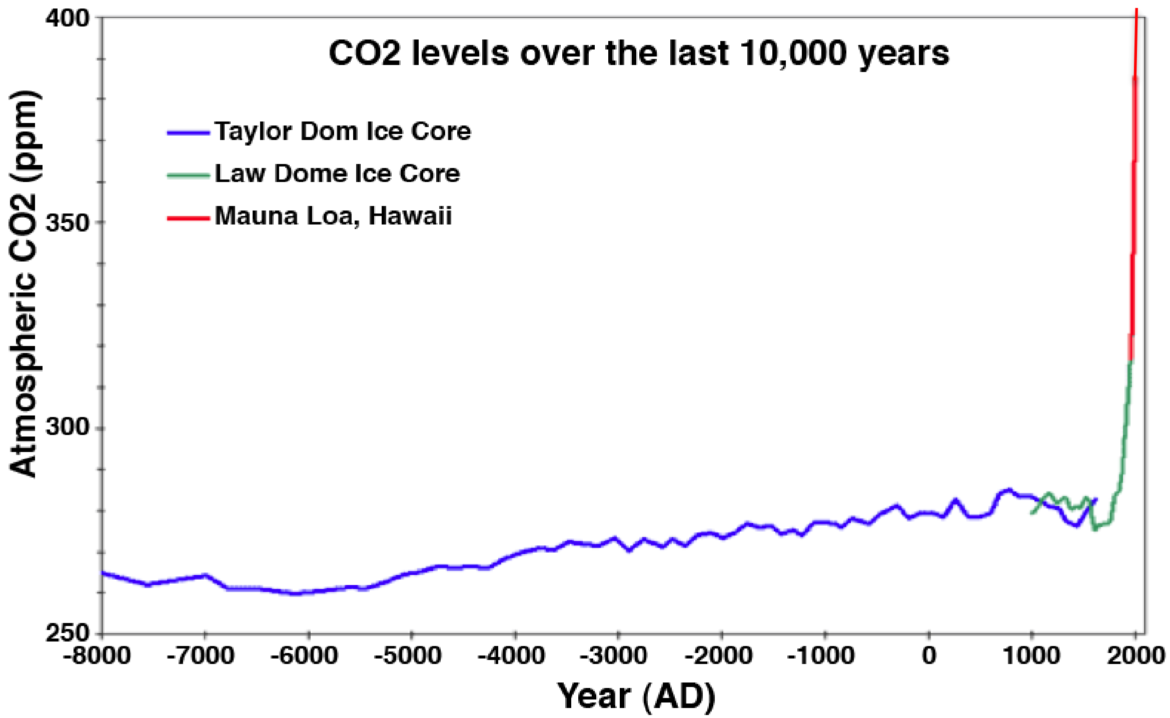
Science and Sustainability: Impacts of Scientific Knowledge and Technology on Human Society and its Environment
Pontifical Academy of Sciences
25-29 November 2016, Casina Pio IV, Vatican City

Sustainable energy

- **A source of energy that will last long enough for an innovative technology to provide a replacement, while its impact on the environment can be reasonably managed**
  - **Sustainability requires R&D** to ensure that the next innovation will come on time
  - The research effort **must include fundamental research**, as it is fundamental research that drives innovation
  - Investing in R&D implies also investing in **education**

One of Society's biggest challenges: transition to a zero carbon society

- **It does not make sense to burn fossil fuels (coal, oil, gas) till the end of supply for several reasons**:
  - **Global warming:** more and more consensus that anthropic carbon emission is a problem



One of Society's biggest challenges: transition to a zero carbon society

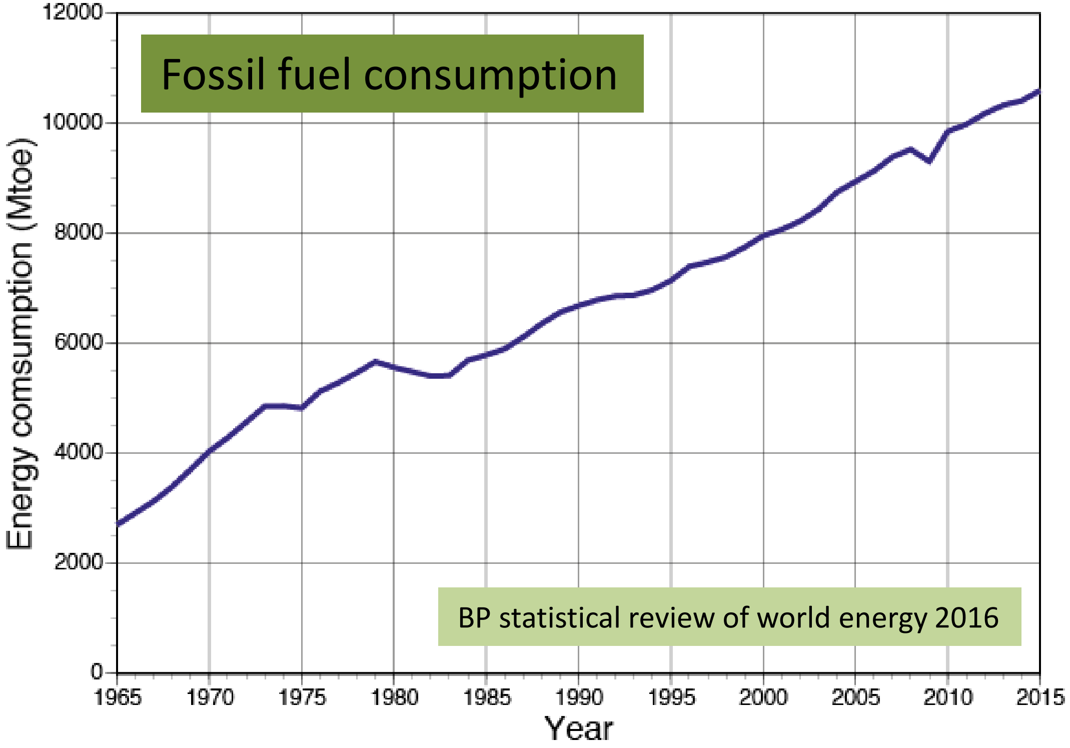
– **Air pollution:** immediate, real, and a very costly major problem

"Air pollution poses the single largest environmental health risk in Europe today"
European Environment Agency

