iThEC

INTERNATIONAL THORIUM ENERGY COMMITTEE

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Sustainable Thorium Energy for the World

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Lund University

November 1st, 2016

international Thorium Energy Committee (iThEC)

- **Non-profit association, under Swiss law, founded in 2012**: Physicists, engineers, politicians and other citizens concerned about energy issues, acting to promote **R&D on the use of thorium in general and on Accelerator-Driven Systems (ADS) in particular**.

- **14 nationalities** represented in iThEC, strong CERN base**:** **Carlo Rubbia** (Nobel Prize Laureate, Honorary President), **Maurice Bourquin** (Former Rector of UNIGE, former President of CERN Council), **Yacine Kadi** (CERN, Isolde), **Frank Gerigk** (CERN, accelerator), **Pierre Mandrillon** (AIMA, accelerator), **Stefano Buono** (AAA, medical radioisotopes), **Jean-Pierre Delahaye** (Former Head of CLIC), etc.

- **First task for iThEC:**
  - **Organize the 2013 Thorium Energy Conference (ThEC13)** at CERN in the Globe of Science and Innovation – **Review of the status of thorium R&D**

ThEC13@CERN

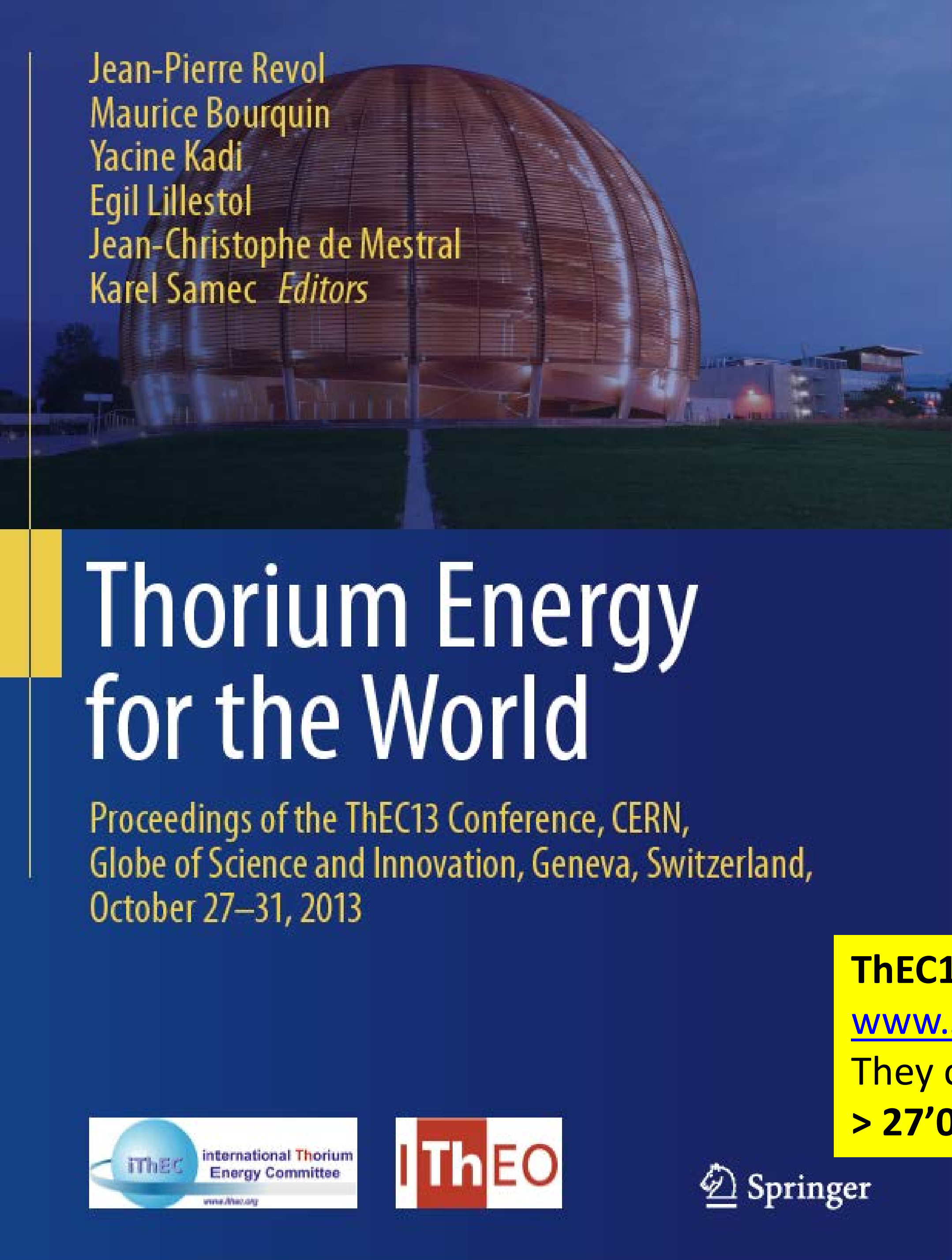
- **Main world actors all represented** (200 participants, 32 countries, more than 5000 Web connections)
- **Support from prestigious scientific and political figures** who understand the importance of R&D in the energy domain, on thorium in particular

Anil Kakodkar, ***Xu Hongjie***

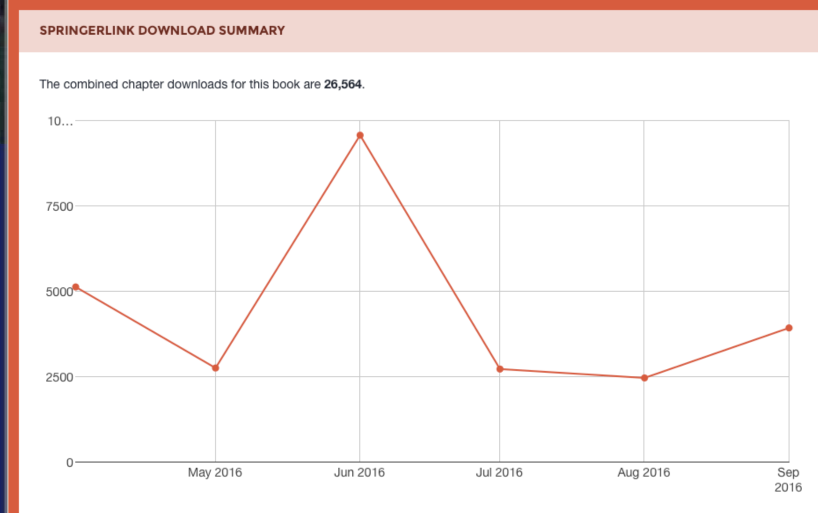
Claude Haegi (President of FEDRE*)
Jean-Christophe de Mestral (Green Atom)
Hans Blix (ex DG of IAEA)
*Foundation for the Economy and sustainable Development of the Regions of Europe

Pascal Couchepin (ex Swiss President)
Carlo Rubbia (Nobel Prize 1984)

- **ThEC13 allowed iThEC to identify strategically important projects**
- **Proceedings published by Springer, 2016**: "***Thorium Energy for the World***", **A basic reference on thorium**



Conference slides and videos publicly available on CERN indico: http://indico.cern.ch/event/thec13



ThEC13 Proceedings available on line: www.springer.com/gb/book/9783319265407

They contain all (> 80) contributions

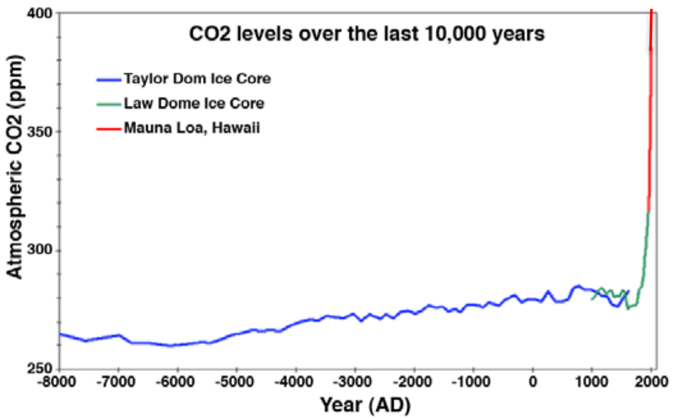
> 27’000 downloads at end of September 2016

iThEC's motivations
or
A physicist's view of the energy problem

Society's biggest challenge: Replacing fossil fuels

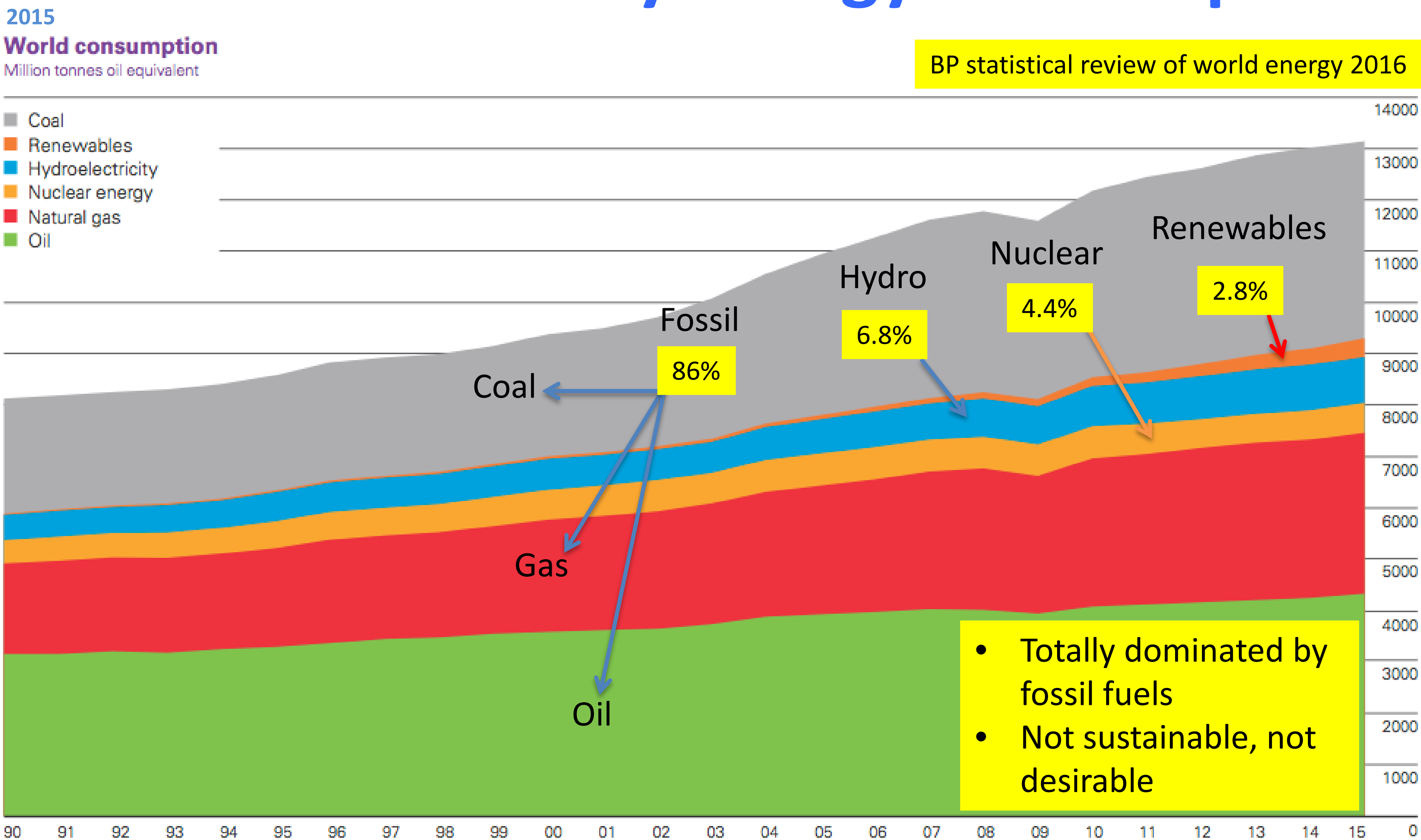
- **Fossil fuels in finite quantities in the Earth's crust** – to run out sooner or later
- **It does not make sense to burn fossil fuels till the end**:
  - **Global warming** more and more of a consensus that it is a serious problem – Precautionary principle
  - **Air pollution** with us today it is a global and urgent issue

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



    - Burning coal costs Europe alone 43 billion Euros in 2014 health care expenses (Heinrich Böll Stfitung);
    - More than 0.5M deaths per year in China due to air pollution (Tsinghua University);
    - 1 in 8 of total global deaths are the result of air pollution exposure (WHO).
  - **Better use of oil:** plastics, rubber, tires, paints, 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



If, by end of the 21st century, **people in developing countries were to live as well as people do in Europe today**, then, the world power consumption would have to increase by a factor 3 or more (**would exceed geothermal power!**). **Europe not representative of the entire world. Today, 1.1 billion people in developing countries do not have electricity.**

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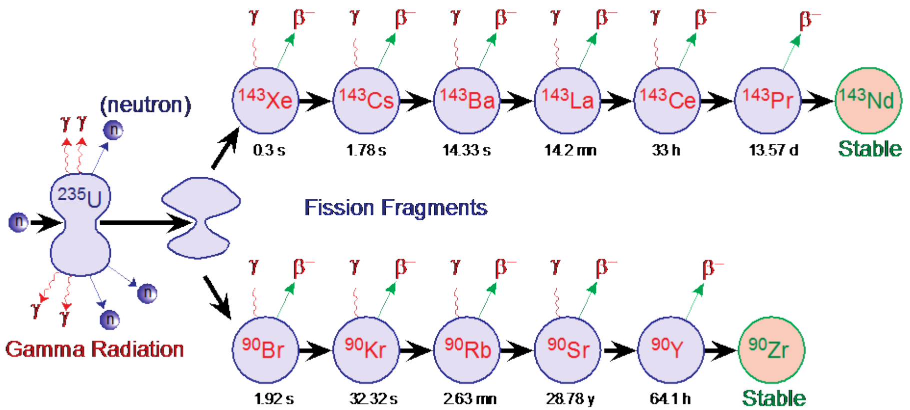
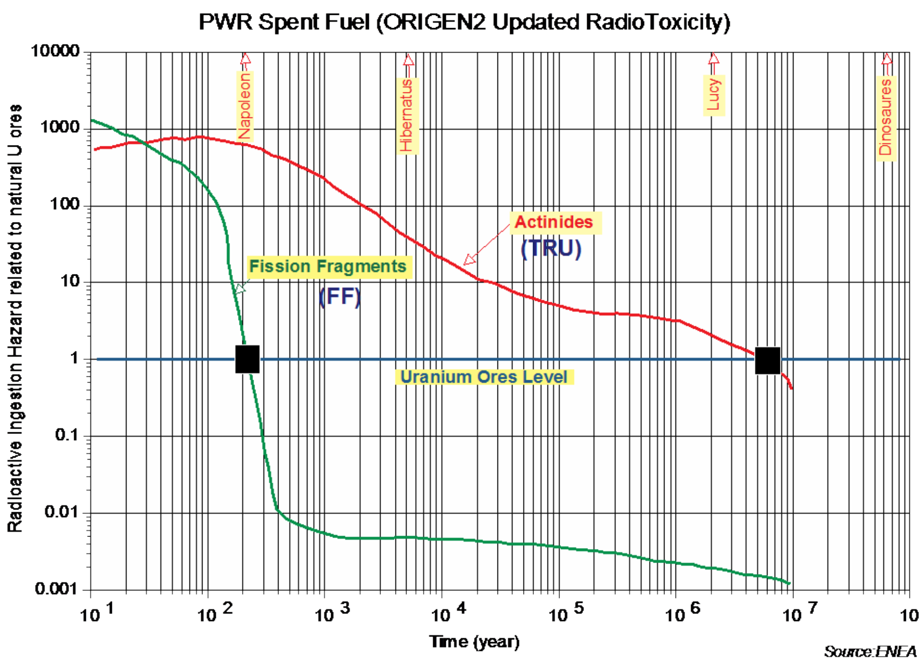
Solutions must come from R&D

- **It is the responsibility of scientists to propose new options, through R&D and innovation.** Politicians cannot invent solutions.
- **R&D must be systematic**, it must include the nuclear domain (opposed by some political groups and by nuclear industry)
- Nuclear energy: **abundant**, **energy-intensive** (1 ton of thorium ≈ 2.6 million tons of coal ≈ 50 km^2 of solar cells), **can ensure base load** production, produces **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 – **Can we make nuclear energy acceptable to society?**
  - Regardless of national policies, the problem of nuclear waste management must be solved

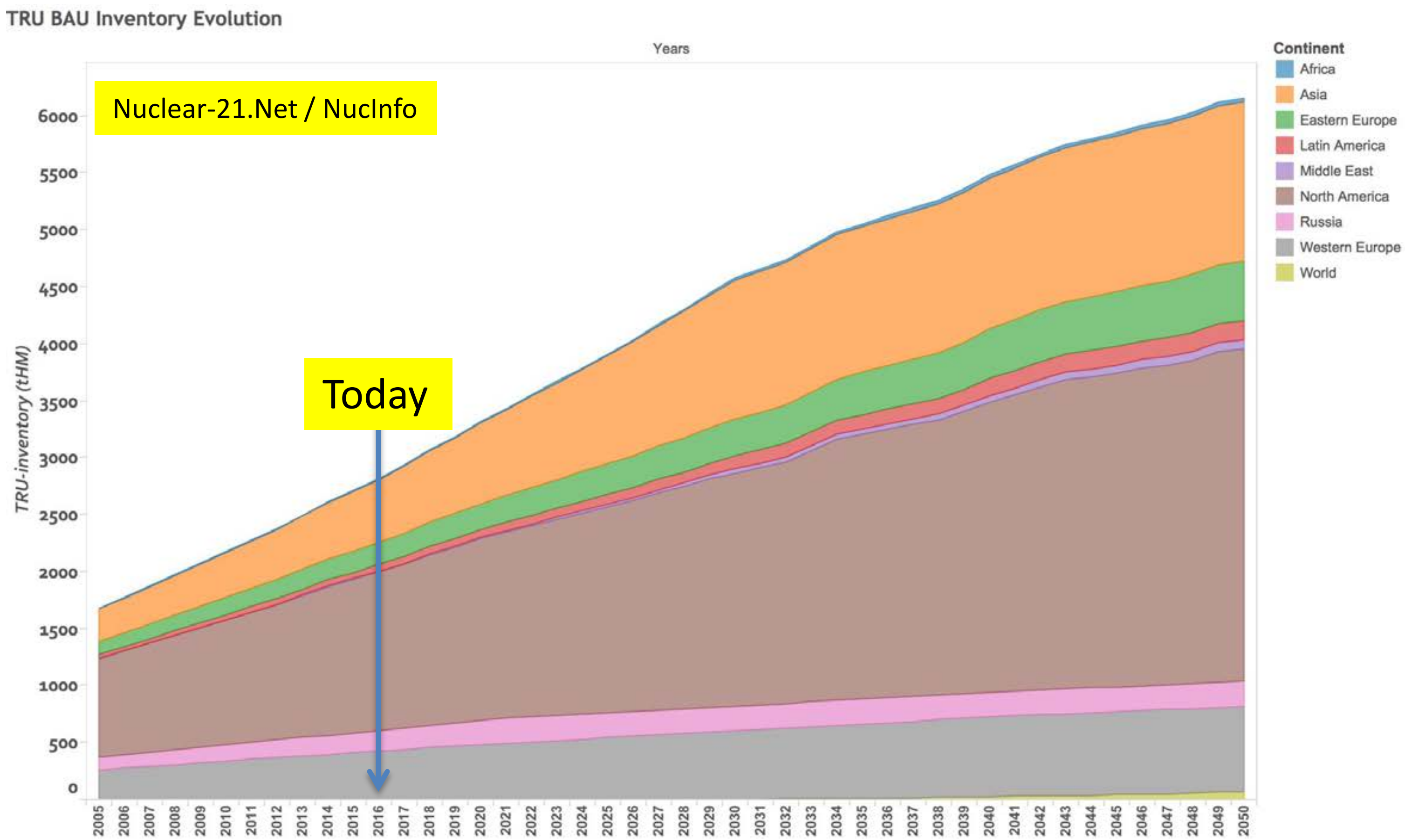
Nuclear waste

- Two components of radioactive waste generated in nuclear fuel cycles:
  - **TRansUranic elements** (**TRU**), 1.1 %: Np, Pu, Am, Cm, Bk, etc., resulting from neutron capture in the fuel and subsequent decay (i.e.: n + ^{238}U $\rightarrow$ ^{239}U($t_{1/2}$ ~ 23 mn) $\rightarrow$ ^{239}Pu, etc.). (~100 t/year of ^{239}Pu produced in the World + Military Pu)
  - **Fission Fragments** (**FF**), ~4%, produced in the fission process