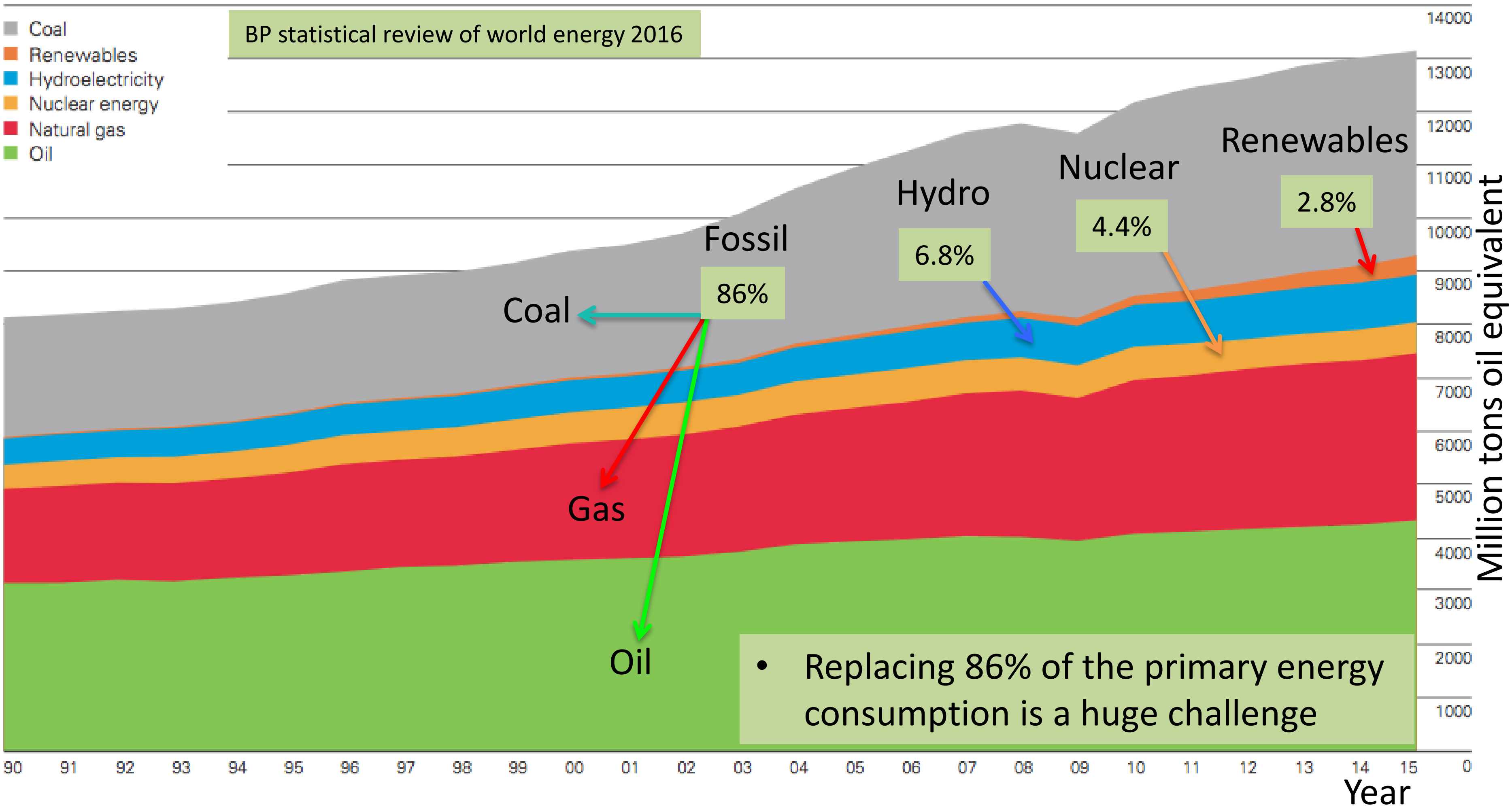
- Burning coal cost Europe alone 43 billion Euros in 2014 health care expenses (Heinrich Böll Stfitung);
- 1.6 M deaths per year in China due to air pollution (Rohde, Muller, Berkeley);
- 1 in 8 of total global deaths are the result of air pollution exposure (WHO).

– **Better use of oil:** plastics, rubber, paint, glue, drugs, cosmetics, detergents, …

- **However, as they are cheap and abundant, the current tendency is still to increase fossil fuel consumption!**



World Primary Energy Consumption



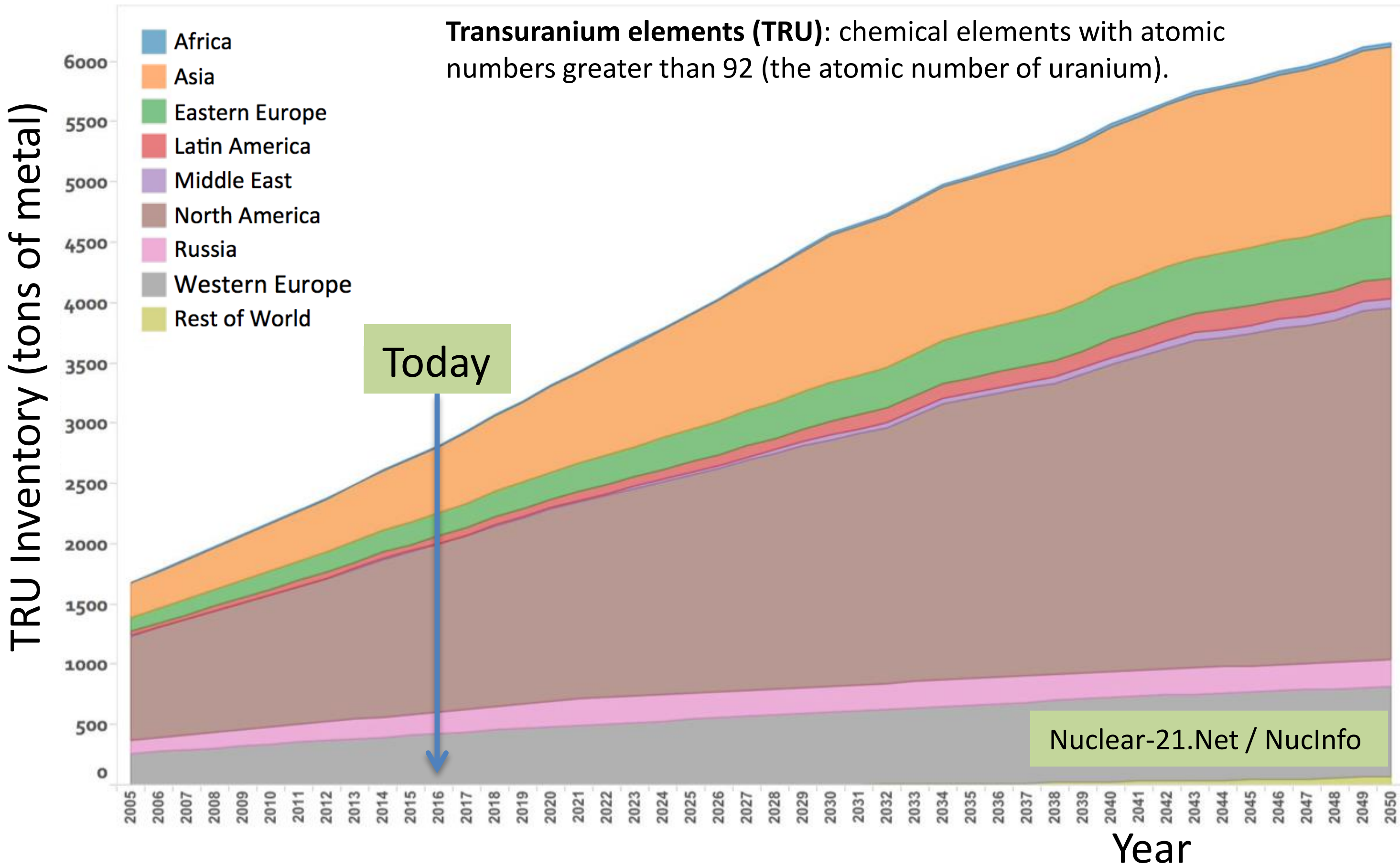
- Replacing 86% of the primary energy consumption is a huge challenge

A different nuclear energy?