Nuclear Waste (TRU) inventory



- The added requirement of retrievability makes geological repository strategy more questionable, so something else must be done

A strategy for nuclear energy

- The present nuclear energy was not chosen to make it acceptable:
  - The uranium fuel cycle was chosen in order to produce plutonium for nuclear bombs
  - Pressurized Water Reactors (PWR) were invented to fit on a submarine
- **Is there a better choice for nuclear energy?**
  - Physicist's answer: **Thorium fuel in fast neutron Accelerator-Driven Systems (ADS)**

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

- **Abundant (1.2x10^{14} tons in the Earth's crust)**, as much as lead, and three to four times more than uranium
  - Known and estimated resources: 6.3x10^{6} tons, probably more (> 2000 years of world electric energy consumption*); "***Thorium is a source of energy essentially sustainable on the human time scale***"

C. Rubbia @ ThEC13

- Thorium occurs in several minerals including thorite (**$ThSiO_4$**), thorianite (**ThO_2 + UO_2**) and monazite (**Ce, La, Nd, Th**)**PO_4**. Often a by-product of rare earths mining, found also in tin, coal and uranium tailings
- **Excellent physical properties**: Higher melting point of metallic thorium (1750°C) compared to metallic uranium (1130°C) and of ThO_2 (3300°C) compared to UO_2 (2800°C). ThO_2 has better thermal conductivity, smaller expansion coef. than UO_2:
  ➔ **Higher margins for design and operation, longer burnup**
- **Smaller production of TRU (Pu and MA) than uranium**
- **Proliferation resistant**

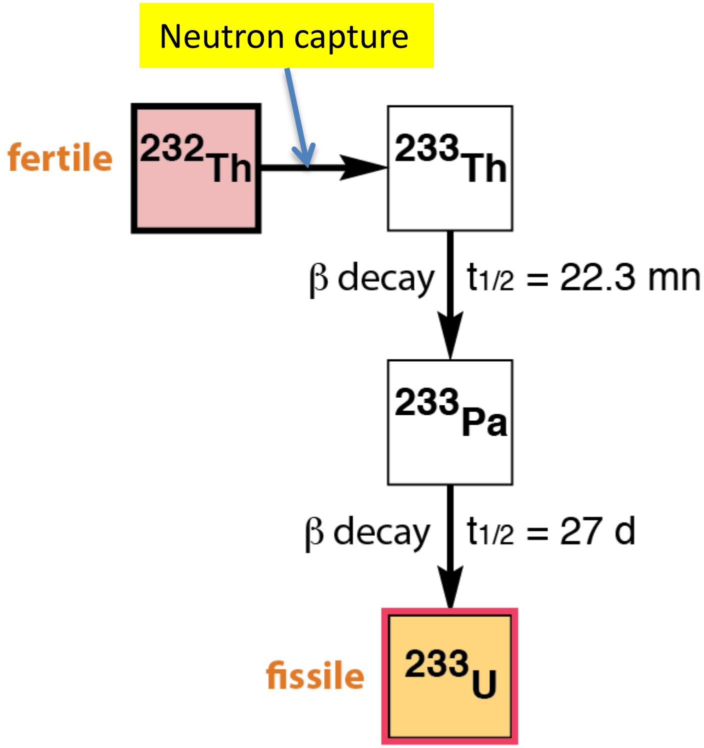
Monazite sample containing 2 to 3% of Th mixed with rare earths, from the Steenkampskraal mine, South Africa.

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**

*World electrical power consumption: ≈2.5 TW

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

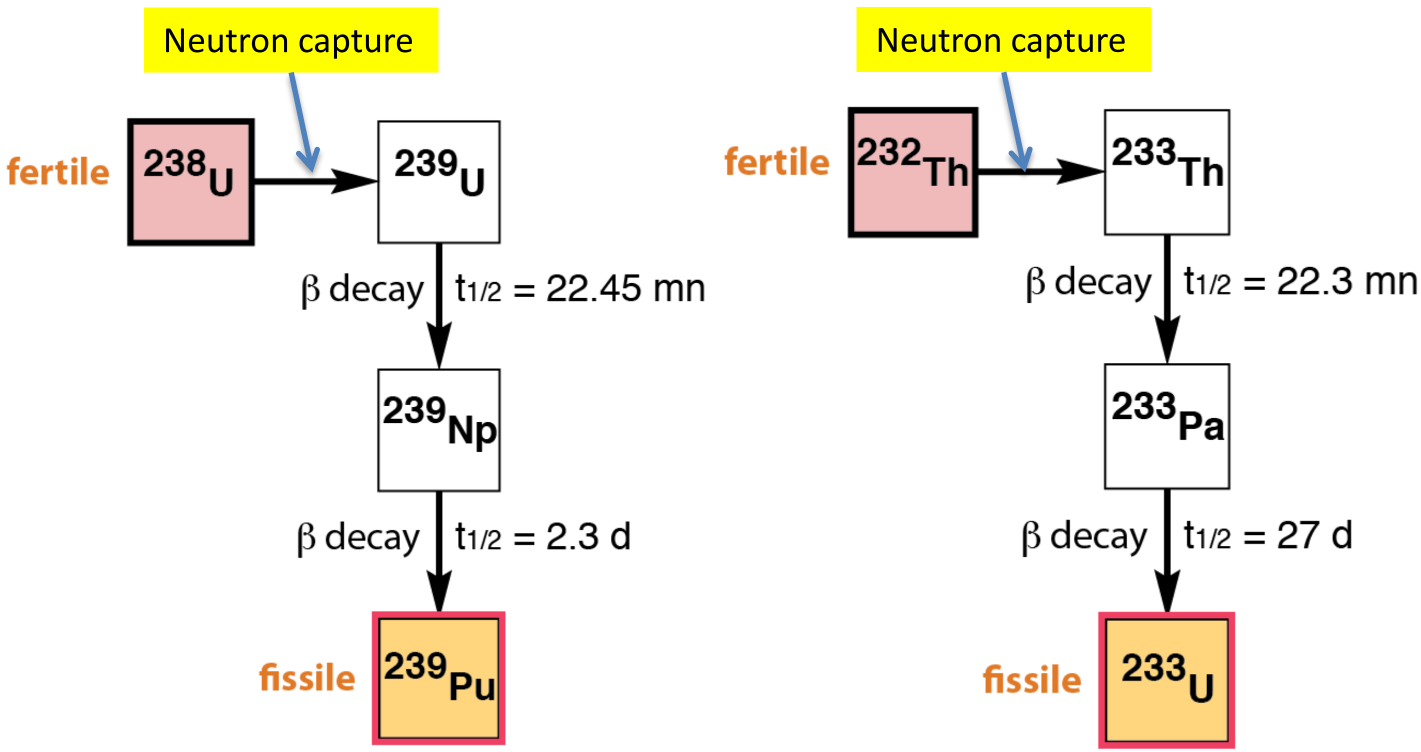
- Thorium is **fertile**, not fissile, so it can **ONLY** be used in breeding mode, by producing ^{233}U which is fissile



Th-U Breeder

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

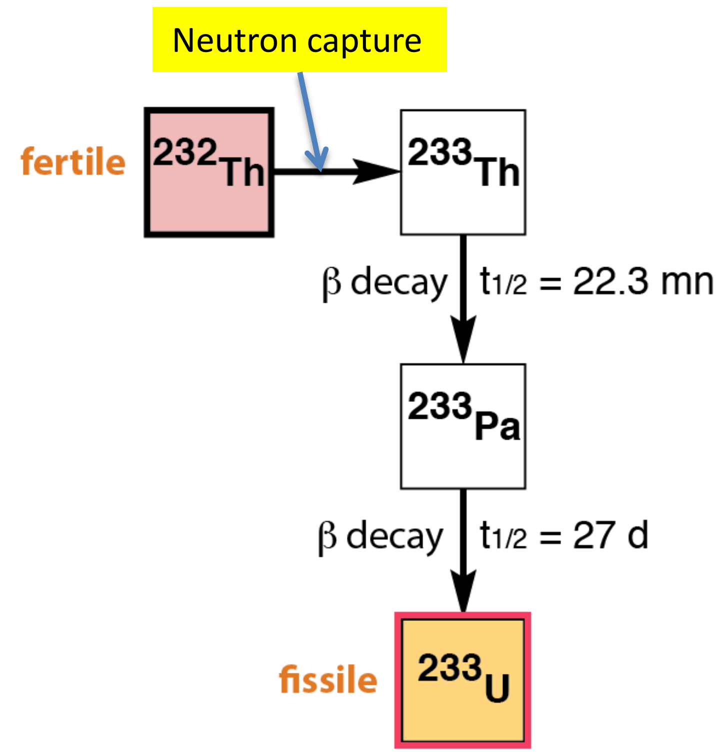
- ^{232}Th chain analoguous to ^{238}U chain (Superphenix type of reactor / GEN IV)



U-Pu Breeder **Th-U Breeder**

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

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



Only 0.7% of natural uranium

PWR

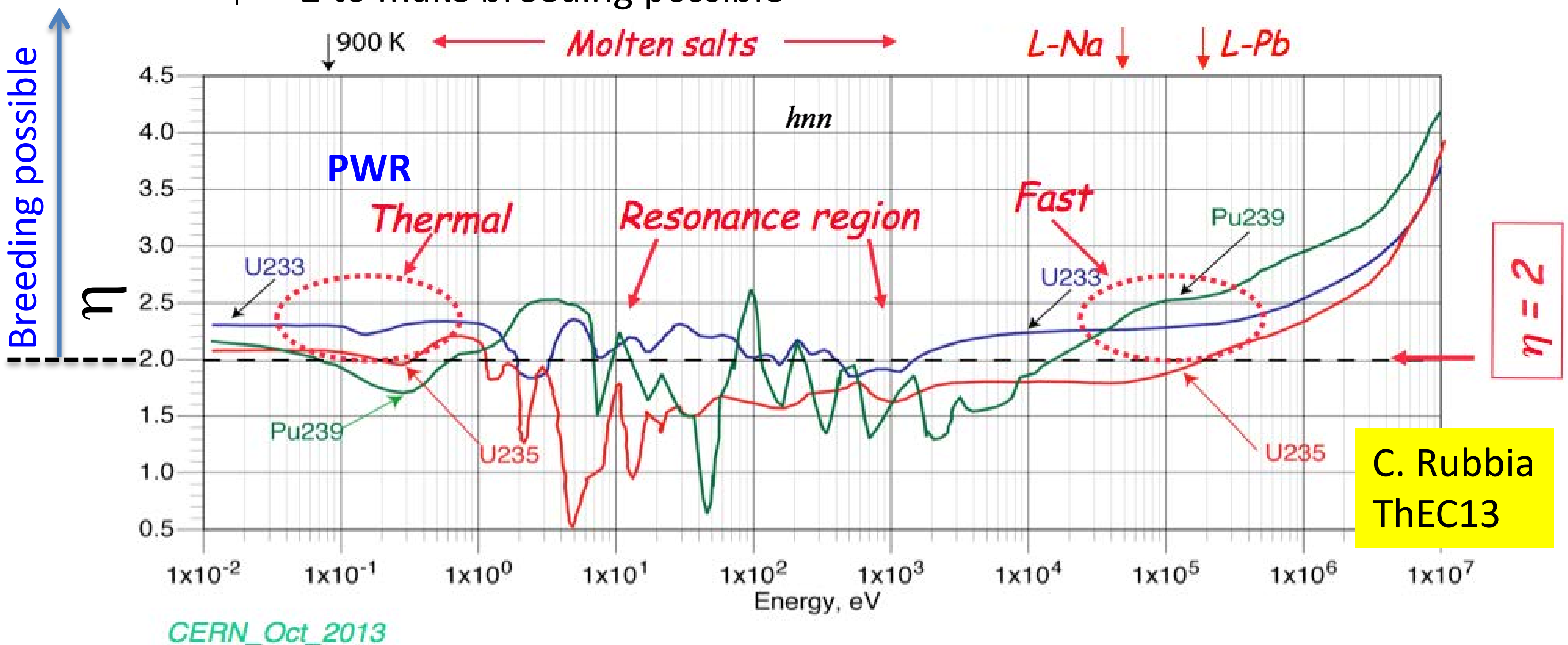
Th-U Breeder

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

Number of neutrons produced per neutron absorbed: $\eta \equiv \nu \frac{\sigma_f}{\sigma_f + \sigma_c}$

= 2 required to maintain chain reaction

> 2 to make breeding possible



^{233}U is an excellent fuel for a breeder system, over the whole neutron energy spectrum, but especially with fast neutrons

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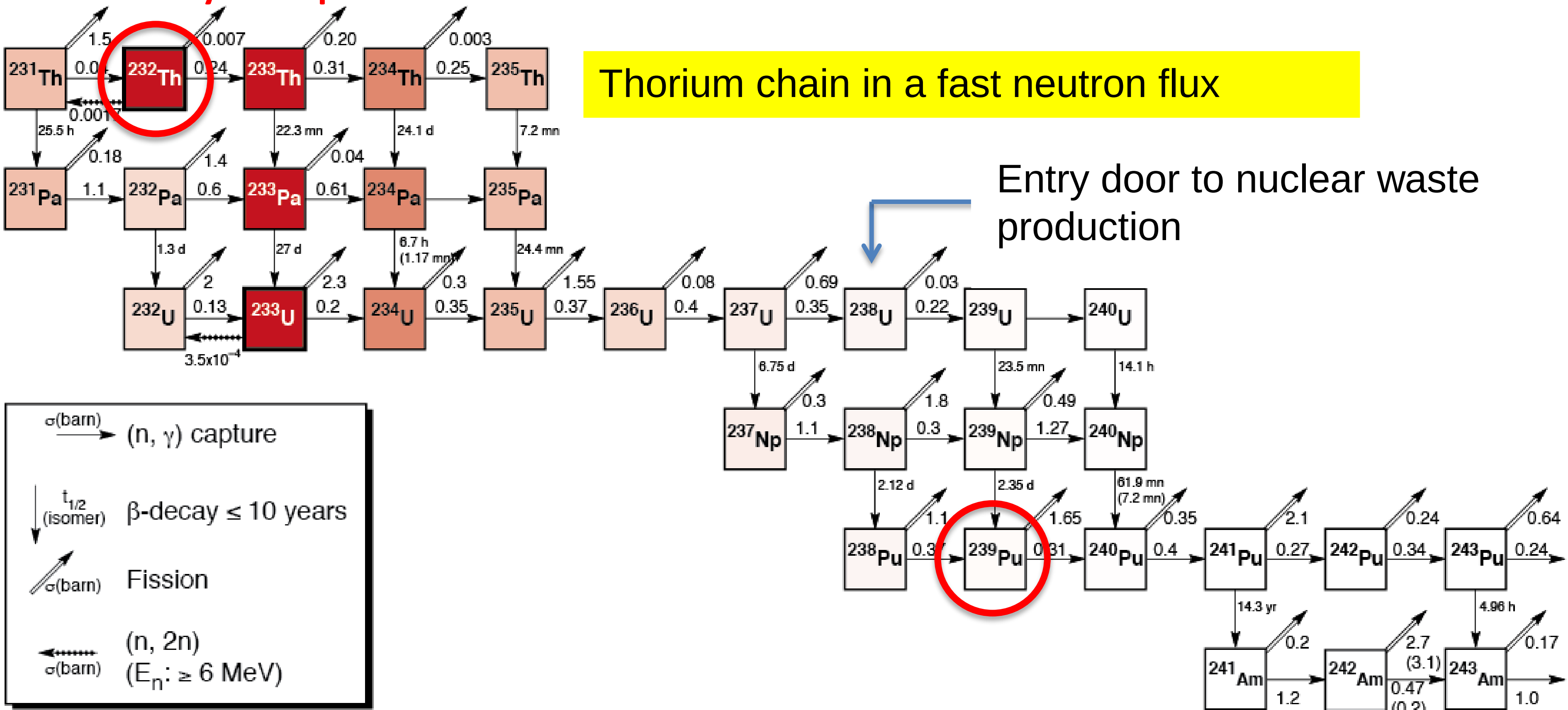
Thorium and nuclear waste

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

Thorium chain in a fast neutron flux

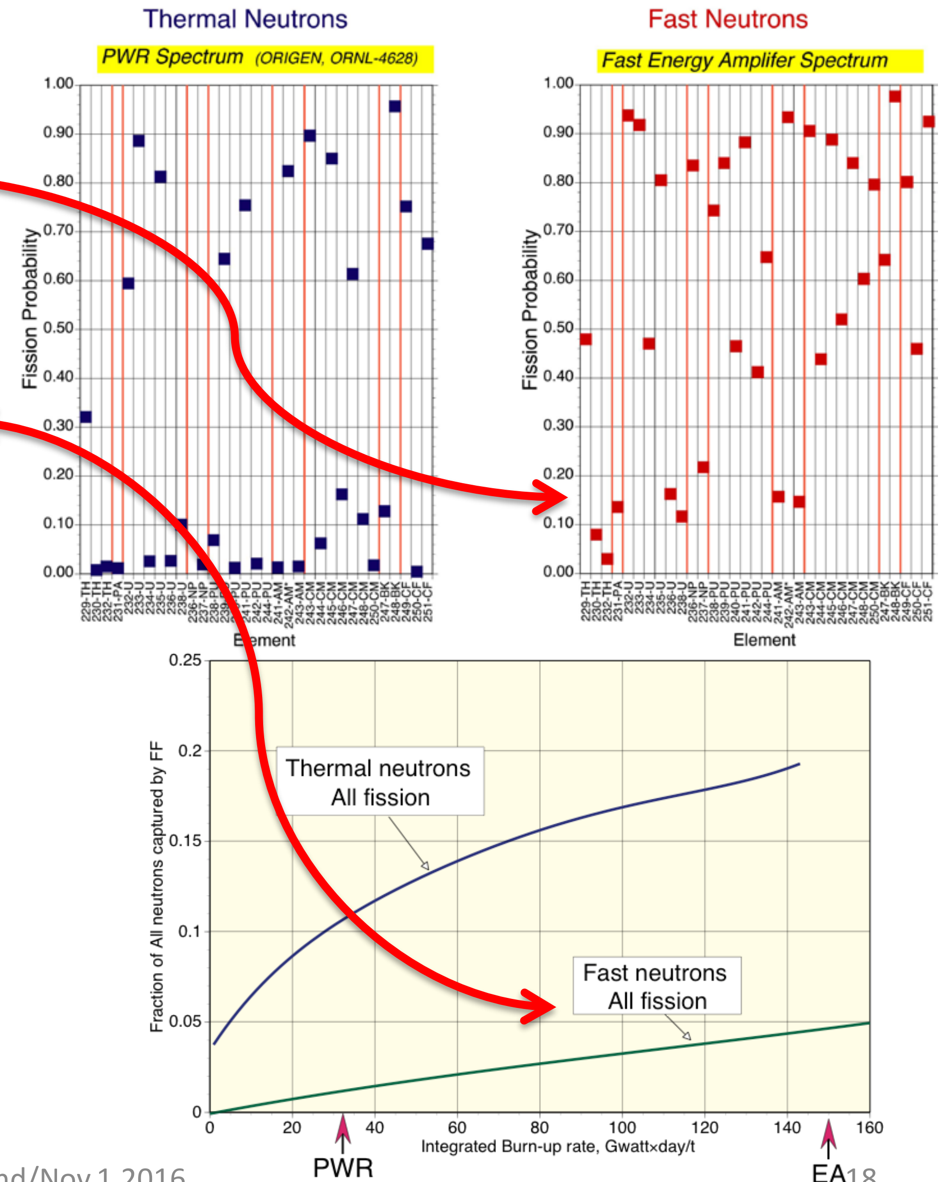
Entry door to nuclear waste production



- If in a **fast neutron flux**, then all TRU can fission, so they can be eliminated and produce energy