- **Solutions must come from R&D.** R&D must be systematic, it must not exclude the nuclear fission domain
- **Nuclear fission energy is abundant, energy-intensive** (1 ton of thorium ≈ 3 million tons of coal), can ensure **base load electricity** production, emits **no greenhouse gases or air pollution**, **could be made sustainable**
  – If it were not for **accidents, waste management, proliferation issues,** nuclear energy would be ideal
- **Question: Can nuclear energy be made acceptable to society?**
- Present nuclear energy technology was not <u>chosen</u> to be acceptable:
  – **Uranium fuel cycle**: to produce plutonium for nuclear bombs
  – **Pressurized Water Reactors (PWR)**: to fit on a boat
- Is there a better way of exploiting nuclear energy?
  – Yes, with "**Thorium fuel in fast neutron Accelerator-Driven Systems (ADS)**"

Comment on nuclear waste

- Regardless of national policies, the problem of nuclear waste management must be solved
- The added requirement of **retrievability** makes the geological repository strategy more questionable



➔ **the idea is to use thorium fuel to destroy a large fraction of this waste**

Thorium: $^{232}\mathrm{Th}^{142\ \mathrm{neutrons}}_{90\ \mathrm{protons}}$

Monazite sample containing 2 to 3% of Th mixed with rare earths, from the Steenkampskraal mine, South Africa.

- Thorium occurs mostly in monazite (**Ce, La, Nd, Th**)PO_4, **often a by-product of rare earth mining**, found also in tin, coal and uranium tailings

- **Excellent physical properties**: Higher melting point of metallic state (1750°C) compared to (1130°C) for uranium and of ThO_2 (3300°C) compared to UO_2 (2800°C). ThO_2 has better thermal conductivity and smaller expansion coefficient than UO_2:
  ➔ **Higher margins for design and operation as nuclear fuel**

- **Abundant**, as much as lead, three to four times more than uranium and **broadly distributed over the world**:
  – Known and estimated resources: 6.3×10^6 tons, probably more (≈ 2500 years of world electric energy consumption*);
  "***Thorium is a source of energy essentially sustainable on the human time scale***"

Nobel Laureate Carlo Rubbia @ ThEC13

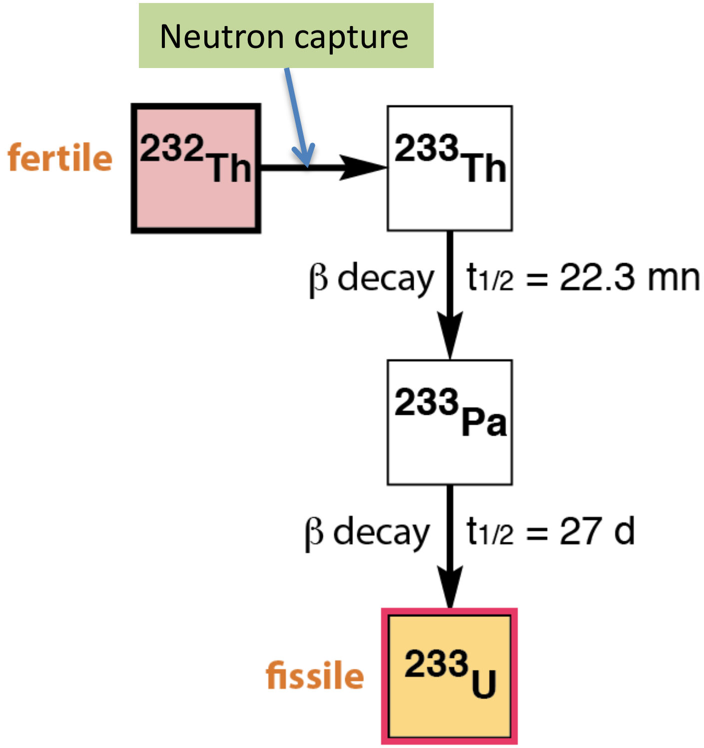
Country	Tonnes
India	846,000
Brazil	632,000
Australia	595,000
USA	595,000
Egypt	380,000
Turkey	374,000
Venezuela	300,000
Canada	172,000
Russia	155,000
South Africa	148,000
China	100,000
Norway	87,000
Greenland	86,000
Finland	60,000
Sweden	50,000
Kazakhstan	50,000
Other countries	1,725,000
World total	**6,355,000**

OECD/IAEA/Uranium 2014

*World electrical power consumption ≈2.5 TW

Fission energy from thorium

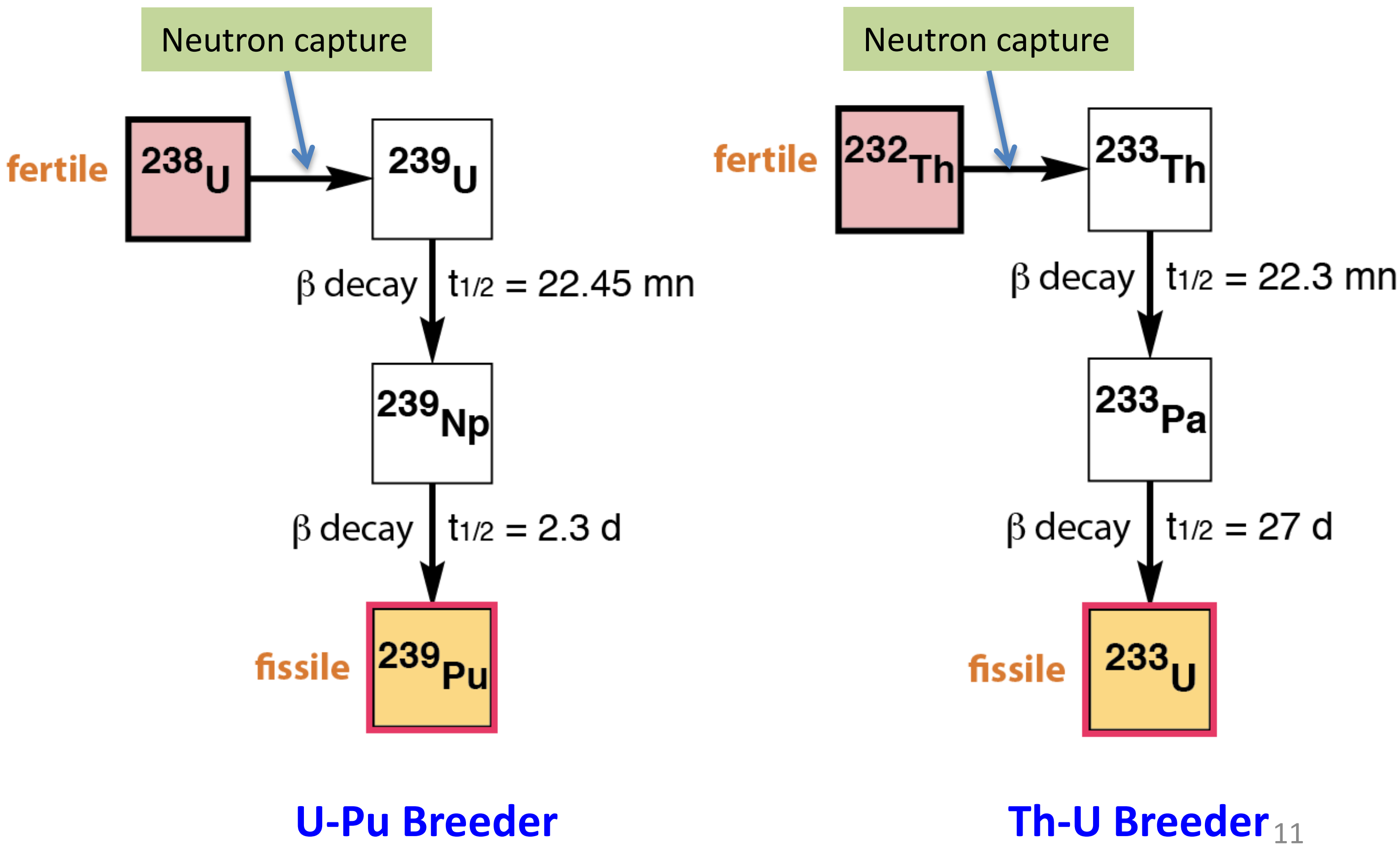
- Thorium is **fertile**, not fissile, so it can **ONLY** be used in breeding mode (to produce ^{233}U which is fissile) **– inconvenience that can be turned into an advantage**