Advantages of fast neutrons

- **Favourable to breeding**
- **Enhanced TRU fission pro**bability hence they can be used a fuel (transmutation of waste)
- **Extended burnup** and longer loading time thanks to reduced captures on FF (120 GW.day/t achieved in the fast electro-breeder at Argonne N.L., and in Rubbia's EA simulation) (System could be sealed for 10 years or more)
- **Simplified reprocessing**
  - Remove fission fragments only
  - No need to separate out Pu! (Pyro-Electro reprocessing?)
- **The future of nuclear energy is with fast neutrons**

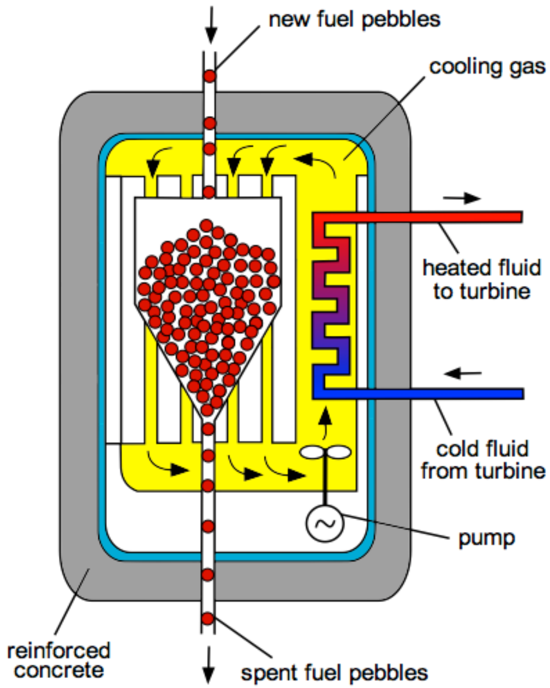


How to use thorium in practice?

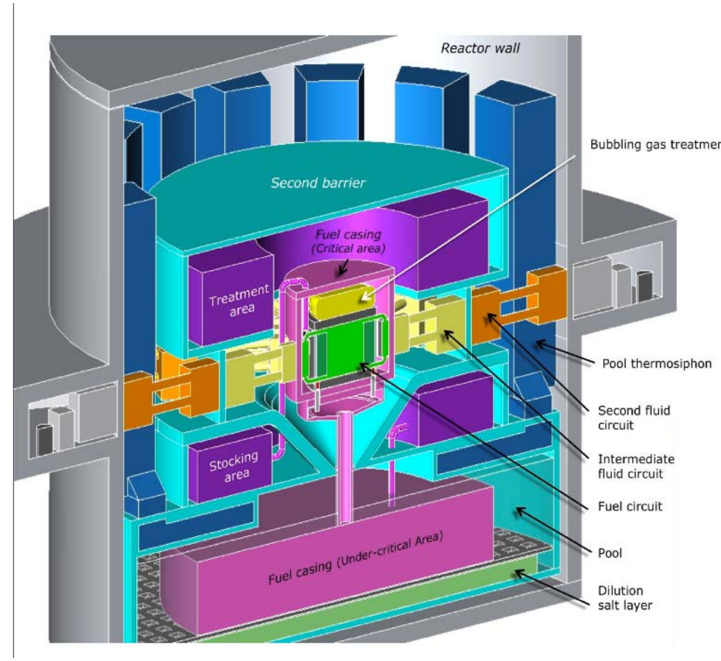
- One cannot simply replace uranium fuel with thorium fuel, because of neutron inventory issues (capture rate on thorium, long half-life of ^{233}Pa, need for breeding)
- **What are the options?**
  - **Use thorium blankets** around fast critical reactors to breed ^{233}U and introduce ^{233}U in fuel (India's strategy)
  - **Continuously move the fuel**, such as to always have fresh fuel
    - ***Pebble bed reactors***
    - ***Molten salt reactors***
    - ***Traveling wave reactor***? (It's the neutron wave that moves. Recently encouraged by Bill Gates in Terra Power, but still to be developed)
  - **Provide an external neutron source to maintain chain reaction** – so-called Accelerator-Driven Systems (**ADS**): this is the solution proposed by Carlo Rubbia at CERN in the 1990's

Moving the fuel

Pebble-Bed Scheme
Initial developments in Germany (AVR Jülich), followed by THTR-300MW (1983-1989)

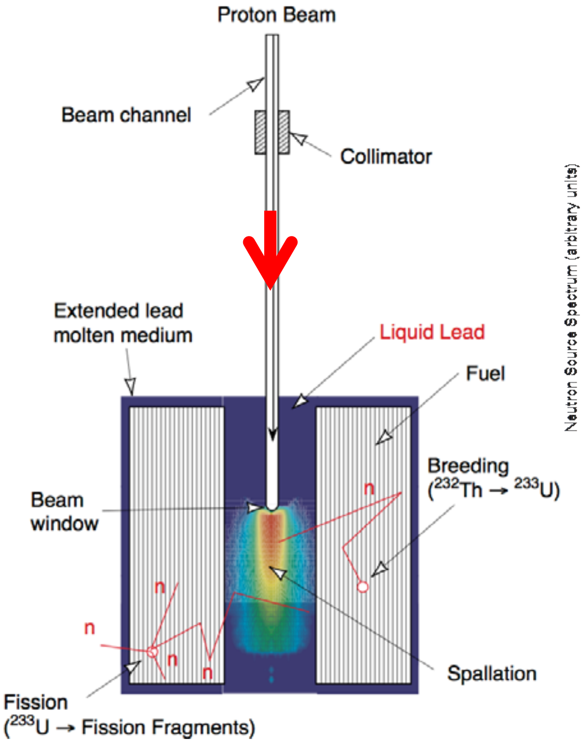


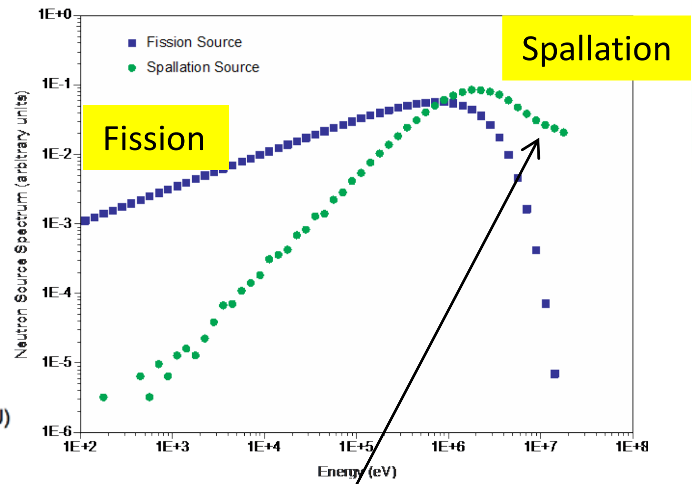
MSR Scheme
Pioneered at Oakridge in 1960 (Molten Salt Reactor Experiment, UF4, 7.4 MWth)



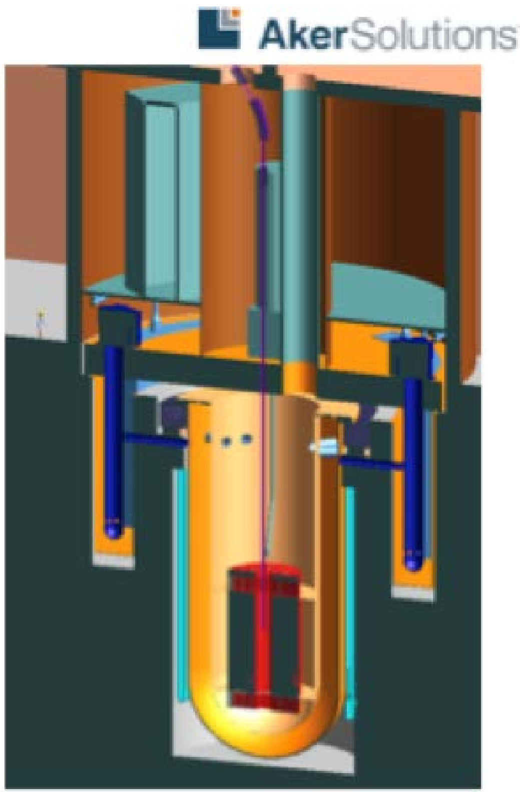
China taking the lead
(Xu Hongjie,
Shanghai Institute of Applied Physics)

Accelerator-Driven Systems (ADS)





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



A Thorium fuelled reactor for power generation

Carlo Rubbia & Aker Solution
1500 MWth/600 MWe

ADS is controlled by the accelerator (non-self sustained mode)

– **can be subcritical (no criticality accident)**

– **much flexibility in the choice of fuel**

A short history of ADS

- **The basic process in ADS is nuclear transmutation**
  - 1919 Rutherford ($^{14}N_7 + {}^4He_2 \rightarrow {}^{17}O_8 + {}^1p_1$): **The accelerator was ^{210}Po (5.3 MeV α)**
  - 1940 E.O. Lawrence/USA and N.N. Semenov/USSR proposed to use a **particle accelerator as a neutron source**
  - 1942 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)

  - 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 beam! [*Pu, no amplification*]
    today ≈ 10 MW beams seem sufficient

A short history of ADS

- 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 launched **Options for Making Extra Gains from Actinides** (OMEGA, now JPARC) at JAERI (now JAEA).
- In the 1990s, ***Carlo Rubbia*** gave ADS a big push, 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)
  - Design and 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

C. Rubbia triggered a major ADS R&D wave worldwide

P. Stumpf/SIPA PRESS

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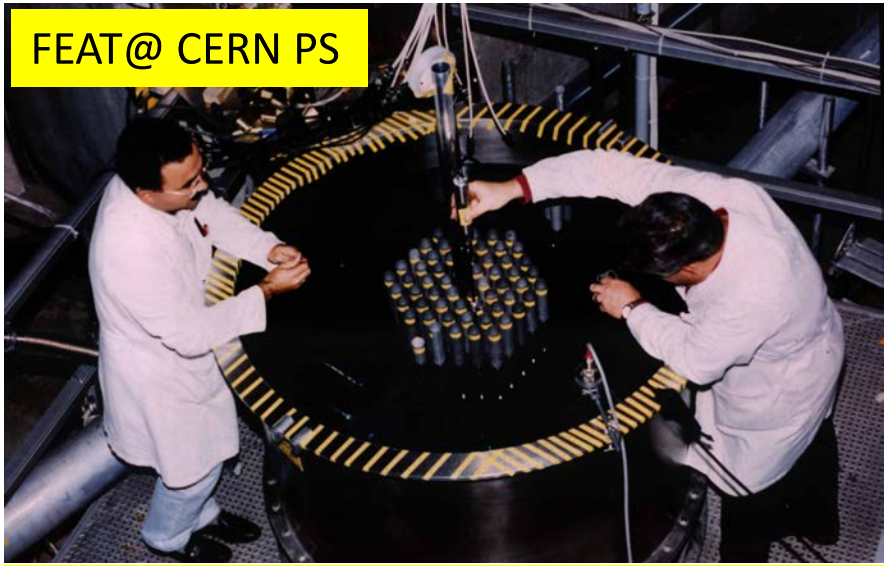
Summary of ADS projects

	Project	Neutron Source	Core	Purpose
1994	FEAT (CERN)	Proton (0.6 to 2.75 GeV ($\sim 10^{10}$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) ($\sim 10^{10}$p/s)	Fast (≈ 1 W)	Lead slowing down spectrometry and transmutation of LLFP - done
	MUSE (France)	DT ($\sim 10^{10}$n/s)	Fast (< 1 kW)	Reactor physics of fast subcritical system - done
	YALINA (Belorus)	DT ($\sim 10^{10}$n/s)	Fast (< 1 kW)	Reactor physics of thermal & fast subcritical system - done
	MEGAPIE (Switzerland)	Proton (600 MeV) + Pb-Bi (1MW)	-----	Demonstration of 1MW target - 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, $\sim 10^{12}$n/s)	Fast (< 1 kW)	Coupling of fast subcritical system with spallation source including MA fuelled configuration – **reactivated after Fukushima accident**
	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 after Fukushima accident**
	MYRRHA (Belgium)	Proton (600 MeV) + Pb-Bi (1.8 MW)	Fast (60 MW)	**Under design, not fully funded, injector up to 100 MeV approved, 2025?**
	ADANES (China)	Protons (0.6 – 1.5 GeV) (10 MW)	Fast (100–>1000MW)	**Four phase project: 2011 – 2032; second phase approved last December**
	U-ADS (Ukraine)	*Electrons* (100 MeV) 100 kW	Thermal (200kW)	Uranium-based ADS prototype (KIPT) **Ready for commissioning**
	ADS (Russia)	Protons (300 MeV)	Fast 1-3 MW	**Using an existing facility at Troitsk – under consideration promoted by iThEC (5 years)**

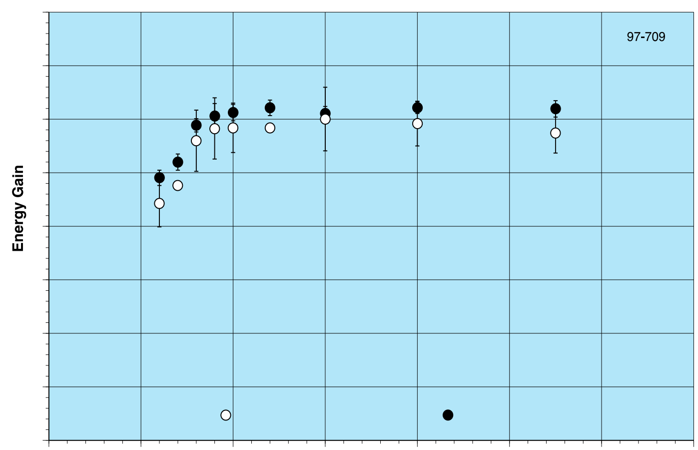
Basic concepts carefully validated

FEAT@ CERN PS

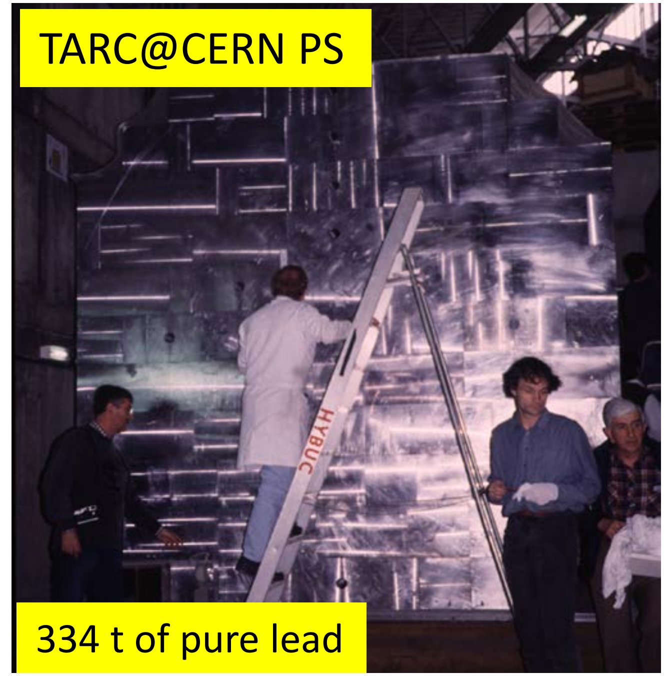


3.62 t of natural uranium at CERN PS; k_{eff} ~ 0.9

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

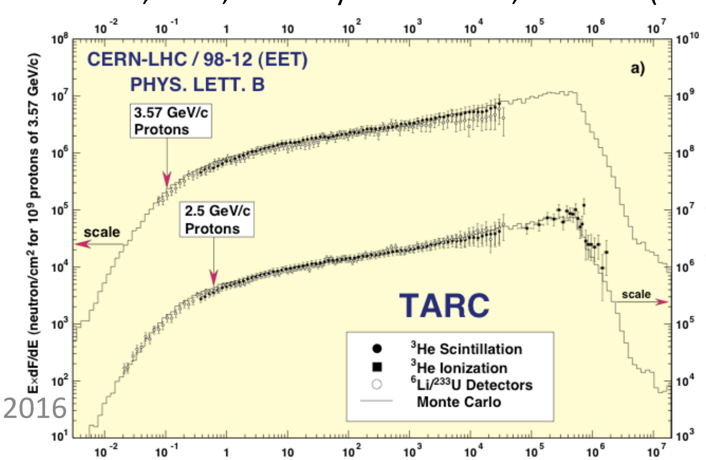


TARC@CERN PS



334 t of pure lead

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



Model 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:

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

Fission — **Spallation** — Absorption — Leakage

Simplified model of subcritical systems

- Example of finite system at equilibrium:

Diffusion length

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

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

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

- All modes are excited

Important theorem:

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

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

Neutron multiplication factor

- The neutron multiplication factor whether the accelerator is on or off:

Fission

$$k_{eff} \approx \frac{\nu \Sigma_f}{\Sigma_a + DB^2}$$

Absorption

Leakage

Non-fission multiplication: For fast neutron systems, (n,xn) reactions on Pb are important, in particular for the source neutrons

Source

$$k_s \approx \frac{\nu' \Sigma_f \Phi(\vec{r},t) + C(\vec{r},t)}{\Sigma_a \Phi(\vec{r},t) - D\nabla^2 \Phi(\vec{r},t)} > k_{eff}$$

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 further away from prompt criticality, k_s to k_{eff}.

20 years history of ADS

√ – ***Phase 1:*** **ADS basic concepts validated** mostly at CERN: FEAT, TARC (CERN patent), MUSE, Yalina, neutron cross section data (n_TOF), simulation tools (FLUKA, **EA-MC,** GEANT4)

completed

√ – ***Phase 2:*** **All ADS basic elements developed and tested separately** – ***spallation neutron sources*** (MEGAPIE/1MW at PSI, SNS, ESS/5MW), ***high power beam targets under development*** (EURISOL DS/5MW at CERN, China DGT), ***high-power accelerators*** – Cyclotrons (PSI, S2CD/AIMA, Texas A&M), IPHI, LINAC4/CERN, ***high-power super-conducting RF structures*** (SRF) – lead loops for ***corrosion resistant steel*** (Eurofer) – **Eurotrans program in the EU**, etc.

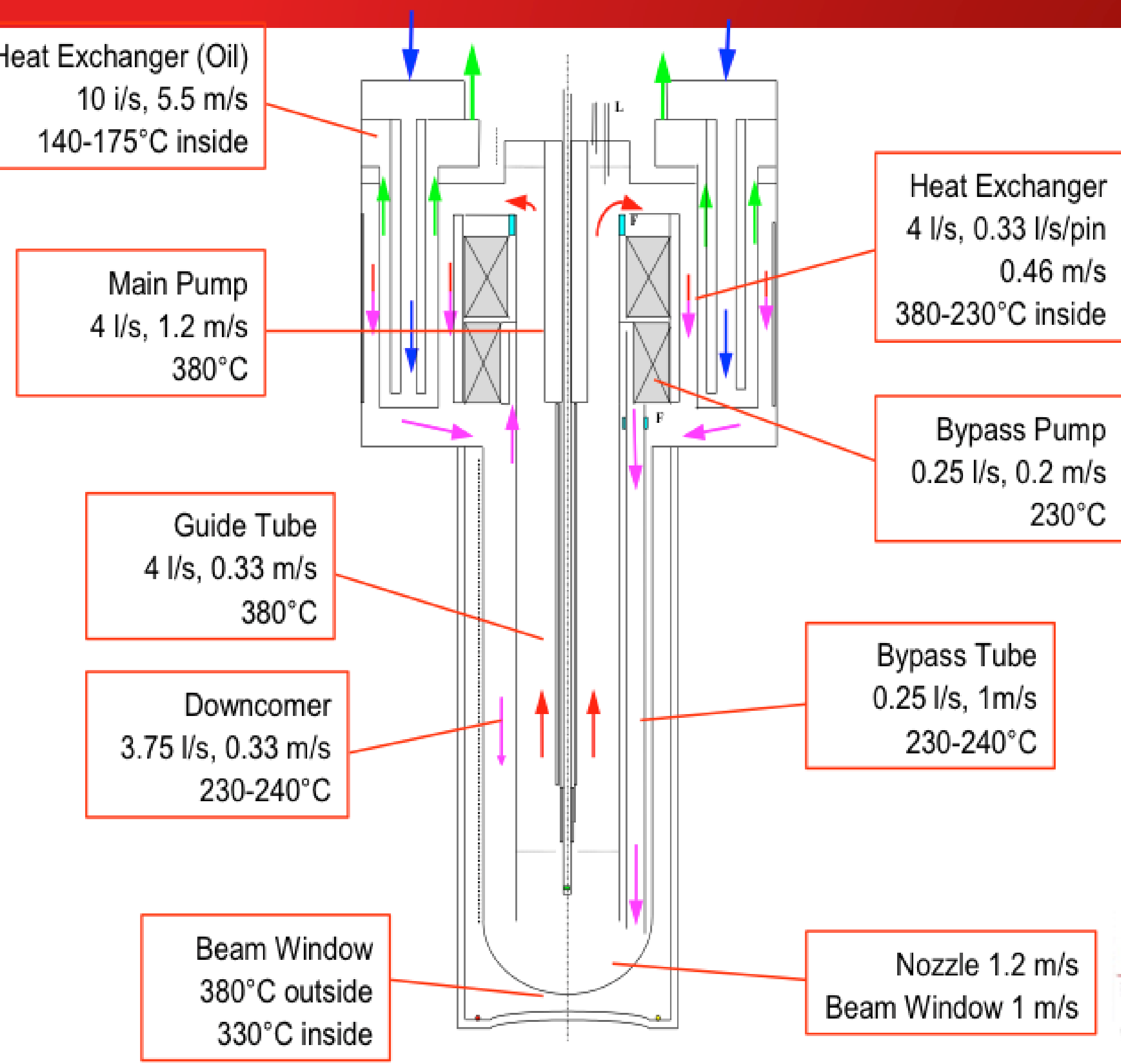
completed

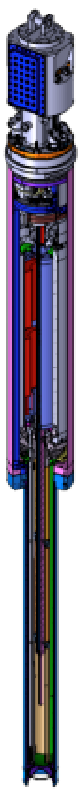
Highest power cyclotron at PSI

Proton beam power of 1.3 MW

Designs exists to reach 10 MW power with both cyclotrons and linacs

MEGAPIE TARGET



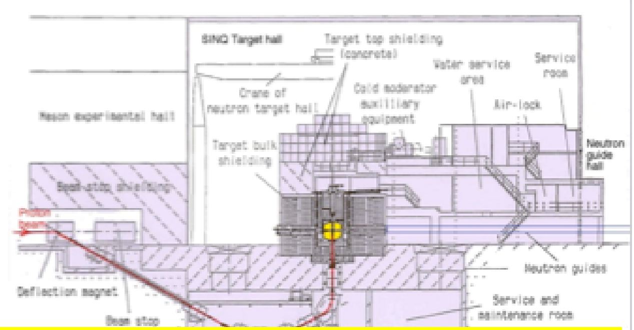


Design parameters

p-beam energy: 575 MeV
p-current: 1.74 mA
Heat removal: 650 kW
Design pressure: 16/10 bar
Design temp.: 400°C
Cover gas press: 3.2 bar
Operation: 1 year
with max 6000 mAh
Radiation damage: 20-25 dpa

Dimensions

Length: 5.35 m
Weight: 1.5 t
LBE-Volume: 89 l



Successful 4 month run at PSI, Switzerland, in 2006, 1 MW
SNS in the USA with 1.4 MW on target (1GeV, 1.4 mA), ESS in Europe (5 MW at 2 GeV)

The next steps for ADS

- ***Phase 3***:
  - **Coupling a proton beam to a fast neutron subcritical core at significant power** (a few MW is sufficient) to characterise the properties of ADS, demonstrate safety, learn how to operate the system, define and adapt instrumentation to monitor ADS **=> optimize the design of an industrial system**;
  - **Development of a high-power proton beam adapted to (optimized for) ADS in an industrial environment**.

iThEC activities are presently centred on Phase 3

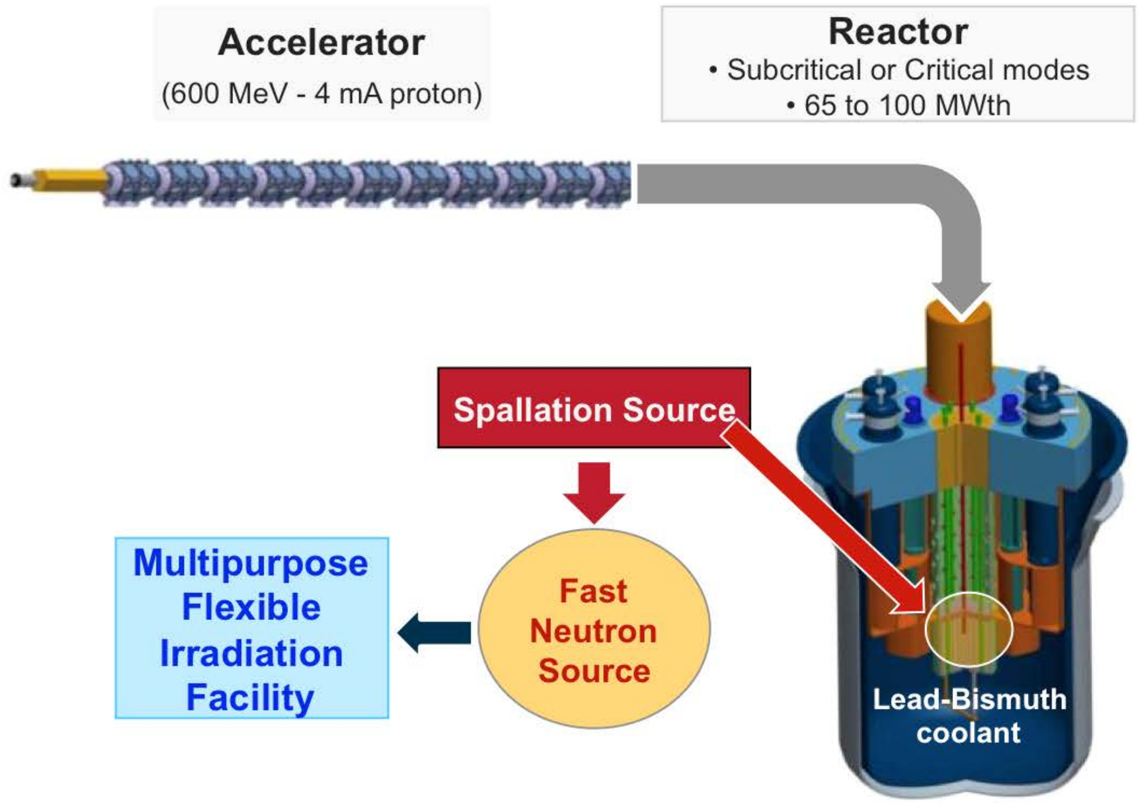
- ***Phase 4***:
  - Design and construction of an industrial prototype (MYRRHA and ADANES) (**≥ 2025**);
  - Development of an appropriate thorium fuel cycle (**≥ 2032**).

Phase 3 should provide invaluable input for Phase 4

Europe ADS: MYRRHA

Hamid Aït Abderrahim
SCK•CEN, Boeretang 200, 2400 Mol, Belgium

MYRRHA - Accelerator Driven System

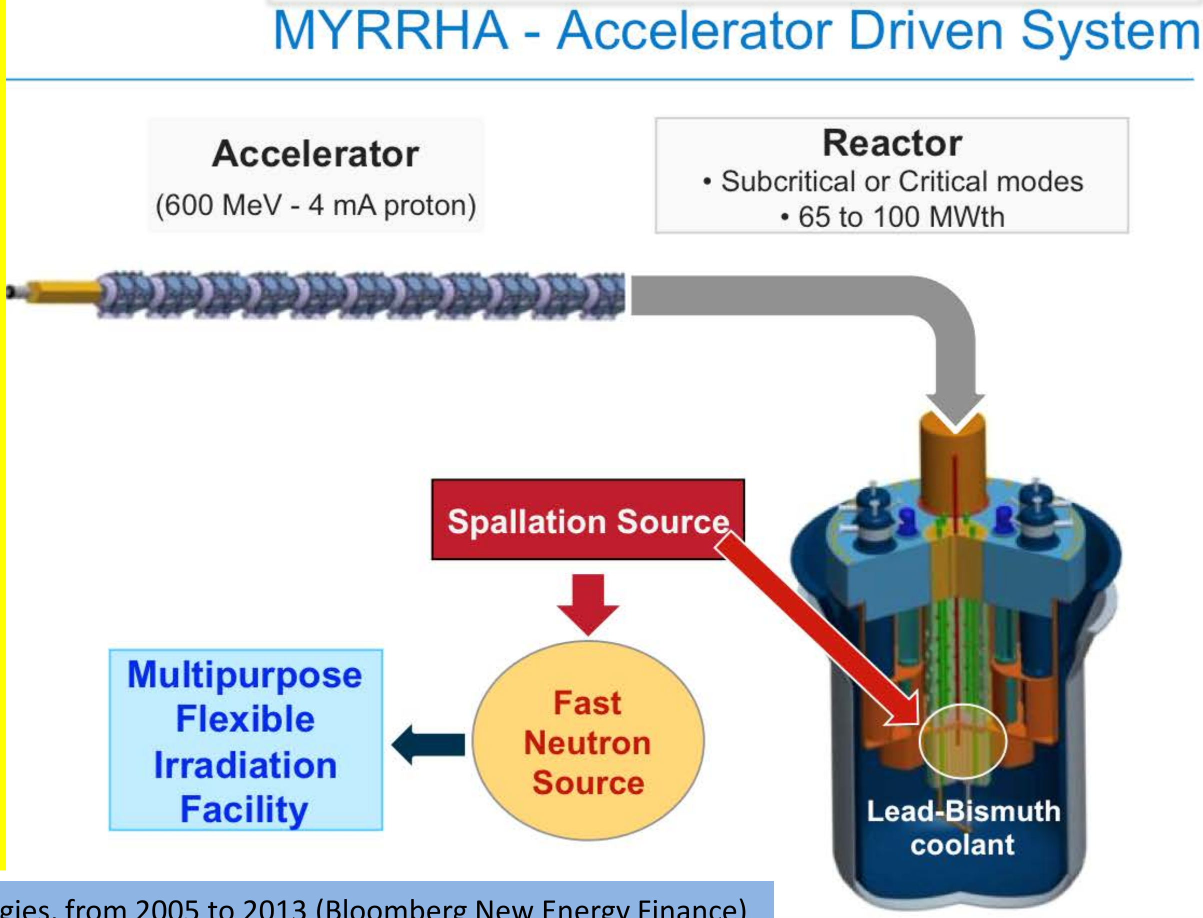


Europe ADS: MYRRHA

The most developed design. In principle MYRRHA should be the flagship of ADS projects.

Strong support from the Belgian government, however:
– several major challenges faced at the same time: the accelerator, the subcritical core and their coupling
– only partially funded* (injector up to 100 MeV approved)
– not before 2025?
– no thorium in the plans
– will not remain an ADS, to be turned into a critical reactor after some time

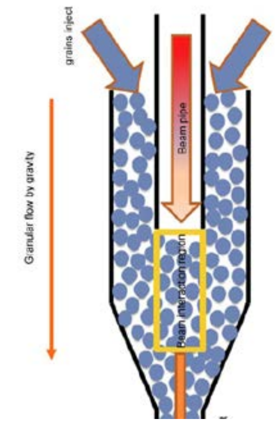
Hamid Aït Abderrahim
SCK•CEN, Boeretang 200, 2400 Mol, Belgium

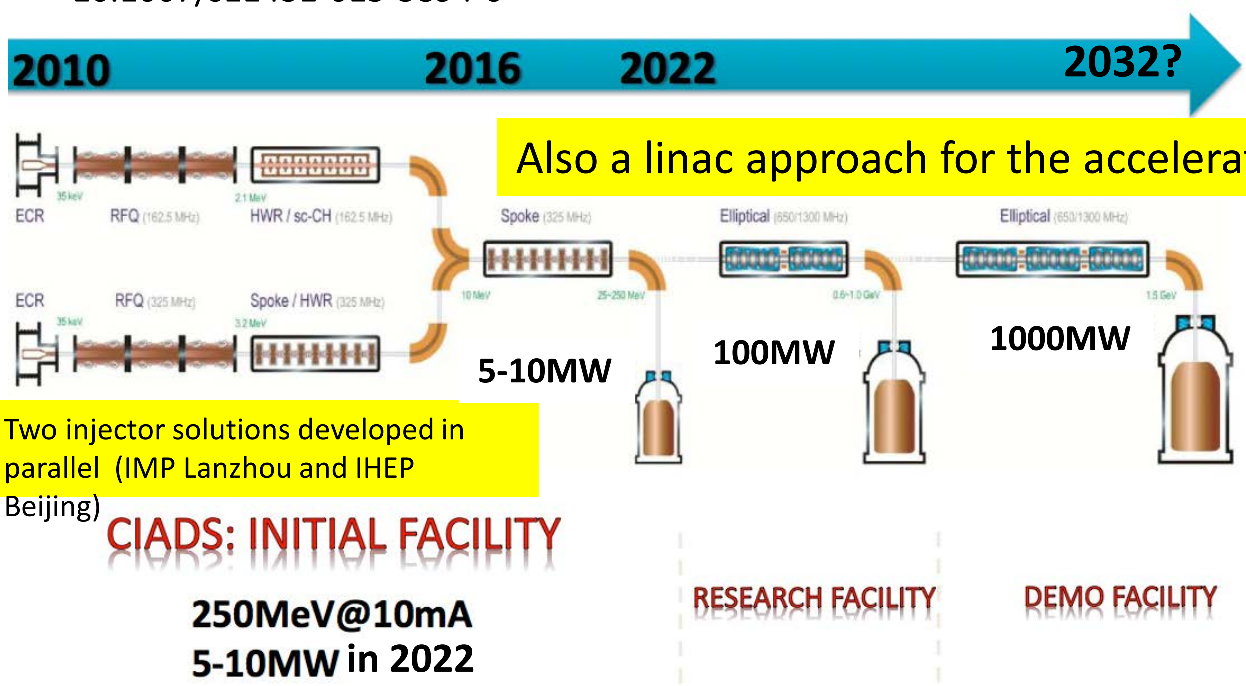


*Europe spent 600 billion Euros on renewable energies, from 2005 to 2013 (Bloomberg New Energy Finance)

China ADS: ADANES

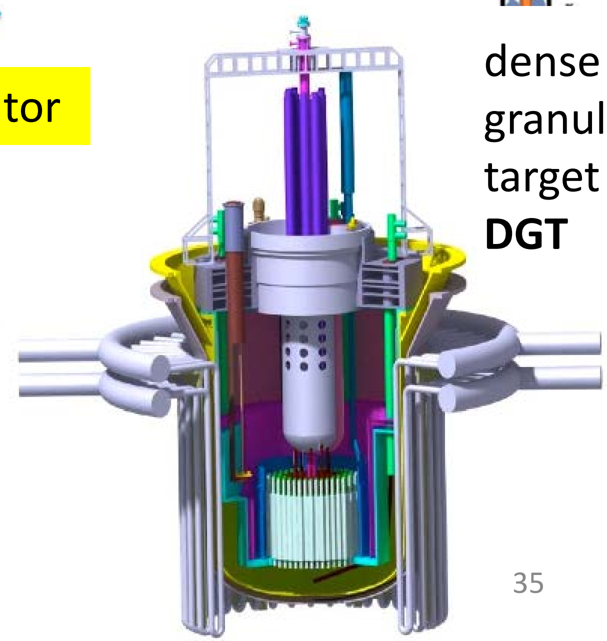
- Accelerator-Driven Advanced Nuclear Energy System (ADANES) proposed by Wenlong Zhan and his team, as a complete energy system, integrating nuclear waste transmutation, nuclear fuel multiplication and energy production, **aiming at 1000 MWe**.
- Includes a systematic R&D program on the various elements of the system, and a lot of new ideas.
  YANG Lei & ZHAN WenLong, New concept for ADS spallation target: Gravity-driven dense granular flow target in SCIENCE CHINA Technological Sciences, Jan. 2015 Vol.58 No.1: 1–7 doi: 10.1007/s11431-015-5894-0





Also a linac approach for the accelerator

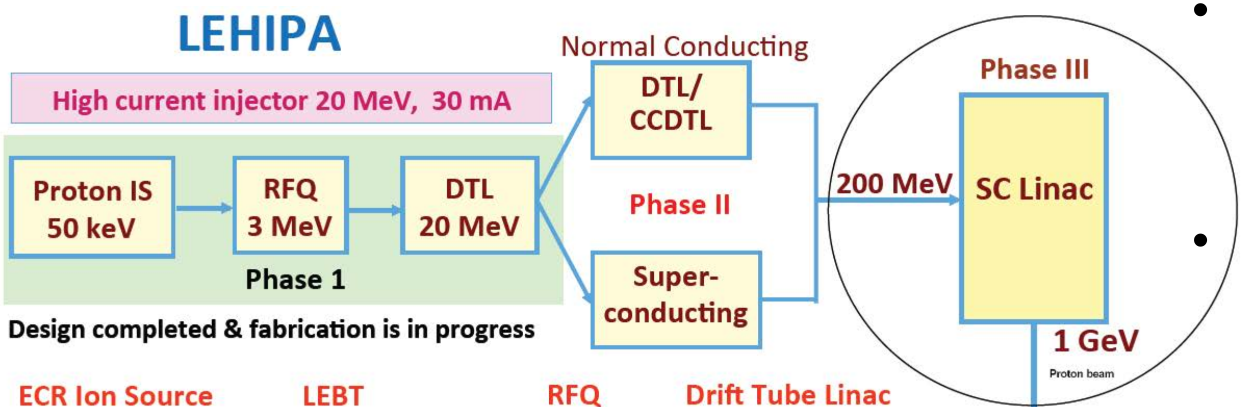
Two injector solutions developed in parallel (IMP Lanzhou and IHEP Beijing)