Th-U Breeder

Fission energy from thorium

- ^{232}Th chain analogous to ^{238}U chain (Superphenix type of reactor / GEN IV)

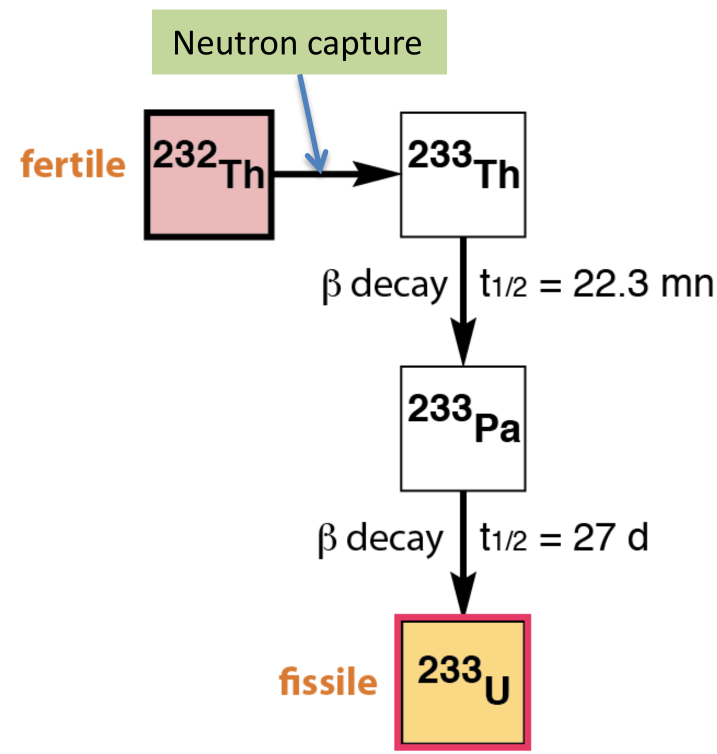


Fission energy from thorium

- However, breeding gives a factor 140 gain compared to ^{235}U in PWR (in addition to the factor 3 to 4 in abundance): **potentially ≈ 500 times more abundant than ^{235}U**

The ^{235}U isotope represents only 0.7% of natural uranium

PWR

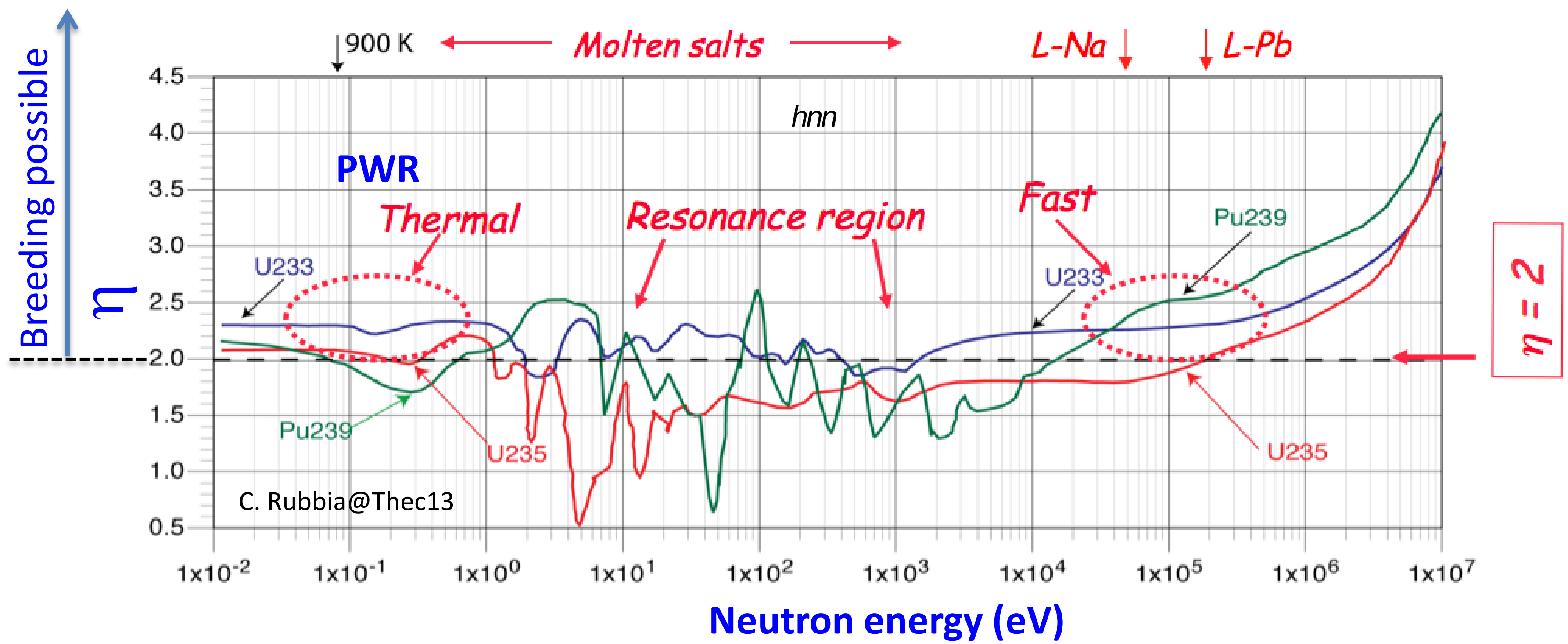


Th-U Breeder

Breeding nuclear fuel

To make breeding possible, the number of neutrons produced per neutron absorbed must be larger than 2