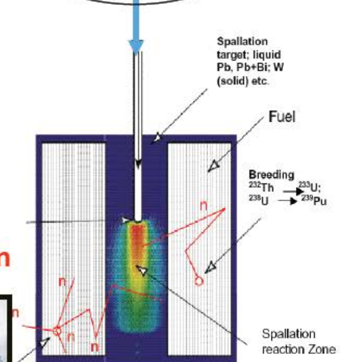


dense granular target **DGT**

iThEC

India ADS: Accelerator





ECR Ion Source

LEBT

RFQ

Drift Tube Linac

50 kW RF Coupler

60 kW RF System

1.3 MW Klystron

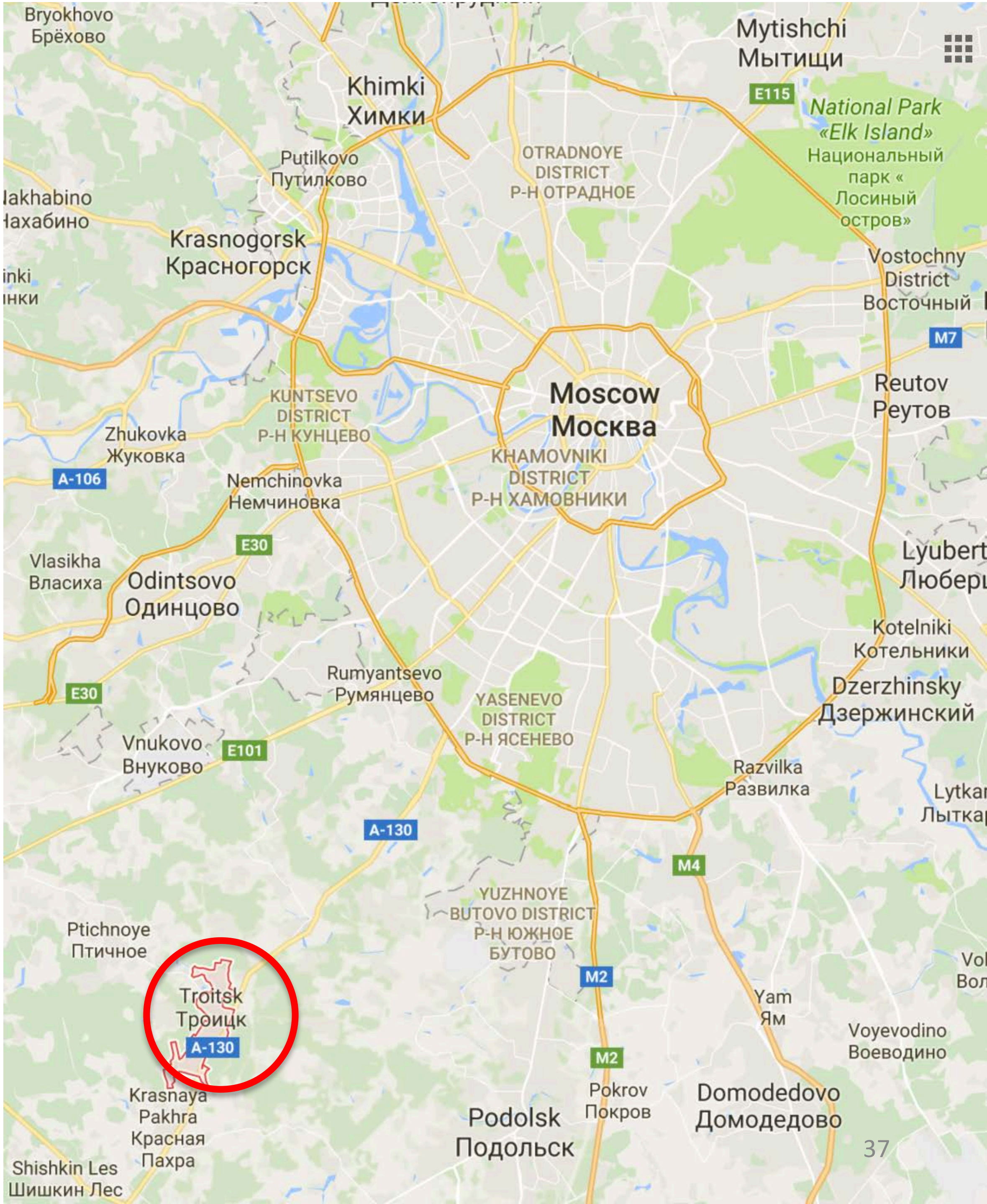
Shashikant Degweker

- India has other plans for the utilization of thorium and 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**: 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.

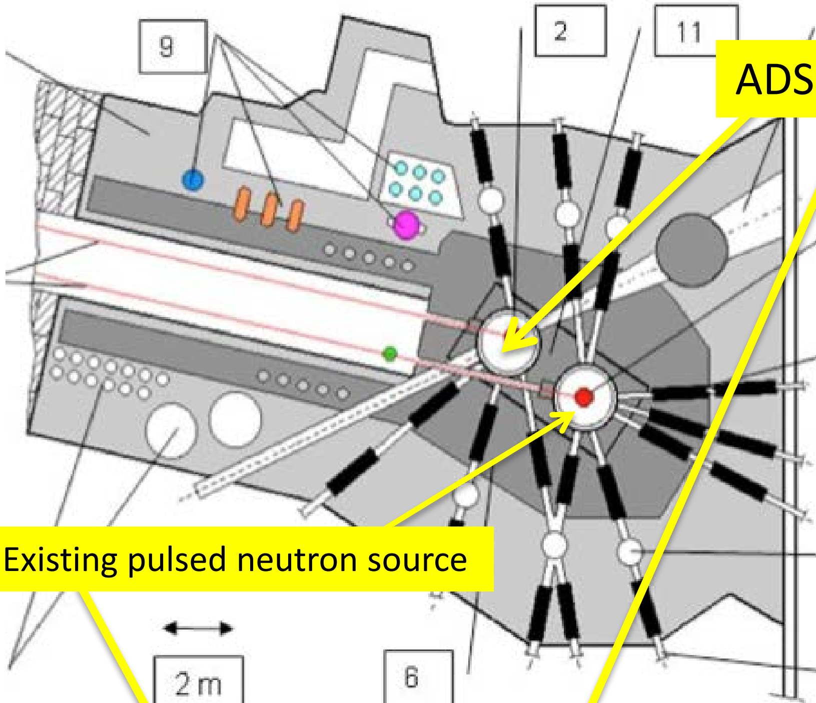
Other ADS R&D activities in many countries Japan, Korea, Turkey, Ukraine, UK (Aker Solutions C. Rubbia), Venezuela, Chile, etc. – **But lack of cooperation and coordination**

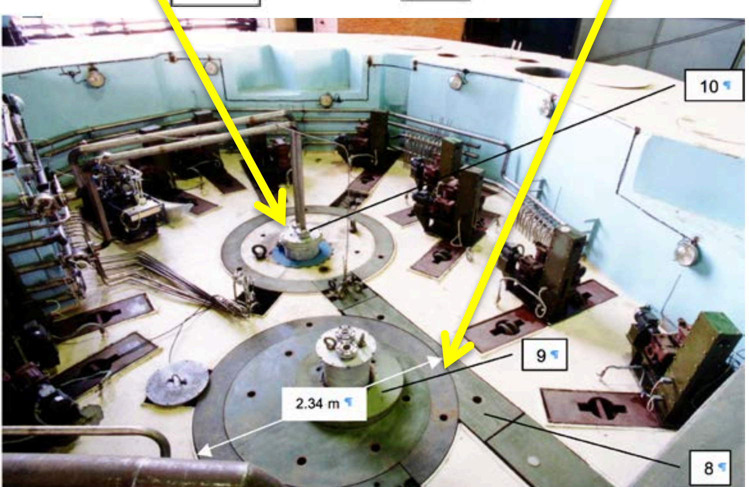
iThEC

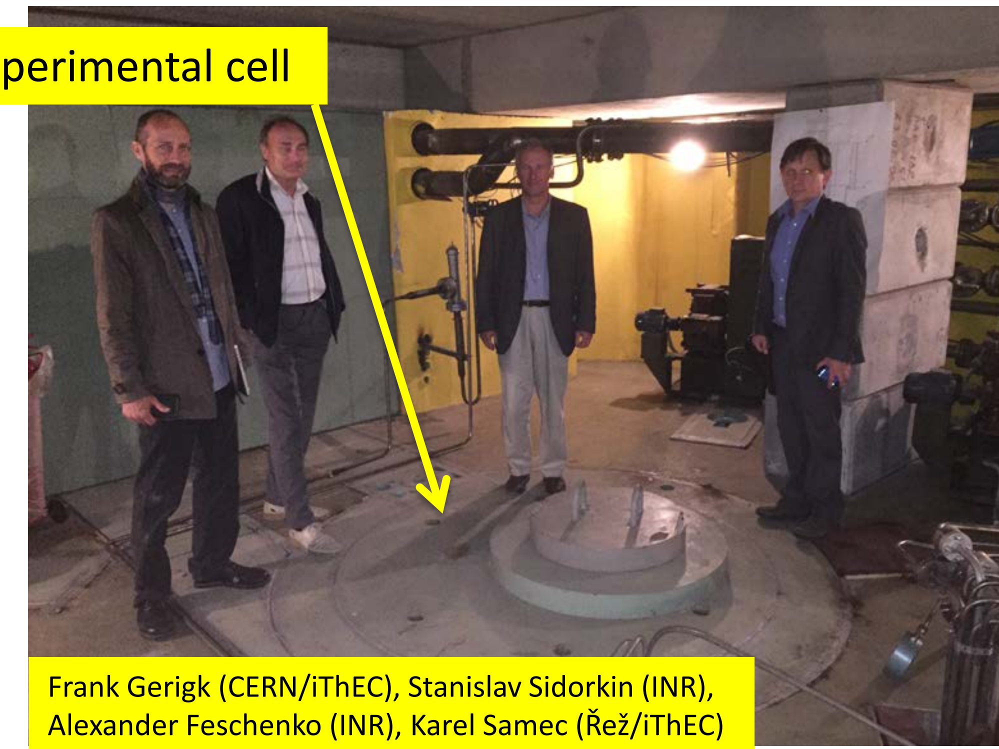
The INR/iThEC ADS project at Troitsk (Moscow area)



Using an existing facility at Troitsk







Frank Gerigk (CERN/iThEC), Stanislav Sidorkin (INR), Alexander Feschenko (INR), Karel Samec (Řež/iThEC)

Existing INR Infrastructure

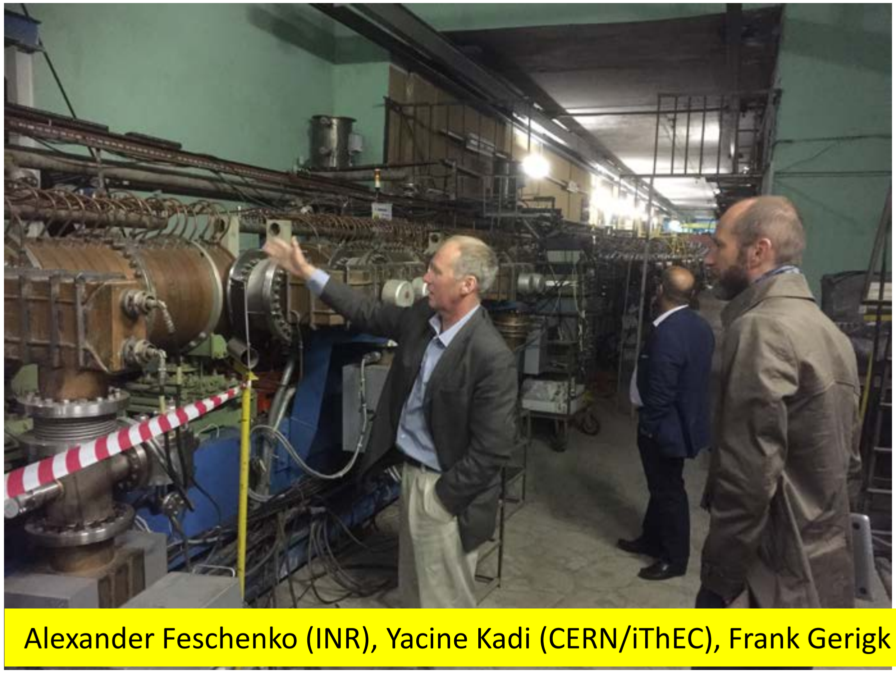
– ***Proton li***nac (design: 600 MeV, 300 kW, needs refurbishing)

– ***Spallation neutron source***

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

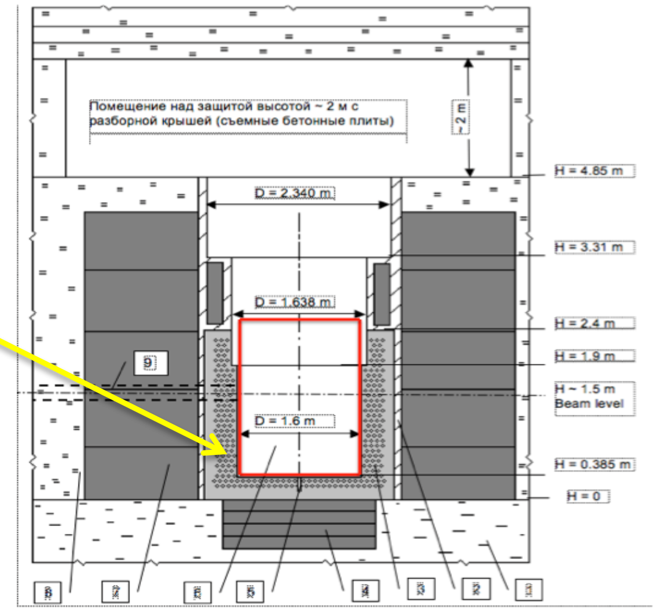
– ***Infrastructure*** (shielding, handling devices) to manipulate highly radioactive material)

Existing infrastructure at INR Troitsk



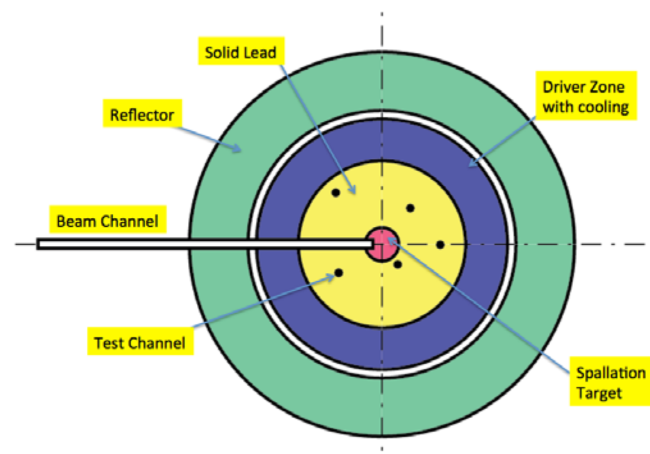
Alexander Feschenko (INR), Yacine Kadi (CERN/iThEC), Frank Gerigk (CERN/iThEC)

Reflector & cooling



Main goals of the Troitsk ADS experiment:

1) Measure physical properties of a 1 to 3 MW fast neutron ADS
2) Demonstrate transmutation of nuclear waste (MA & LLFP/TARC)
3) Test the production of specific radioisotopes
4) Provide unique fast neutron subcritical test facility



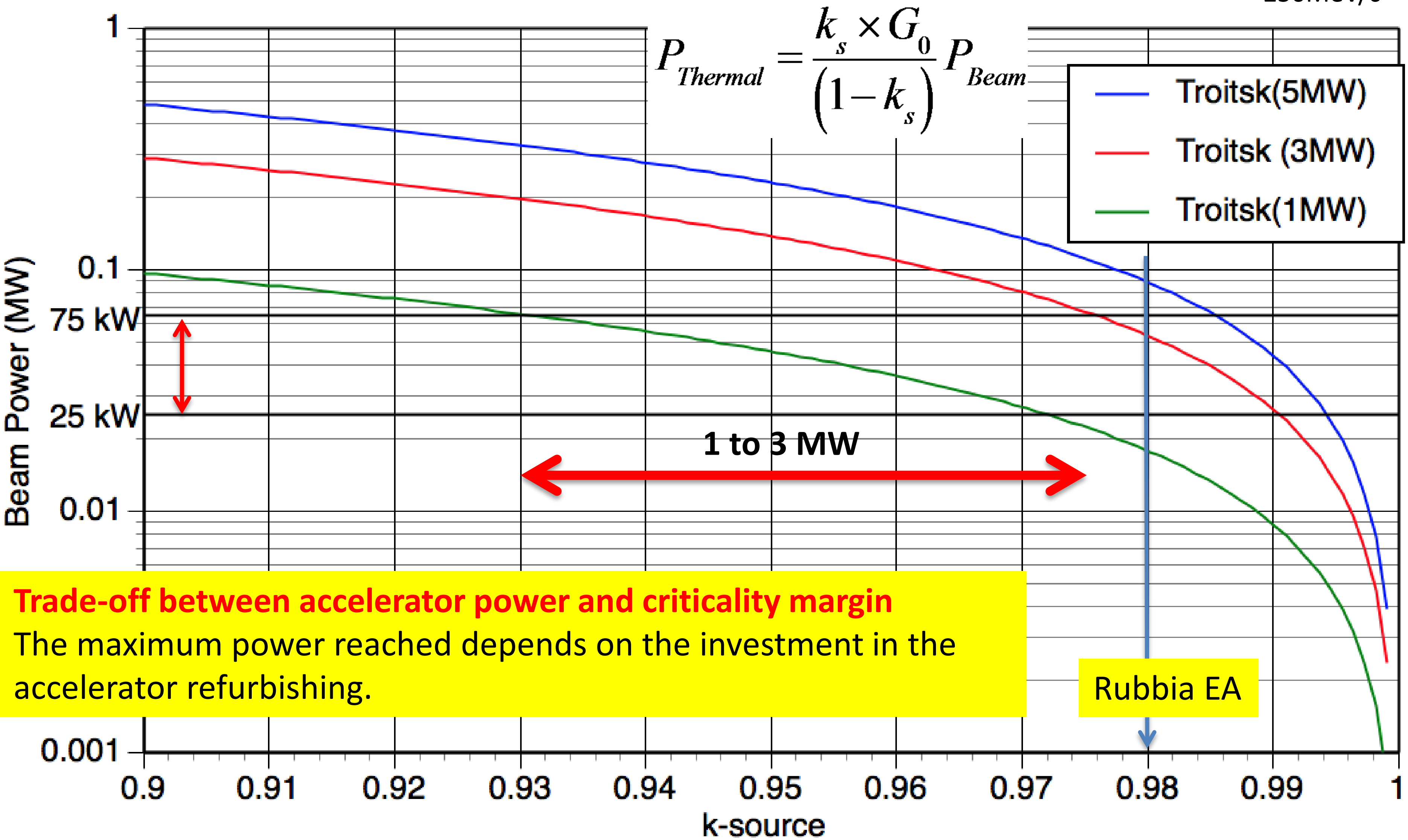
Core conceptual design

Initial proposal by **S.F. Sidorkin, A.D. Rogov, L.I. Ponomarev, E.A. Koptelov, "Thorium Energy for the World", Proceedings of ThEC13, Springer, 2016**

Reaching MW power at Troitsk

$E_{beam\ (Min)}$
250MeV/c

$$P_{Thermal} = \frac{k_s \times G_0}{(1-k_s)} P_{Beam}$$



Trade-off between accelerator power and criticality margin

The maximum power reached depends on the investment in the accelerator refurbishing.


Meeting with Troitsk management at CERN: January 18-21, 2016
Stanislav Sidorkin
Alexander Feshchenko
Leonid Kravchuk
JPR
Karel Samec
Yacine Kadi
Maurice Bourquin

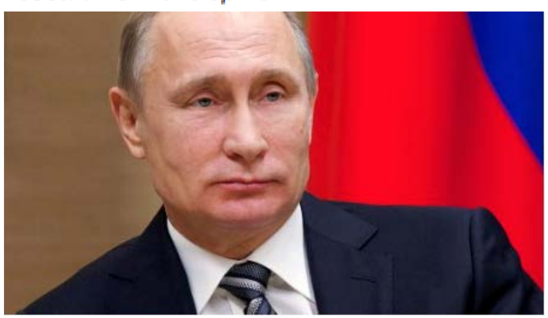
ADS Experiment at INR Troitsk

- **Positive feedback from** the Russian Academy of Sciences (RAS), however, Russian authorities would like to see international support (iThEC's task is to help collect such support)
- Recently, President Putin asked for a Russian strategy concerning thorium:

16.08.2016_No161 / News in Brief

Putin Asks For 'Coordinated Position' On Use Of Thorium

Research & Development



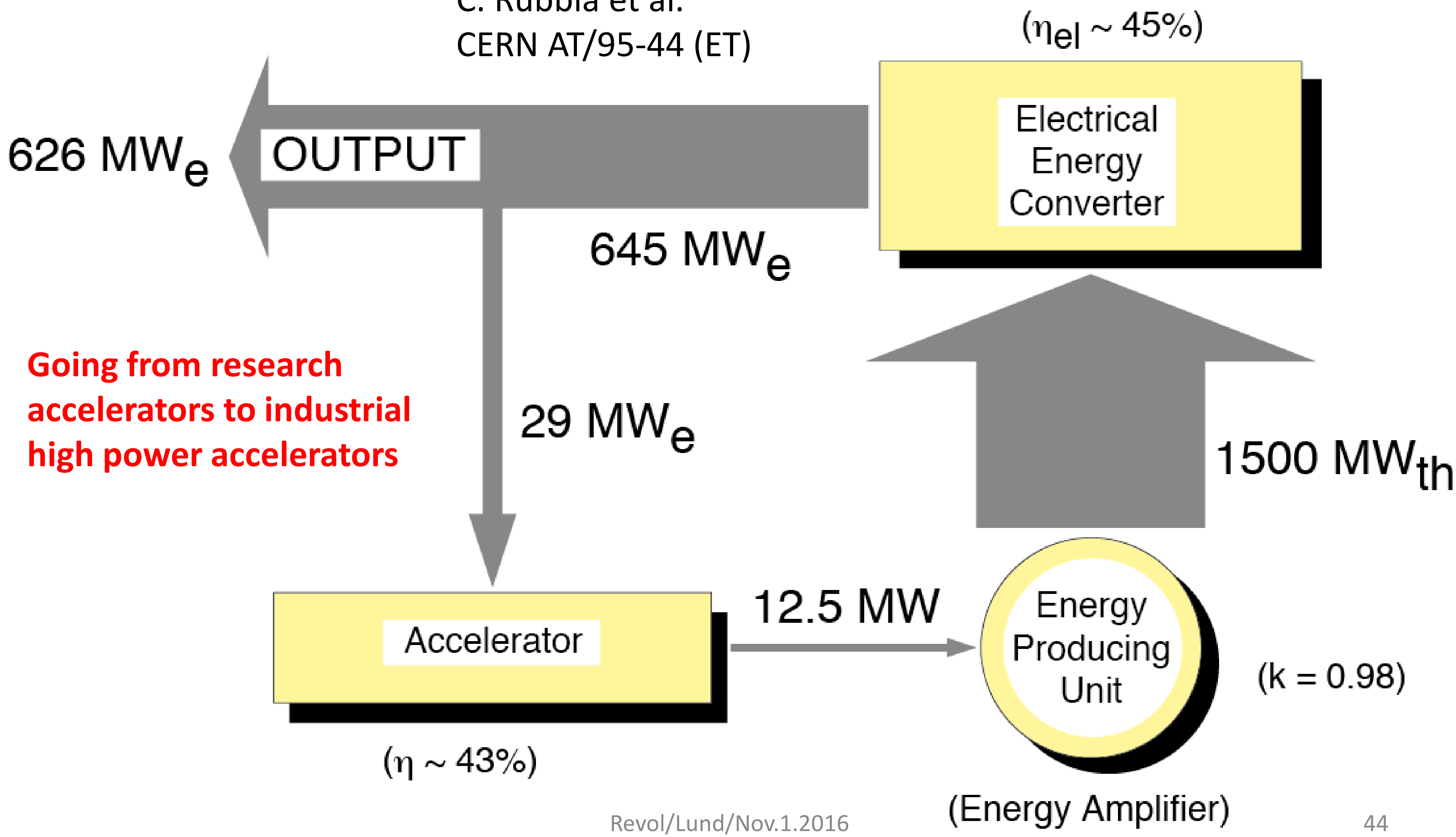
Yacine Kadi, Vladimir E. Fortov (President of RAS), Jean-Pierre Revol, Boris F. Myasoedov (Academician in charge of thorium).

- **Collaboration**: INR Troitsk and iThEC will put together an international collaboration Discussion with other institutes in Russia, with PSI in Switzerland, China, Řež in the Czech Republic, South Korea, Chile, India – **if approved it could become a CERN recognized** experiment (700 k$ required by ROSATOM to submit to safety authorities)
- ADS workshop to be organized at CERN in 7-8-9 February 2017
- Good contacts with IAEA to set up a Coordinated Research Programme (CRP)

The CERN/iThEC superconducting high-power cyclotron project

C. Rubbia's Energy Amplifier

C. Rubbia et al.
CERN AT/95-44 (ET)

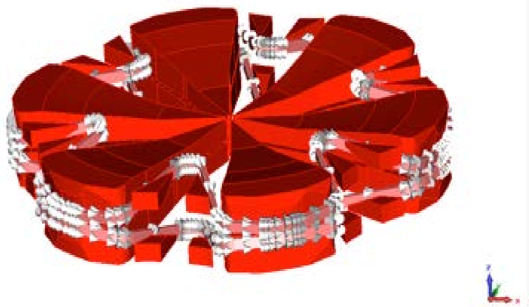


Going from research accelerators to industrial high power accelerators

Accelerator requirements

- Beam parameters are well established:
  - Protons of **energy E_{proton} ≈ 1 GeV** (See FEAT experiment), **beam power** ranging from **a few to ≈ 10 MW** depending on the application. Large operational range desirable to follow fluctuating demand, if associated to wind or solar energies
- Three possible accelerator techniques: **linear accelerator** (linac), **cyclotrons and FFAG**
- For industrial applications, there are several specific requirements, which in some cases make the accelerator challenging, and are the object of R&D, mainly:
  - **Beam losses**: minimize irradiation of the accelerator components (impact on accelerator maintenance). For cyclotrons losses are localized, at injection and for linacs they are distributed all along the structure extraction
  - **Reliability**: Limitation mainly from thermal stress inducing fatigue in beam window, fuel cladding and vessel structure: minimizing beam trips is a significant challenge; for instance, for MYRRHA:
    - No limit for trips for $T_{trip} < 0.1$ s
    - Not more than 100 trips per day $0.1 \text{ s} < T_{trip} < 3$ s
    - Not more than 10 trips in three months for $T_{trip} > 3$ s
  - **Cost**: It is obviously most important to minimize the cost for industrial applications

High-power superconducting cyclotron project



- ***European Union proposal***: **Project coordinated by CERN**; partners: iThEC, PSI*, AIMA** (France), ASG (Italy), Hydromine Nuclear Energy (Italy), Nuclear-21 (Belgium)
- ***EU H2020 Call***: *"**Future and Emerging Technologies (FET)** shall support collaborative research in order to extend Europe's capacity for advanced and paradigm-changing innovation. It shall foster scientific collaboration across disciplines on radically new, high-risk ideas and accelerate development of the most promising emerging areas of science and technology as well as the Union wide structuring of the corresponding scientific communities."*
- **Project baseline**: **Conceptual design of a superconducting one stage H_2^+ cyclotron**, 600 MeV, 6 mA (3.6 MW)
- **Applications**: ADS, high flux particle beams, radioisotopes for medicine, various other industrial applications

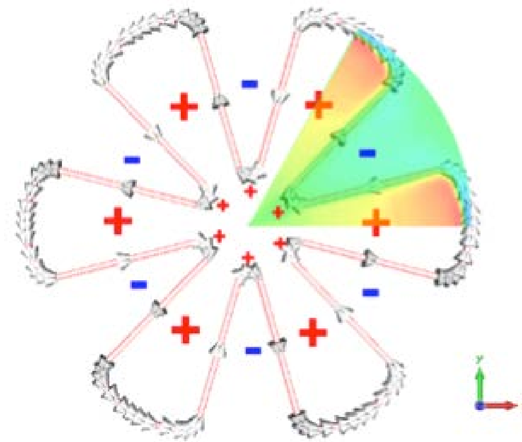
Proposal to be submitted by January 17, 2017

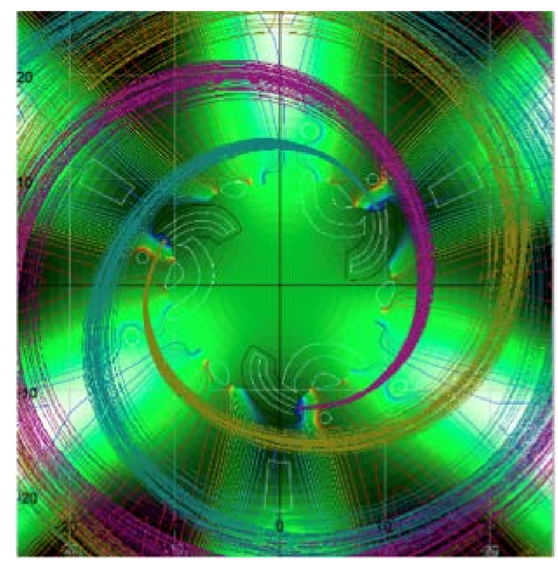
** Paul Scherrer Institute, Switzerland, operating the highest power cyclotron*

***P. Mandrillon, cyclotron expert, designer of the EA cyclotron with Carlo Rubbia*

A superconducting cyclotron for ADS

- **An innovative simpler separate sector cyclotron, with reverse valley B-field**
- The concept was first presented by Pierre Mandrillon (AIMA) at ThEC13: **Cyclotron Drivers for Accelerator-Driven Systems**
- **High reliability through redundancy:** 3 sources; smaller number of components compared to a linac
- **High efficiency:** cavities see the beam several times; superconductivity reduces ohmic losses
- **Low impact on the environment**: beam losses localized
- **Cheaper infrastructure**: the gain comes from the much more compact infrastructure compared to a linac
- **Cost**: the overall cost expected to be 2 to 3 times lower than the cost of an equivalent linac (it is one of the goals of the FET project to determine the cost in a reliable way)





CONCLUSION

- **Thorium is an energy resource of the future**, essentially sustainable, which cannot be neglected
- The ADS technology to use thorium is well understood and requires only modest developments. It may even represent an opportunity for countries developing their own nuclear industry
- iThEC's priority is to get two initiatives approved:
  - **A first ADS experiment of significant power at Troitsk**
  - **An innovative high-power cyclotron**

  which are the next natural steps toward an industrial ADS prototype
- **iThEC and INR are seeking partners** from the international scientific community, **and funding to obtain approval**

Sustainable Thorium Energy for the World

Jean-Pierre Revol

Abstract

To meet the tremendous world energy needs, systematic R&D has to be pursued to replace fossil fuels. Nuclear energy, which produces no green-house gases and no air pollution, should be a leading candidate. How nuclear energy, based on thorium rather than uranium, could be an acceptable solution is discussed. Thorium can be used both to produce energy and to destroy nuclear waste. It is seriously considered by some major developing countries as a key element of their energy strategy. However, developed countries do not seem to move fast enough in that direction, while global cooperation is highly desirable in this domain. Various possibilities of using thorium, which is not fissile, will be reviewed. An elegant option is a subcritical system driven by a proton accelerator (ADS). Two new projects related to ADS proposed by iThEC will be described.

What can ADS do?

- **Breeding nuclear fuel** (Pu^{239} or U^{233} from U^{238} orTh^{232}), and generate energy;
- **Extracting energy from nuclear waste**, in particular minor actinides, but also commercial and military Pu;
- **Producing radioelements** by transmutation (alternative to nuclear reactors – distributed systems)
  - Radioisotopes for medicine and industry
  - Anything that can be produced through transmutation
- **Providing fast neutron flux environment**, for material tests in subcritical systems (flexibility thanks to subcriticality)
- **Provide high fluxes of elementary particles** (mesons, neutrinos) for ultra high precision experiments in fundamental research

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 fuel** 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**.

CERN: European laboratory dedicated to **fundamental research** in the field of **particle physics**, located near Geneva, across the border between **France and Switzerland**,

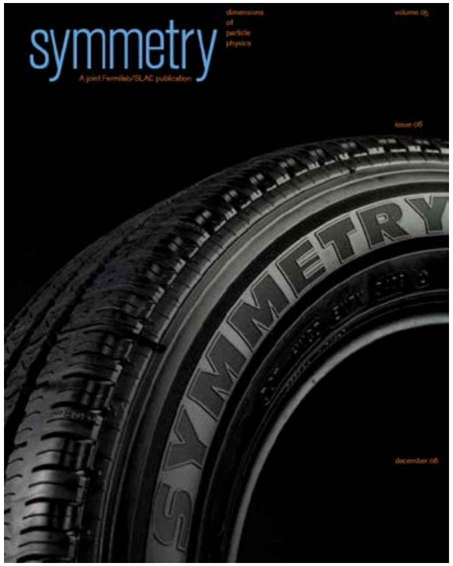
Today, the **Large Hadron Collider (LHC)** is the flagship of the laboratory

iThEC

ThEC13 in CERN Globe of Science and Innovation

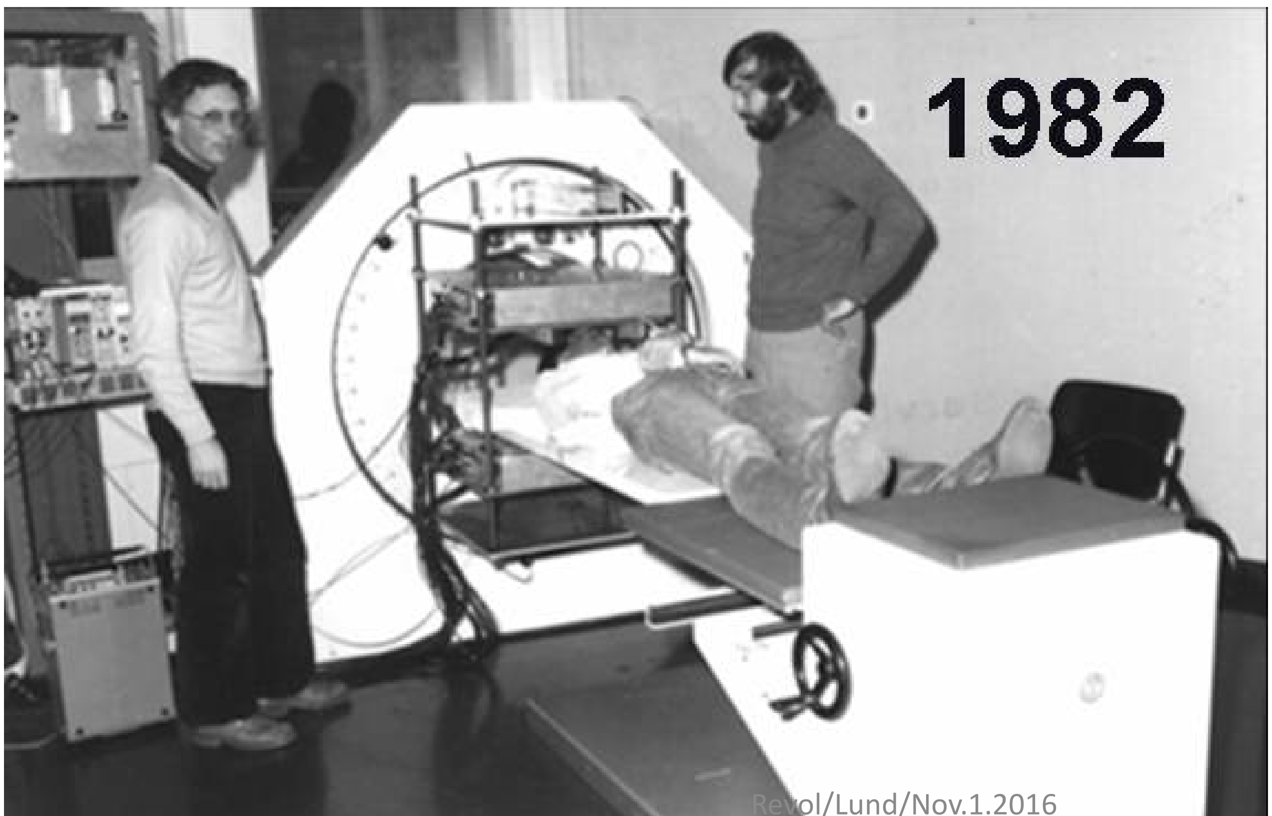
How does fundamental research feed innovation?