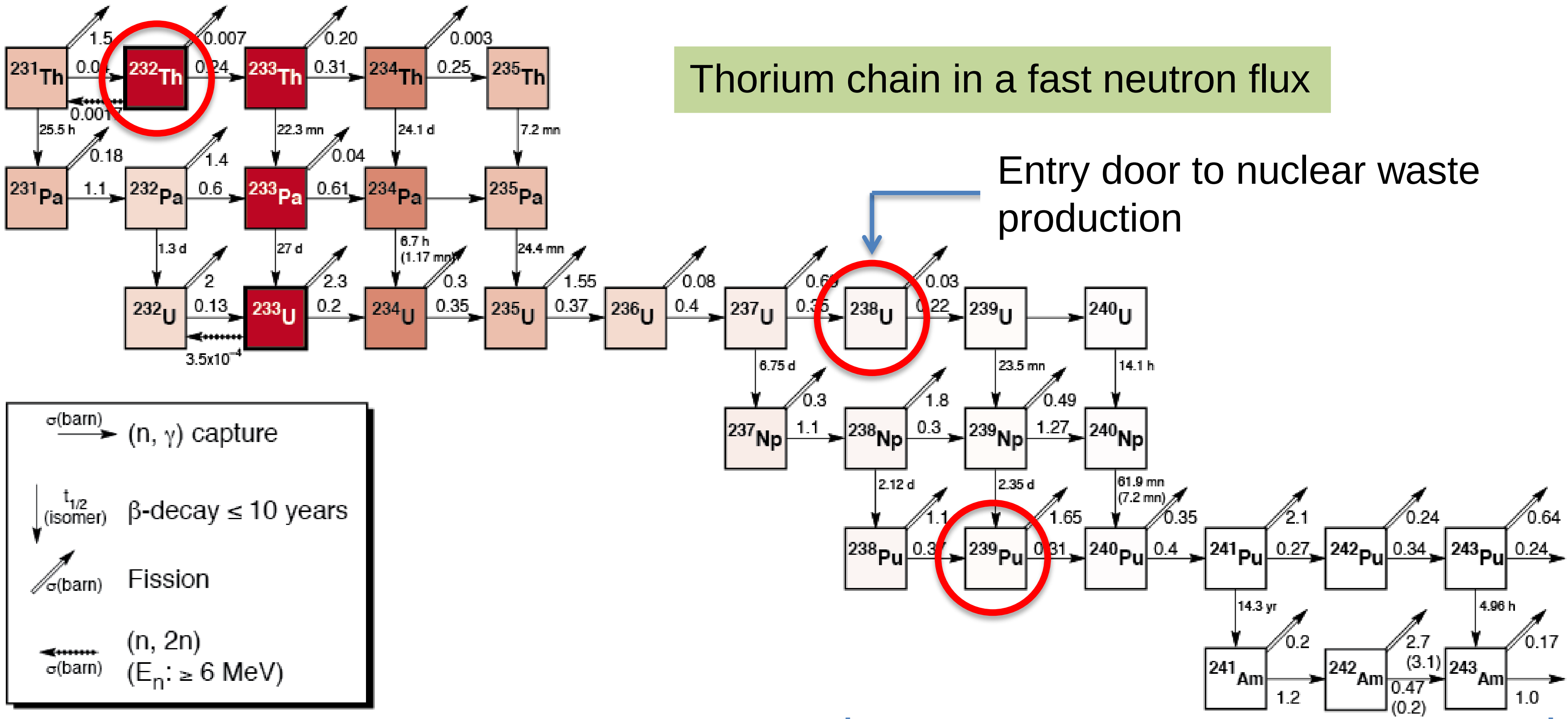
$$h^{o}\, n \frac{s_{f}}{s_{f} + s_{c}} > 2$$



Breeding ^{233}U is most efficient with fast neutrons

Thorium and nuclear waste

Thorium chain in a fast neutron flux



Entry door to nuclear waste production

TRU

- **Thorium minimizes nuclear waste production and is proliferation resistant**
- In a **fast neutron flux**, TRU can be eliminated while producing energy

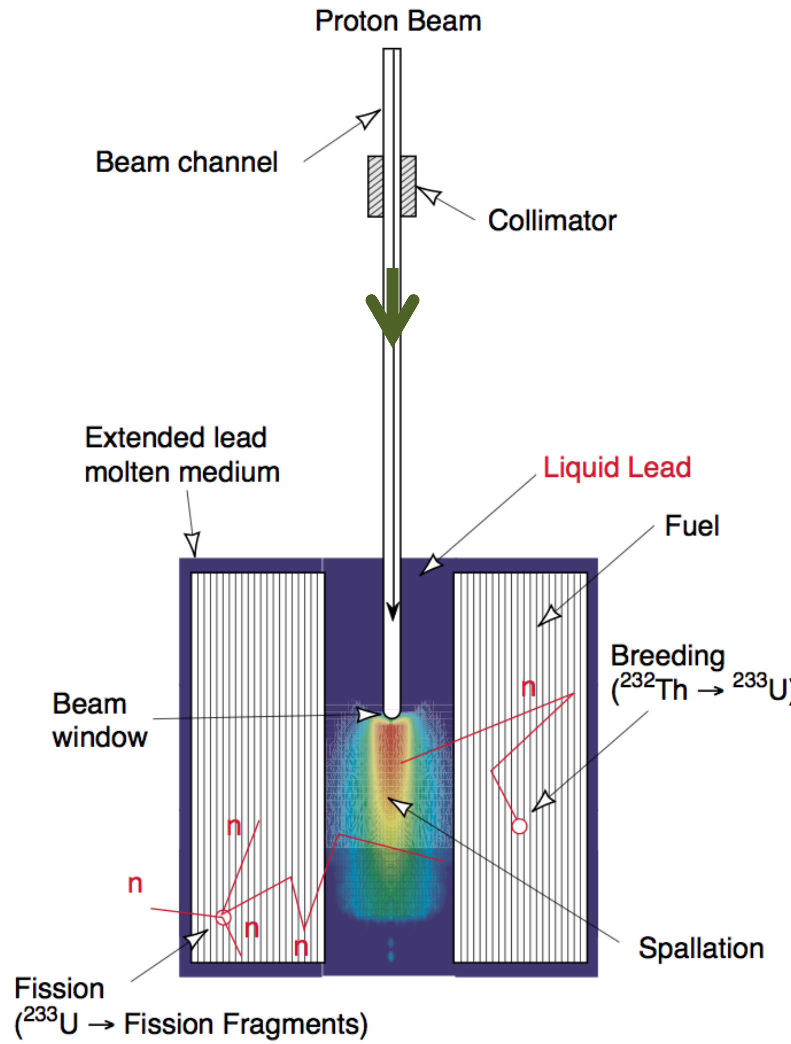
How to use thorium in practice?

- **One cannot simply replace uranium fuel with thorium fuel**
- **What are the options?**
  - **Use thorium blankets** around fast critical reactors to breed ^{233}U and introduce ^{233}U as fuel in new critical reactors (India's strategy)
  - **Continuously move the fuel**, such as to always have fresh fuel
    - ***Pebble bed critical reactors***
    - ***Molten salt critical reactors***
    - ***Traveling wave critical reactor***? (yet to be developed)
  - **Provide an external neutron source to maintain the chain reaction:** Accelerator-Driven Systems (**ADS**)

Accelerator-Driven Systems (ADS)

– **Proposal to use a particle accelerator as a neutron source** by E.O. Lawrence/USA and N.N. Semyonov/USSR in 1940

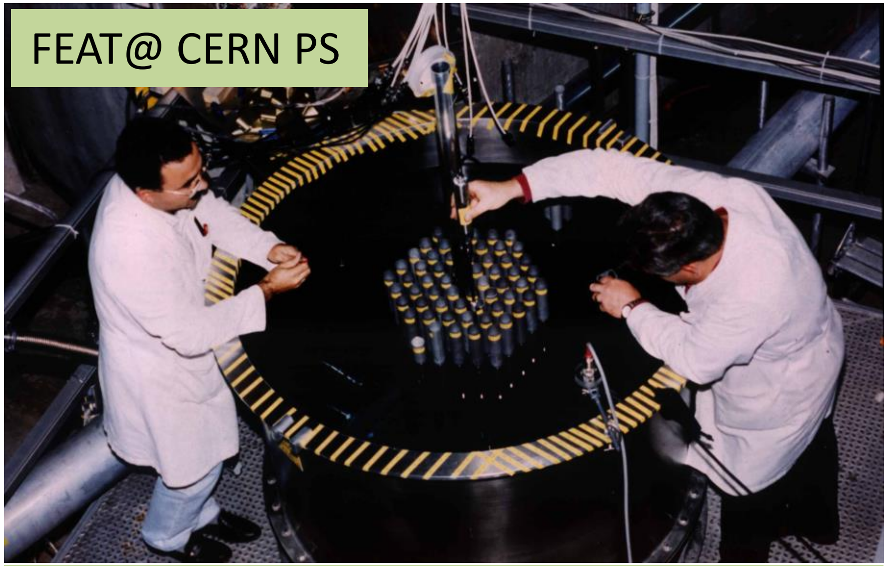
– Beam inserted from the top
– neutrons produced by spallation
– runs in subcritical mode (no criticality accident)
– flexibility in the choice of fuel, **including TRU from nuclear waste**



iThEC

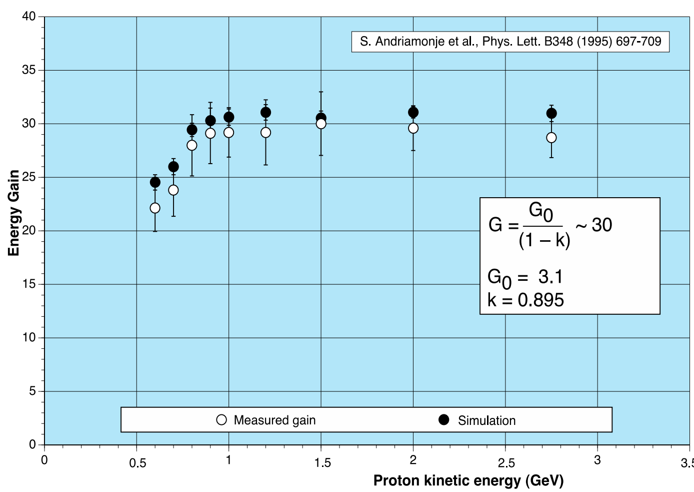
Basic concepts carefully validated 1990s

FEAT@ CERN PS

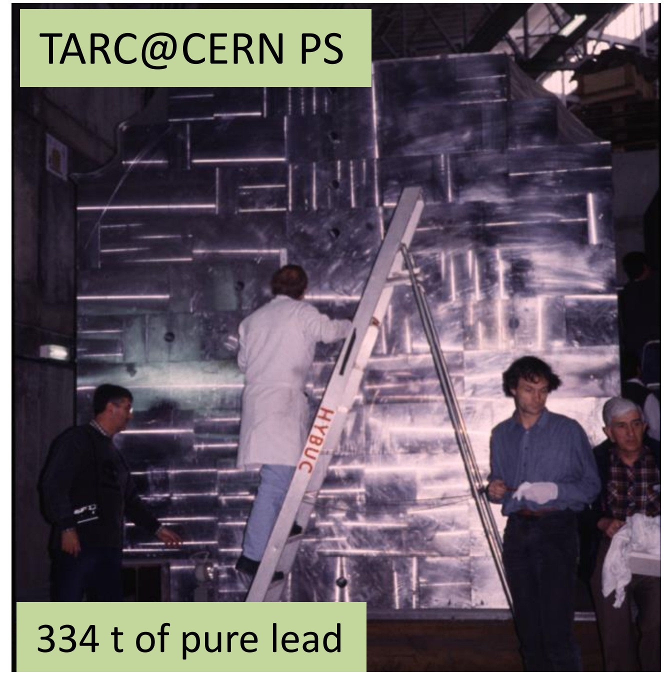


3.62 t of natural uranium at CERN PS; k_{eff} ~ 0.9

S. Andriamonje, et al.; Phys. Lett. B348, 697–709 (1995)

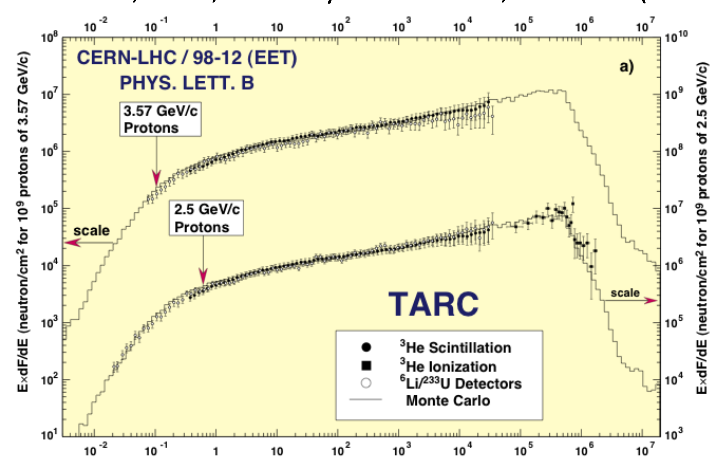


TARC@CERN PS



334 t of pure lead

A. Abánades, et al.; NIM Phys. Res. A 478, 577–730 (2002)

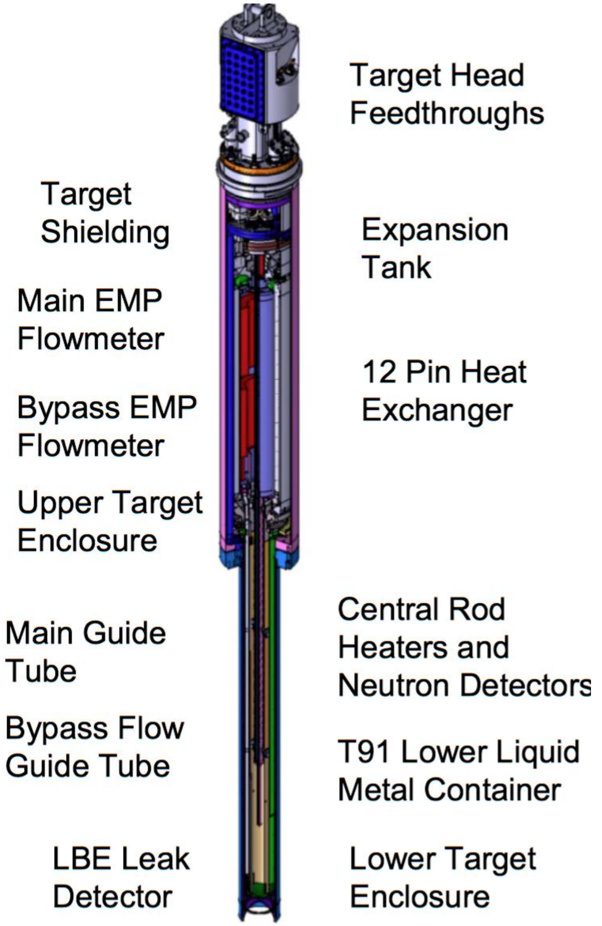


High-power (> 1 MW) proton beams exist

Paul Scherrer Institute (PSI) at Villingen, Switzerland:
– proton beam power of 1.3 MW
– Today, designs exists to reach a power of 10 MW