- **Direct ways:**
  - For instance **Faraday's work**
  - The **discovery of the spin of the proton** opened the way to medical imaging by **Nuclear Magnetic Resonance technique**
  - **Quantum Field Theory** led to using antimatter (e^+e^- tomography), etc.
- **Indirect ways: Tools** developed for fundamental research find applications in other areas:
  - Application of **accelerator & detector technology** to medicine
    - Hadron therapy (cyclotrons) [Centre Lacassagne, TERA, …]
    - Production of radioactive isotopes medicine & industry
  - Industrial processes using accelerators
  - Accelerator driven power plants using thorium for energy production and destruction of nuclear waste
  - **WWW, Education, training, etc.**



CERN and PET/CT scanners

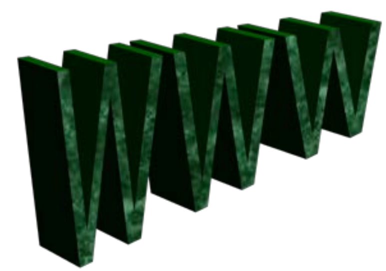
- First PET scanner developed in collaboration between CERN and Geneva Cantonal Hospital.
  (David W. Townsend, Alan Jeavons and Prof. Alfred Donath)



W.C. Röntgen,
22 Nov. 1895

CERN invention of the World Wide Web

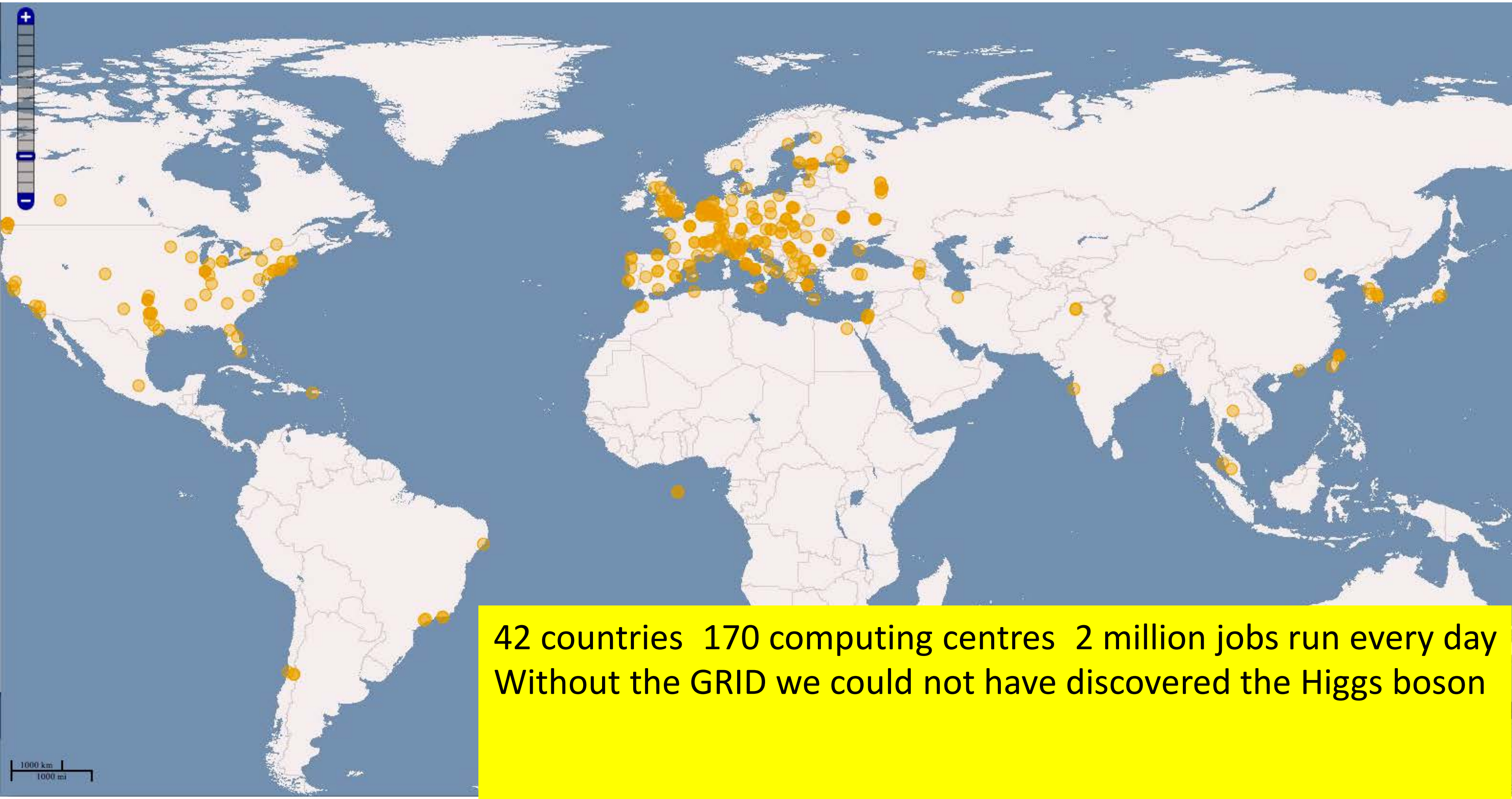
1990 Tim Berners-Lee



"WWW … changed forever the way information is shared"

WWW >>> Sharing information

CERN and the World LHC Computing Grid

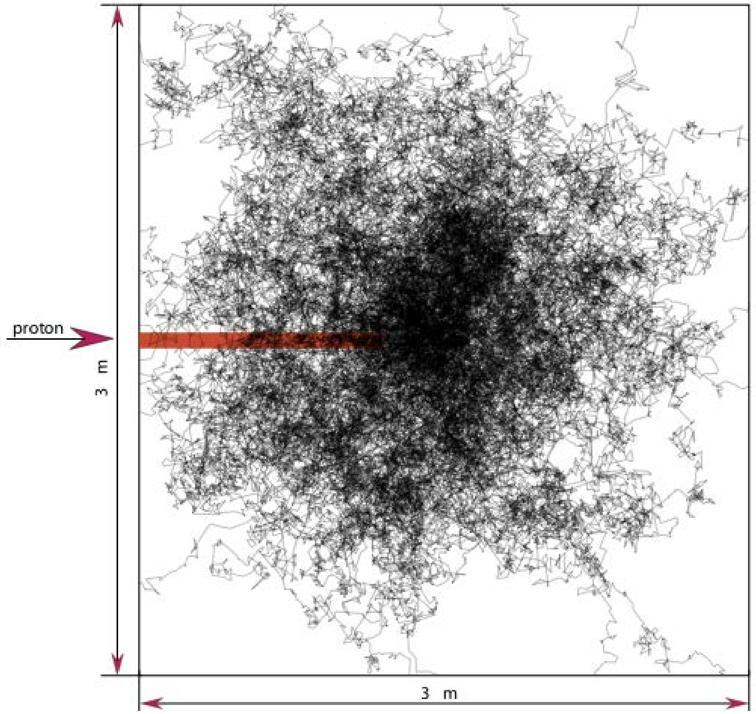


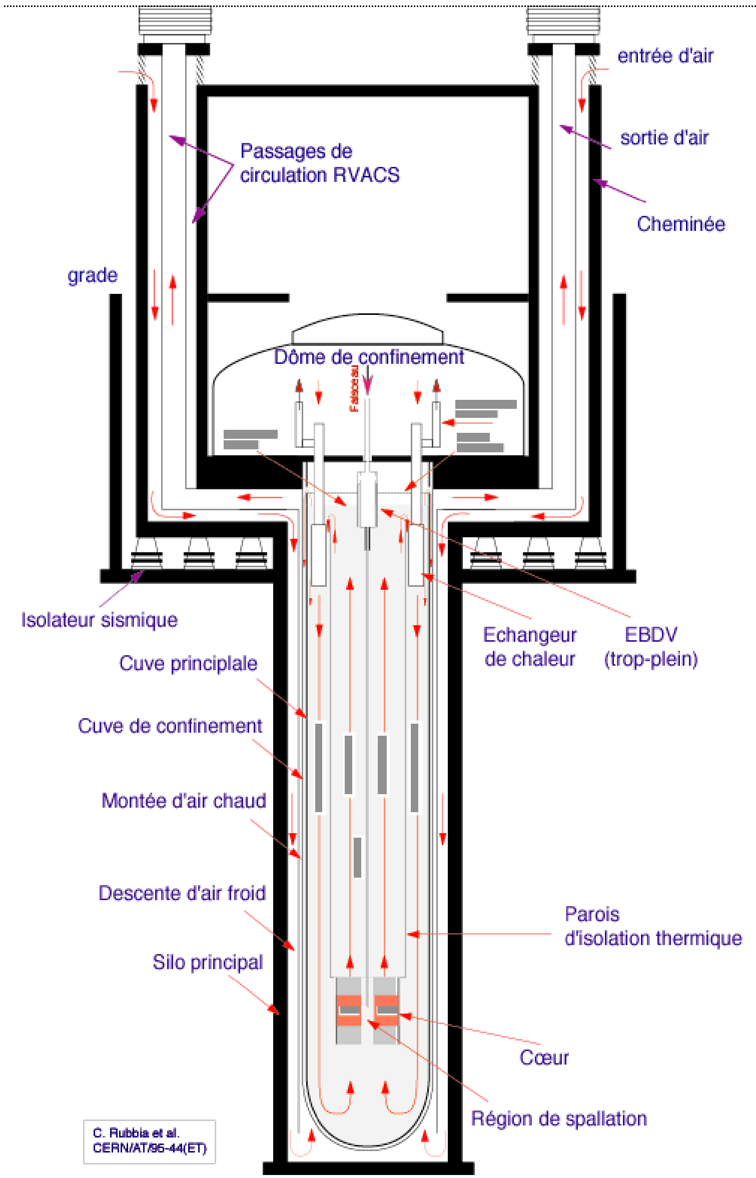
42 countries 170 computing centres 2 million jobs run every day
Without the GRID we could not have discovered the Higgs boson

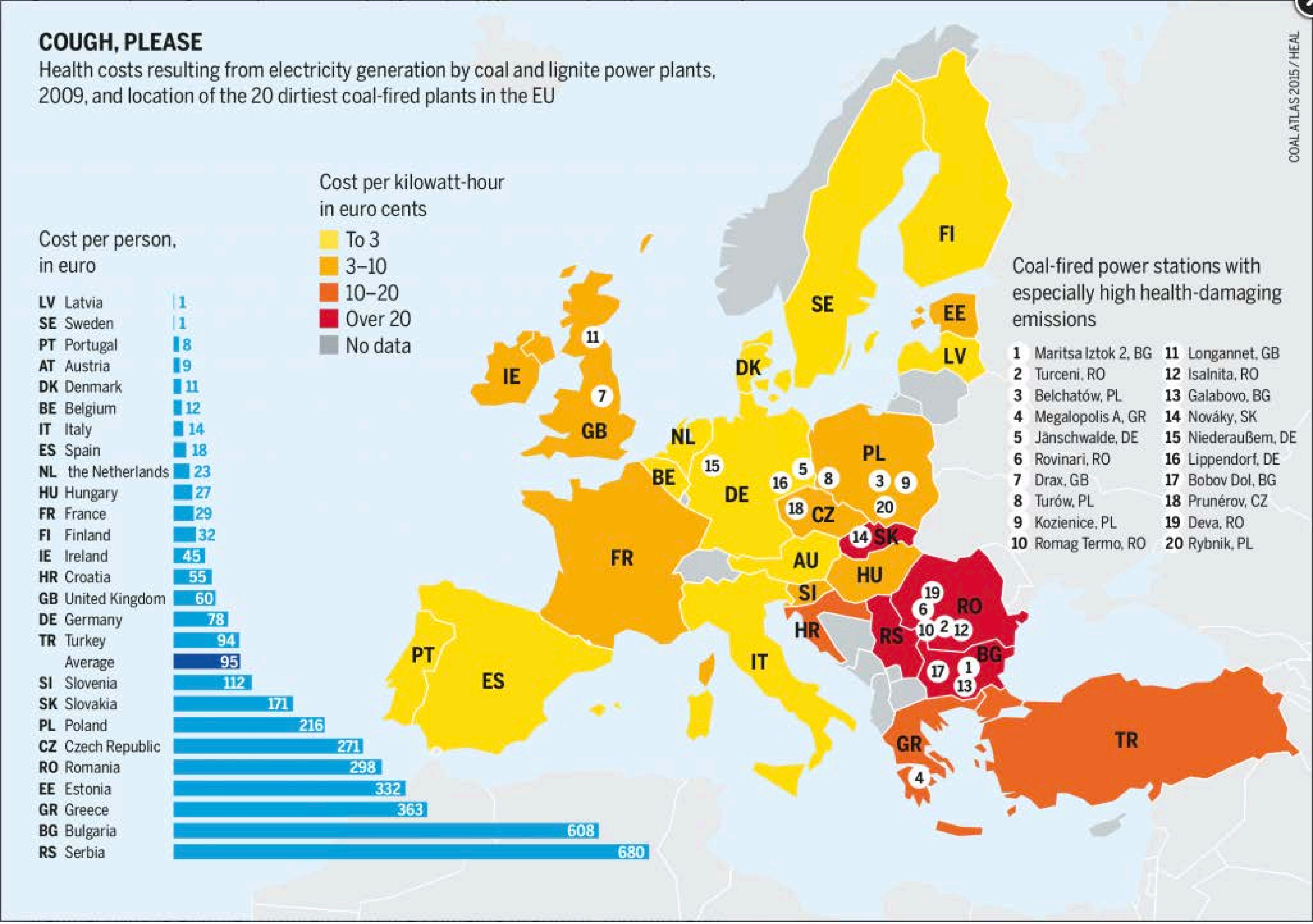
GRID >>> Sharing computing resources

CERN and thorium energy

- ***The Energy Amplifier***, an accelerator-driven system proposed at CERN by **Nobel Laureate Carlo Rubbia**
- Concept validated by CERN **FEAT and TARC** experiments, which led to other applications:
  – Isotope production for medical diagnostics (**CERN Patent**)
  – Neutron facility **n_TOF**]






COUGH, PLEASE
Health costs resulting from electricity generation by coal and lignite power plants, 2009, and location of the 20 dirtiest coal-fired plants in the EU
COAL ATLAS 2015 / HEAL
Cost per kilowatt-hour in euro cents
To 3
3–10
10–20
Over 20
No data
Cost per person, in euro
LV Latvia 1
SE Sweden 1
PT Portugal 8
AT Austria 9
DK Denmark 11
BE Belgium 12
IT Italy 14
ES Spain 18
NL the Netherlands 23
HU Hungary 27
FR France 29
FI Finland 32
IE Ireland 45
HR Croatia 55
GB United Kingdom 60
DE Germany 78
TR Turkey 94
Average 95
SI Slovenia 112
SK Slovakia 171
PL Poland 216
CZ Czech Republic 271
RO Romania 298
EE Estonia 332
GR Greece 363
BG Bulgaria 608
RS Serbia 680
Coal-fired power stations with especially high health-damaging emissions
1 Maritsa Iztok 2, BG
2 Turceni, RO
3 Belchatów, PL
4 Megalopolis A, GR
5 Jänschwalde, DE
6 Rovinari, RO
7 Drax, GB
8 Turów, PL
9 Kozienice, PL
10 Romag Termo, RO
11 Longannet, GB
12 Isalnita, RO
13 Galabovo, BG
14 Nováky, SK
15 Niederaußem, DE
16 Lippendorf, DE
17 Bobov Dol, BG
18 Prunérov, CZ
19 Deva, RO
20 Rybnik, PL
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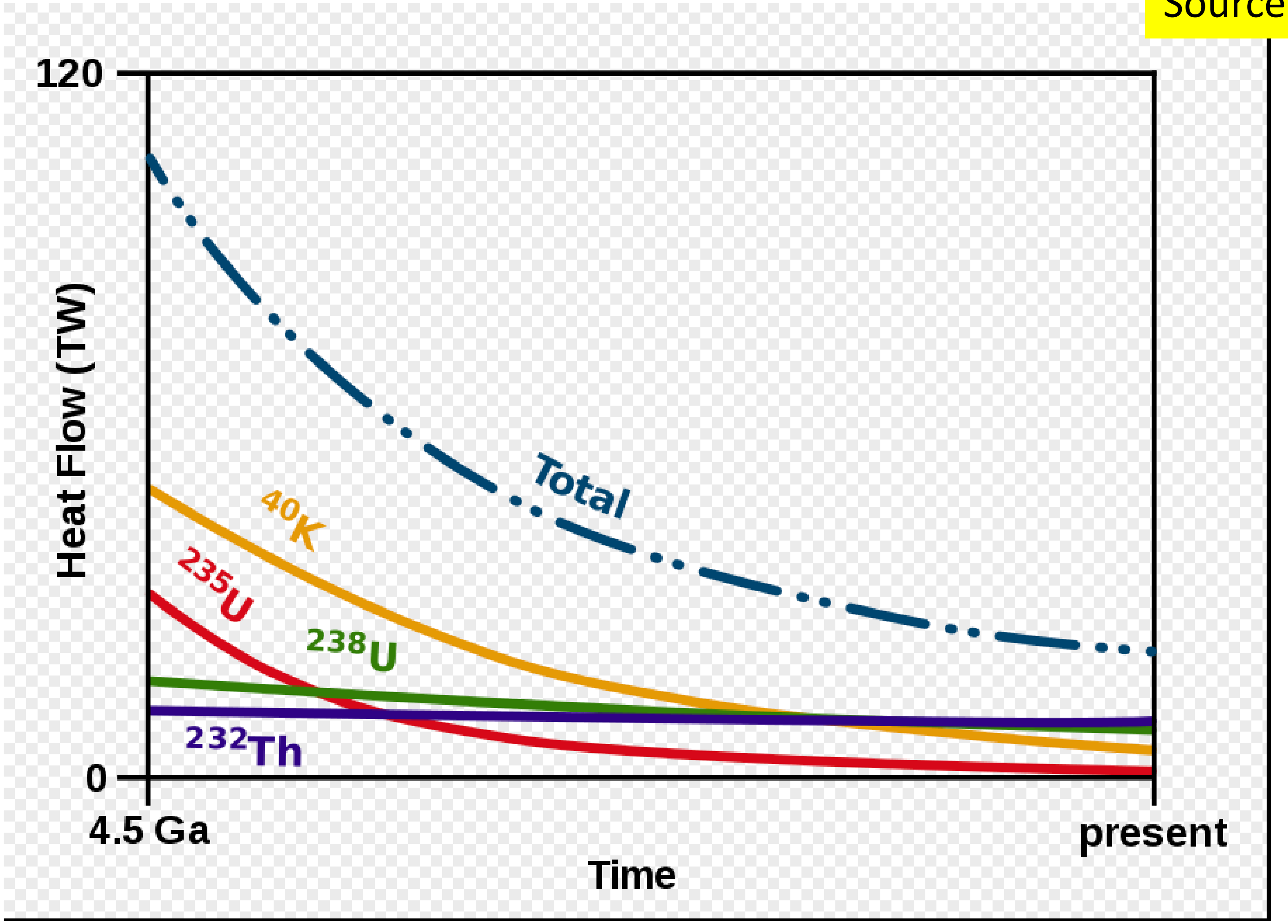
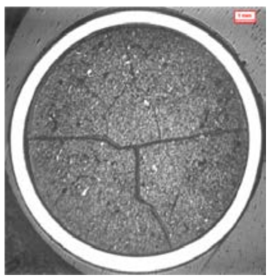
Source: Wikipedia

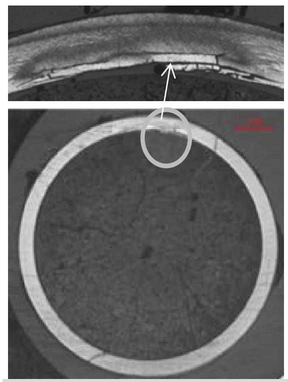


The total heat loss from the Earth is estimated at 44.2 TW (4.42 × 10^{13} watts). The heat of the Earth is replenished by radioactive decay at a rate of 30 TW. The radiogenic heat from the decay of 238U and 232Th are now the major contributors to the earth's internal heat budget. **Thorium dominates!**