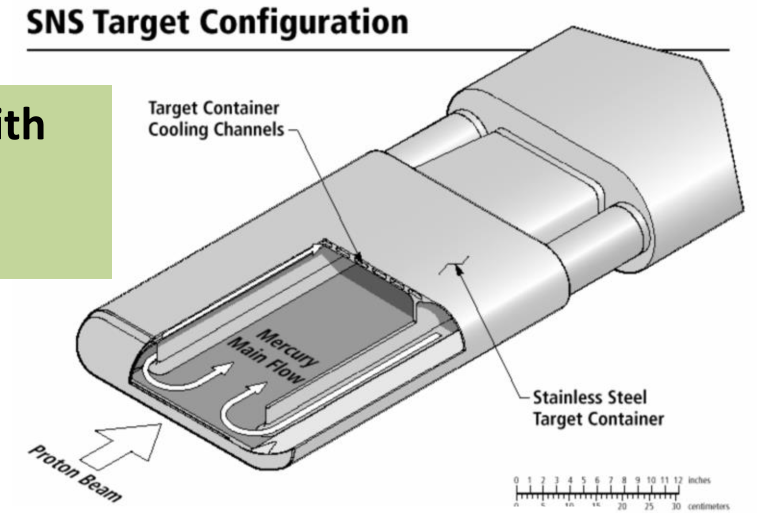
High-power spallation neutrons sources

MEGAPIE target @ PSI



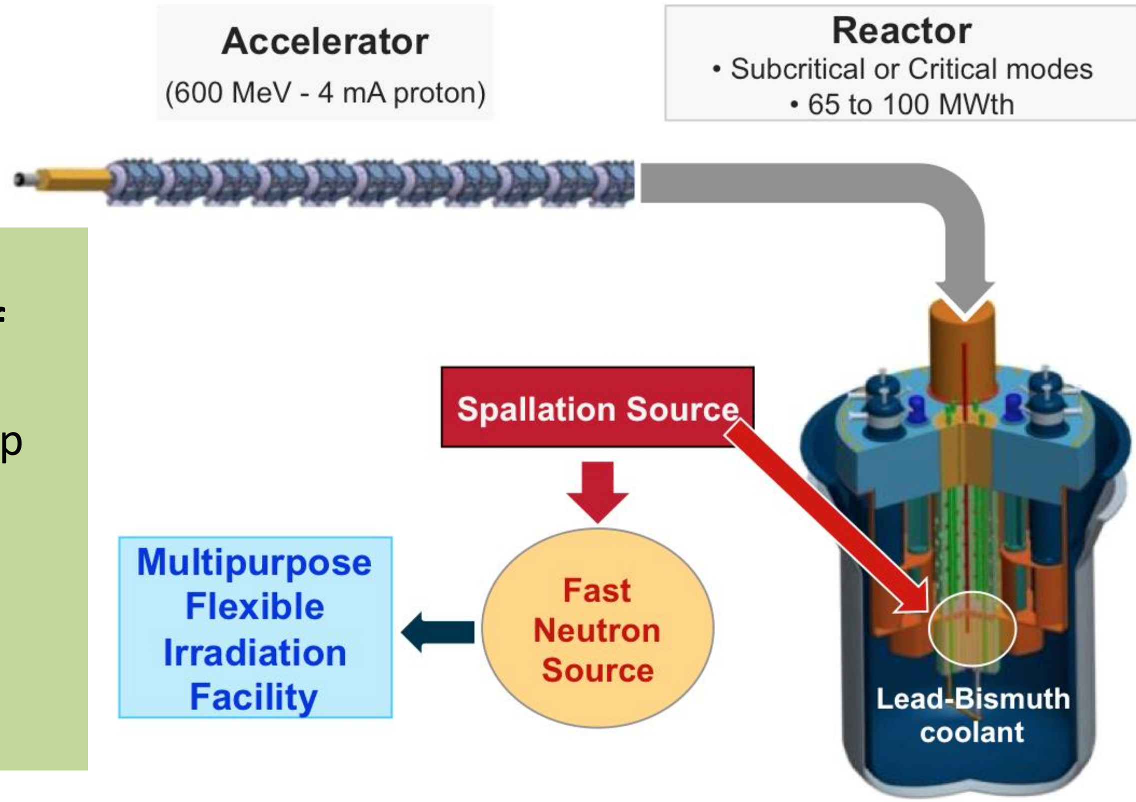
Successful 4 month run at PSI, Switzerland, in 2006, 1 MW

SNS in the USA with 1.4 MW on target (1 GeV, 1.4 mA)



ESS under construction at Lund (5 MW at 2 GeV)

Europe ADS project: MYRRHA



The most developed design.
MYRRHA should be the flagship of ADS projects, however:

– only partially funded* (injector up to 100 MeV recently approved)
– not before 2025?
– no thorium in the plans
– will not remain an ADS, will be turned into a critical reactor

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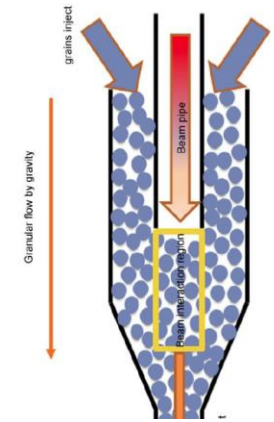
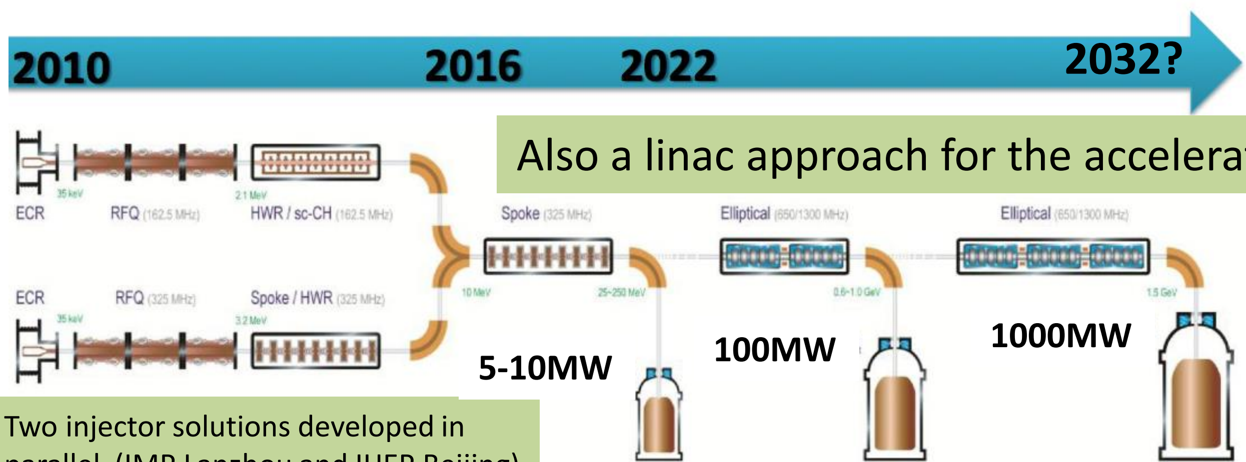
*Europe spent 600 billion Euros on renewable energies, from 2005 to 2013 (Bloomberg New Energy Finance)

China ADS project: ADANES

- Accelerator-Driven Advanced Nuclear Energy System (ADANES) led by Wenlong Zhan (CAS), as a **complete energy system**, integrating nuclear waste transmutation, nuclear fuel multiplication and energy production, **aiming at 1000 MWe**.

- **Includes a systematic R&D program** on the various elements of the system.





Also a linac approach for the accelerator

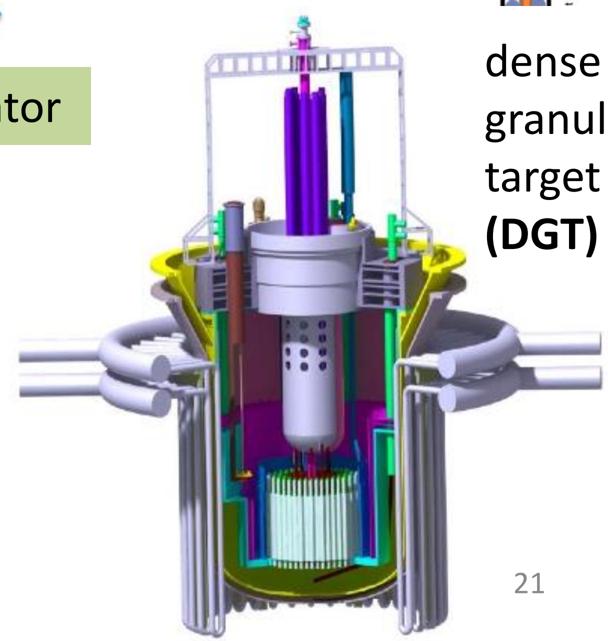
Two injector solutions developed in parallel (IMP Lanzhou and IHEP Beijing)

CIADS: INITIAL FACILITY

250MeV@10mA
5-10MW in 2022

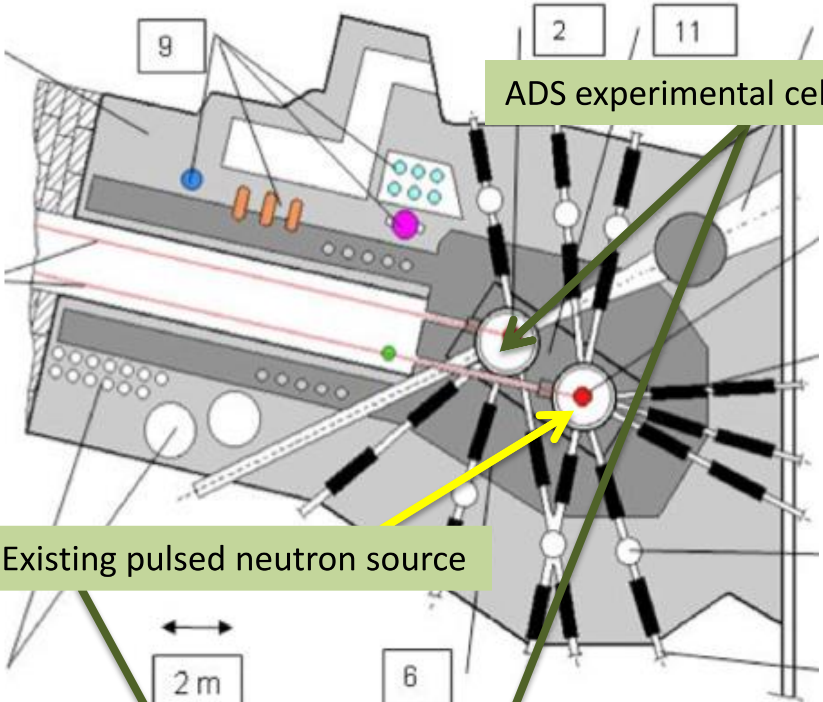
RESEARCH FACILITY

DEMO FACILITY

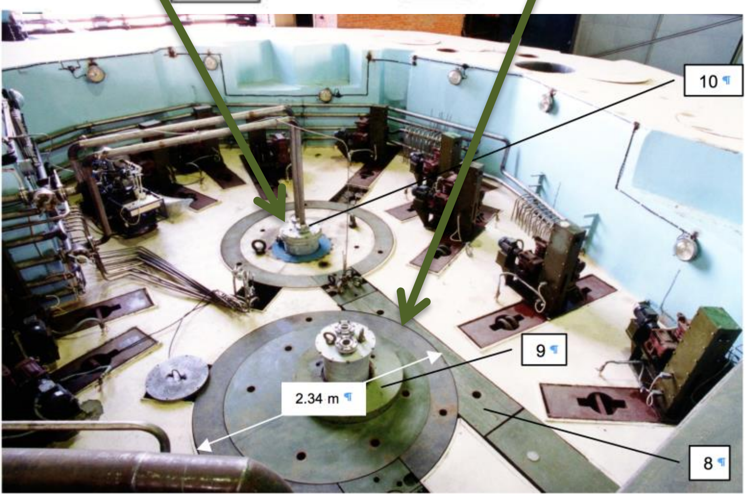


dense granular target **(DGT)**

iThEC's initiative: Use an existing facility at INR Troitsk for ADS phase 3



Alexander Feschenko (INR), showing Troitsk 450 m accelerator to Yacine Kadi (CERN/iThEC) and Frank Gerigk (CERN/iThEC)



Existing INR Infrastructure

– ***Proton linac*** (design: 600 MeV, 300 kW)

– ***Spallation neutron source***

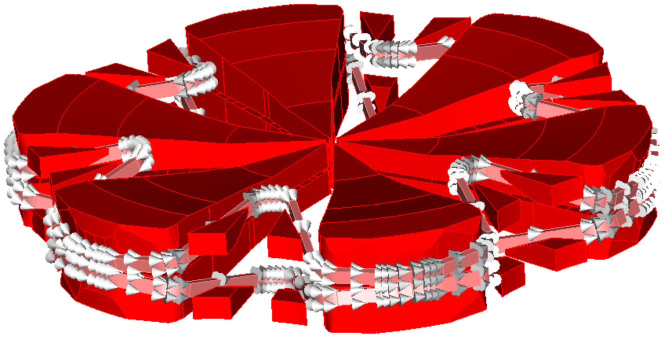
– ***Pit on a beam line*** to host a subcritical core

– ***Infrastructure*** (to manipulate radioactive material)

5 years at 4% of the cost of MYRRHA

But initial funding for approval not yet found

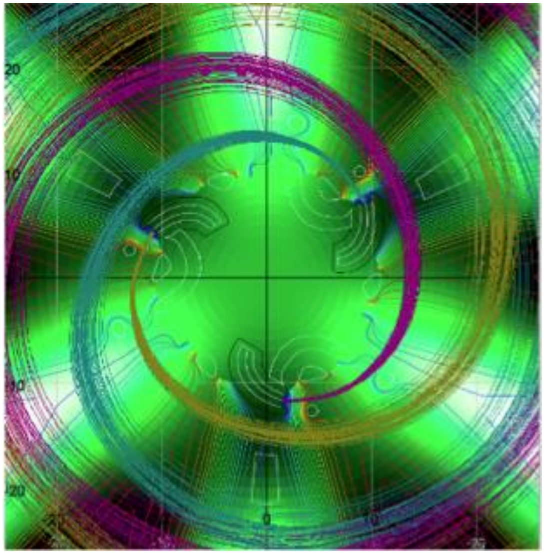
iThEC's initiative: An innovative cyclotron for ADS



- **Project baseline**: **one stage superconducting cyclotron**, 600 MeV, 6 mA (3.6 MW)
  - **High reliability through redundancy**
  - **High efficiency**
  - **Lower cost**

- **Proposal to be submitted to EU H2020 "*Future and Emerging Technologies (FET)*" programme***,* a collaboration between CERN, iThEC, **PSI**, **AIMA** (France), **ASG** (Italy), Hydromine Nuclear Energy (Italy), and Nuclear-21 (Belgium)

- **Other applications of high-power accelerators**:
  - Production of new alpha emitters for medicine (TRT and TAT), and other radioisotopes
  - High intensity beams for fundamental research



S2CD by AIMA DEVELOPPEMENT

CONCLUSION

- **Arriving at a zero carbon society** in a sustainable way, requires innovation, hence a systematic R&D effort, including nuclear fission energy
- Fast neutron accelerator-driven systems (ADS) using thorium fuel offer the possibility to transmute a major part of the long-lived nuclear waste and produce energy
- **Thorium is a potentially sustainable source of energy for the future**
- The availability of high power proton beams will bring further benefits to society, in particular in the production of new medical radioisotopes