P.K. Vijayan, ThEC13



ThO_2-4%PuO_2



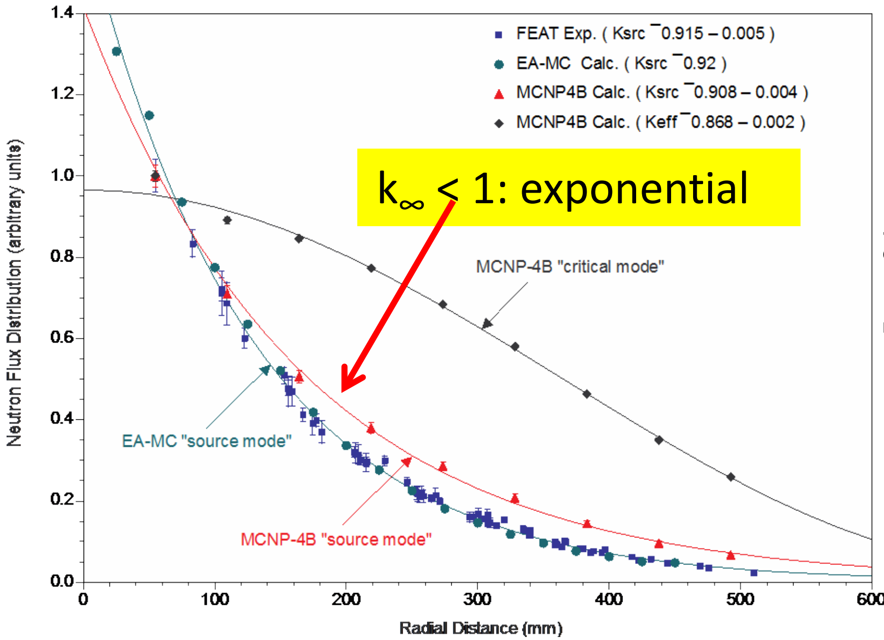
Failed ThO_2-4%PuO_2

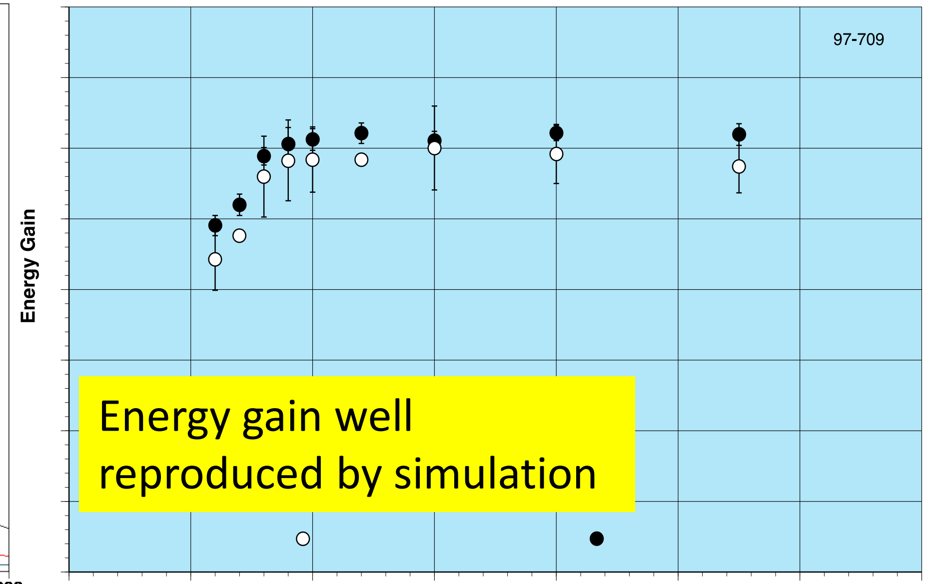
Failed UO_2

UO_2-4%PuO_2

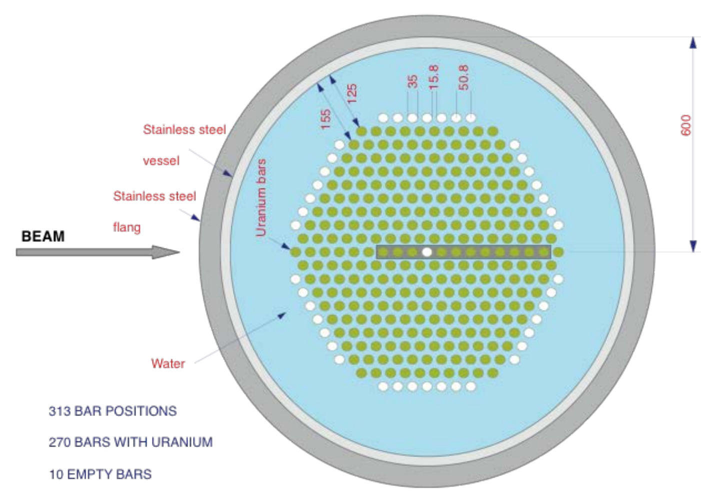
Comparison of failed ThO_2–4% PuO_2 (18500 MWd/tonne), UO_2 (400 MWd/tonne), and UO_2–4% PuO_2 (16000 MWd/tonne) fuels at indicated burnups

Main results from FEAT





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

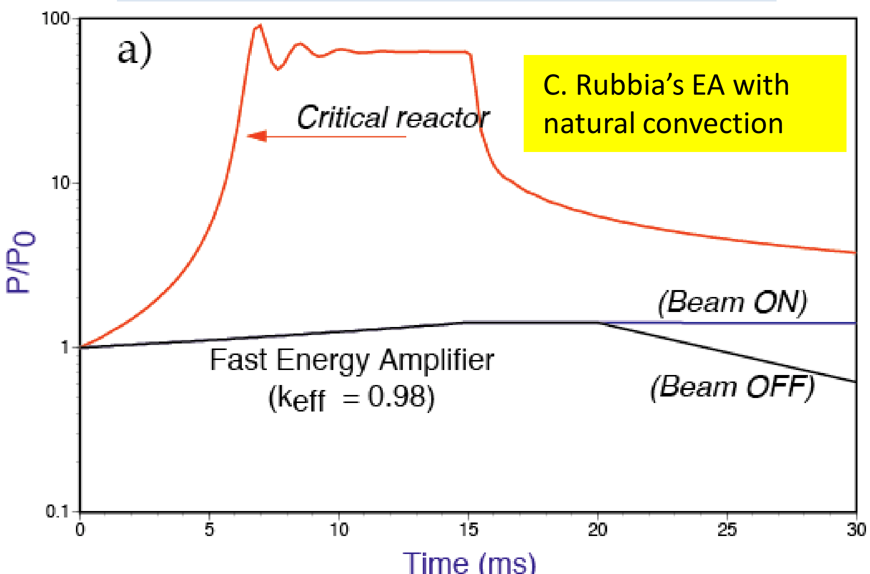


Physics of subcritical systems

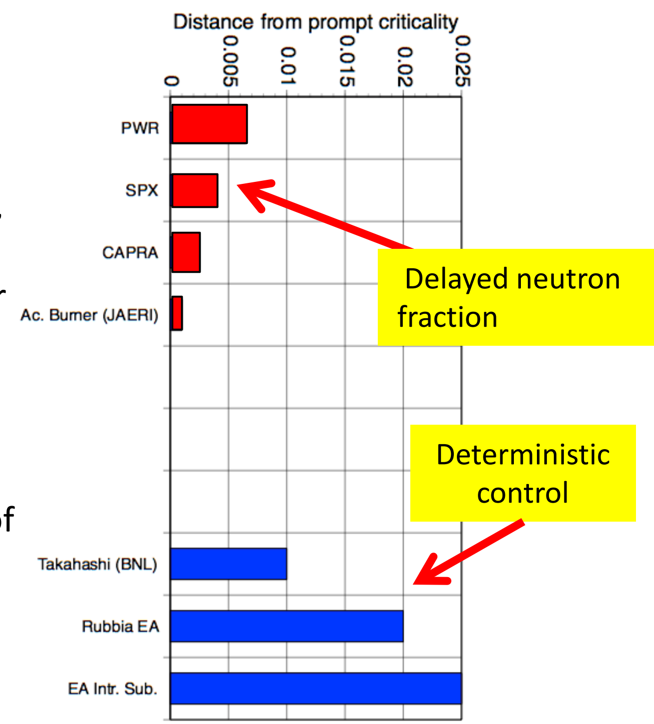
- Subcritical systems are insensitive to delayed neutron fraction (β); **safety margin** (distance from prompt criticality) **is a design choice**, it is not imposed by Nature!

- 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)

Response to reactivity insertion



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.

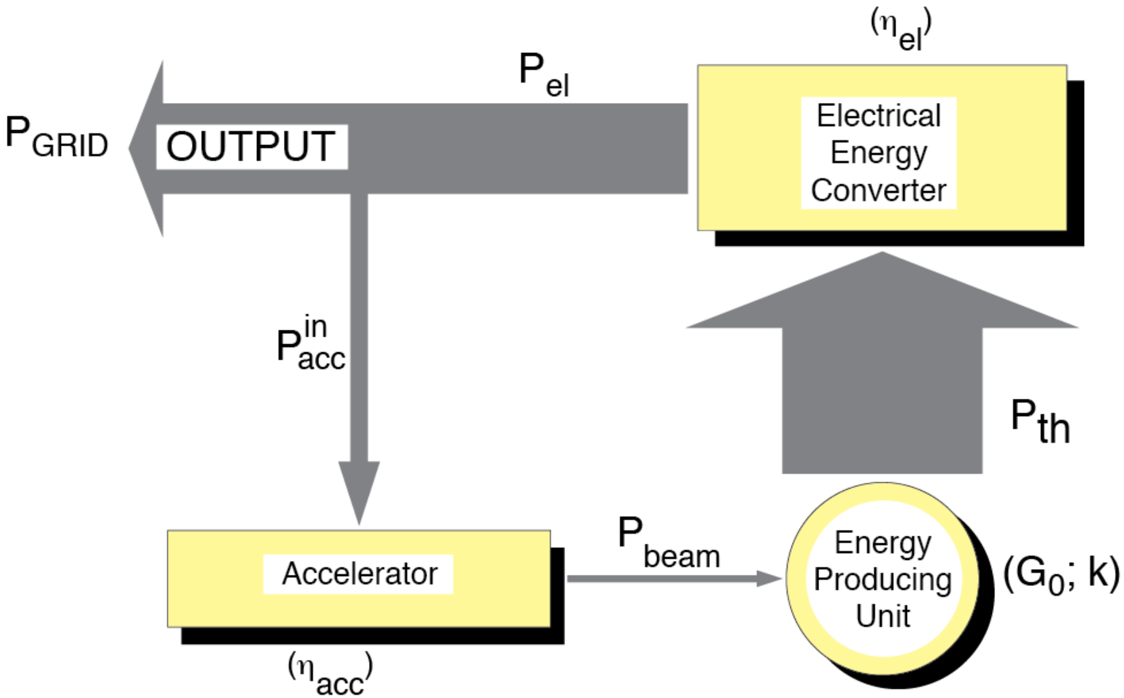


Annual production of a 900 MWe PWR

- Assuming 33% efficiency and a duty factor of 70 %: 7.9 TWh => 5.5 TWh. Typically 225 kg of TRU and 745 kg of FF

Electricité	**5,5 milliards de kWh**
Combustible usagé (à 33,000 MWd/t)	**21,5 t de UO_2**
Actinides	**20 620 kg**
Uranium ^{238}U (avec 1,1% de ^{235}U)	**20 400 kg**
Plutonium ^{239}Pu, ^{241}Pu (71%)	**209 kg**
Actinides mineurs (Np, Am, Cm, etc.)	**16 kg**
Fragments de fission (total)	**745 kg**
Fragments de fissions à vie longue	**50 kg**
Déchets de classe A (Gaines, matériaux structurels, etc.)	**100 – 200 m^3**

ADS Accelerator Efficiency



Electric conversion efficiency

$$P_{el} = \eta_{el} \times P_{th}$$

Energy gain in core

$$P_{th} = P_{beam} \times \frac{G_0 k}{(1-k)}$$

Running the accelerator

$$P_{beam} = \eta_{acc} \times P_{acc}^{in}$$

$$P_{GRID} = P_{el} - P_{acc}^{in} = P_{beam}\left[\frac{\eta_{el} G_0 k}{1-k} - \frac{1}{\eta_{acc}}\right]$$

Electric power produced

Electric power to run the accelerator

ADS Accelerator Efficiency

$$P_{GRID} = P_{beam}\left[\frac{\eta_{el} G_0 k}{1-k} - \frac{1}{\eta_{acc}}\right]$$

For a typical ADS (Rubbia) the first term is of the order of 50

- The electric power to run the accelerator must be small compared to the power produced in the ADS core:

$$\frac{1}{\eta_{acc}} << 50 \Rightarrow \eta_{acc} >> 0.02$$

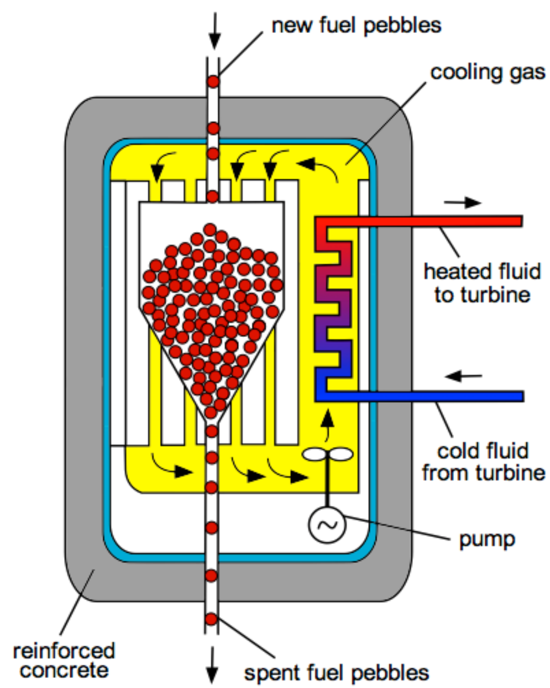
- Minimum is η_{acc} = 0.2, but η_{acc} = 0.4 should achievable and in that case the accelerator takes only 5% of the electric power produced by the ADS, which seems reasonable
- For very high power beams (≥ 10 MW), every MW saved matters, and it is useful to have the highest possible accelerator efficiency, if it does not compromise other properties (cost, reliability, etc.)

iThEC

Pebble bed critical reactors

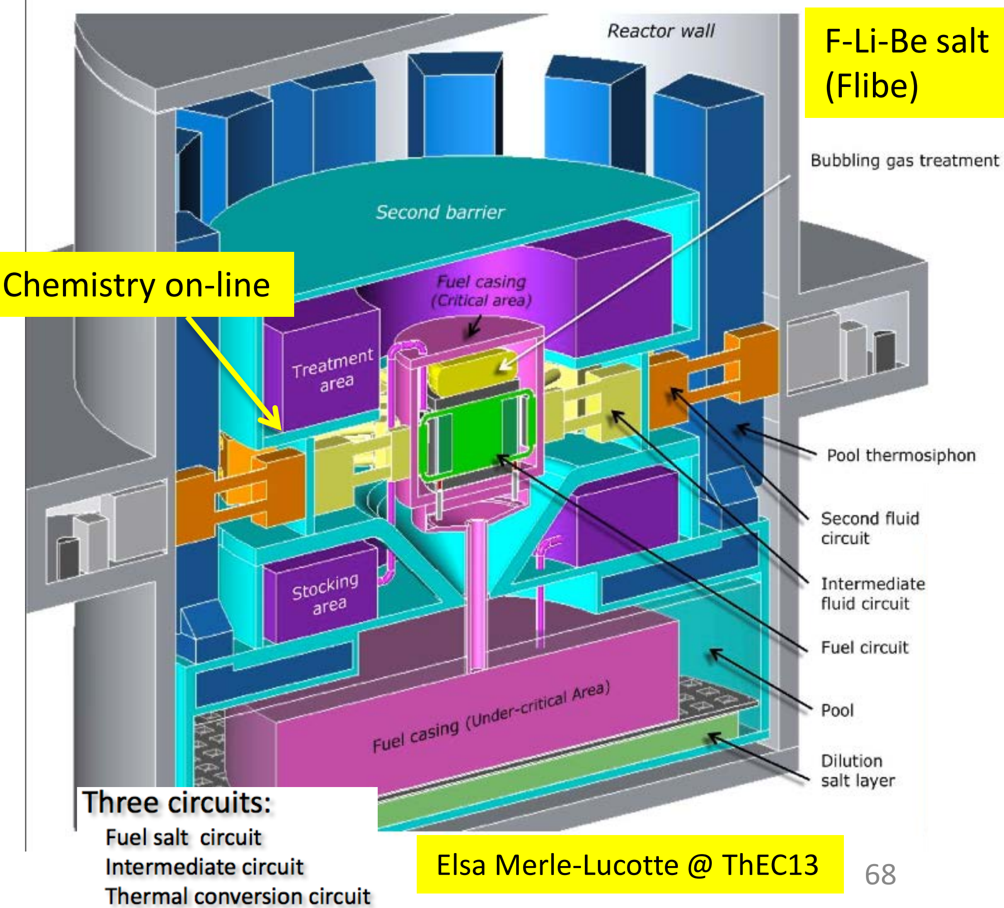
- Proposed by Farrington Daniels at Oakridge, in the 1940s. Initial developments in Germany (AVR Jülich), followed by THTR-300MW (1983-1989). New developments in South Africa, now in the United States and Turkey.
  - Presented as passively safe, as high temperature systems can be cooled by natural air 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 issue
  - Reprocessing virtually impossible

Pebble Bed Reactor scheme



Molten salt critical reactors

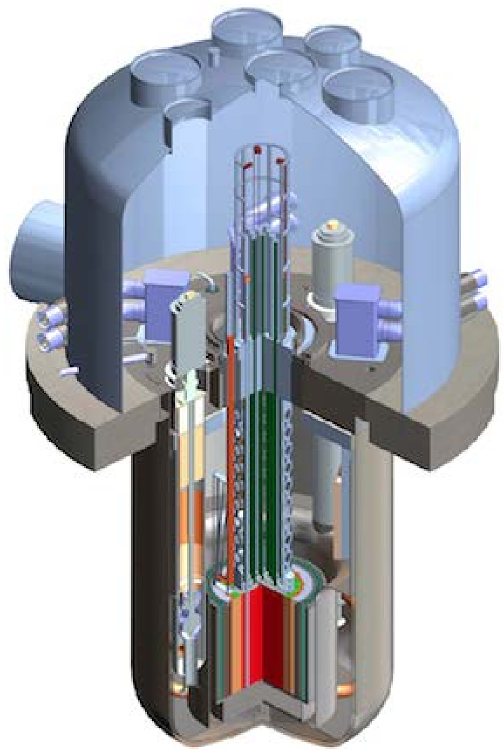
- This is clearly a technology that is concentrating interest including in nuclear industry (10 talks on MSR at ThEC13): China, India, UK, USA, Czech Republic, France, Switzerland
- Pioneered at Oakridge in 1960 (Molten Salt Reactor Experiment, UF4, 7.4 MWth)
- Advantages:
  - Liquid fuel allows extending burnup indefinitely, because of reprocessing on-line
  - High temperature (500˚C – 600˚C), heat produced directly in heat transfer fluid
  - Passive safety based on liquid expansion
  - Passive cooling for decay heat removal
- **Several severe issues to be resolved**:
  - Neutron emission outside the core, 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)



Elsa Merle-Lucotte @ ThEC13

Traveling wave reactor

- Wave of fission/breeding neutrons moving through the fuel
- Critical sodium cooled reactor breeding 239Pu
- Still to be developed



TerraPower

Turns depleted uranium into electricity, using a simple fuel cycle without requiring separations.

SIZE	600 MWe (Prototype Plant) 1150 MWe (Commercial Plant)
TEMPERATURE	510°C
PRESSURE	Low (Atmospheric)
PRIMARY FUEL	Depleted Uranium
COOLANT	Sodium
ENERGY CONVERSION	Steam (Rankine Cycle)
WASTE REPROCESSING	Not Required


1 x 1,600 / 2 x 800
Brunsbüttel
800 to 1,100
Kiel
Wilhelmshaven 800
1,640
Hamburg
2 x 800
Lubmin
800
Emden
900
Dörpen
800/800/1,000 Stade
800
Berlin
750
Duisburg
1,100
Datteln
each 820
Hamm
750 / 900
Lünen
660
Profen
670
Boxberg
750
Krefeld
400 Düsseldorf
2,200
Neurath
1,100
Staudinger (Hanau)
Source: Friends of the
Earth Germany (BUND)
2,200
Niederaussem
750
Mainz
900
Mannheim
800
Karlsruhe
DER SPIEGEL
New coal-fired
power stations
Planned locations,
output in megawatts
Black
coal
Lignite