iThEC

international Thorium Energy Committee

www.ithec.org

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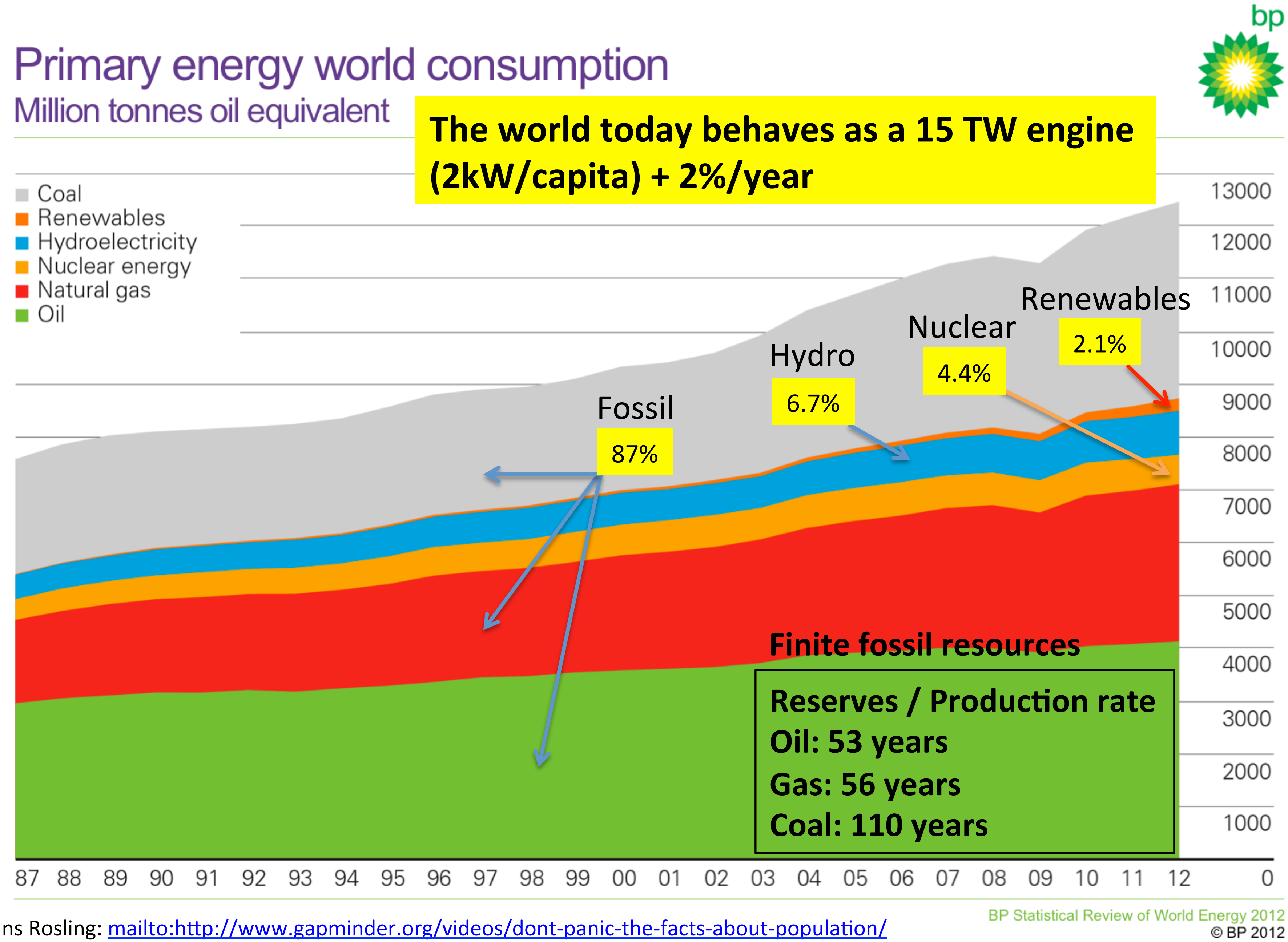
The iThEC Strategy

October 13, 2015
ThEC15 Plenary
Mumbai, India

Jean-Pierre Revol
Centro Fermi, Rome, Italy
iThEC, Geneva, Switzerland

Introduction

- Within a century or hopefully sooner, humankind will have to move from an economy entirely based on fossil fuels to a fossil fuel free economy:
  - **Fossil fuel reserves are finite**
  - **The impact of fossil fuel burning on the environment** is becoming unbearable

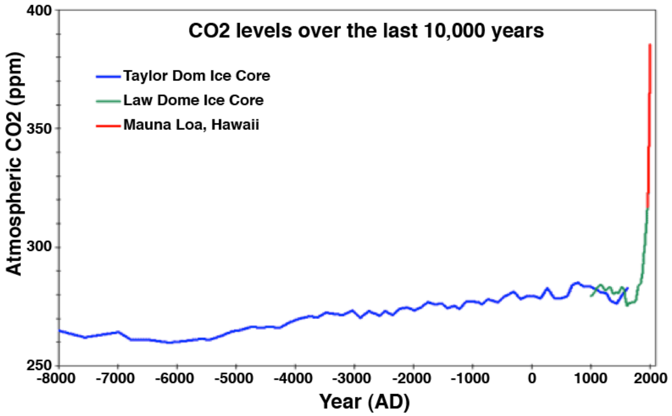


Hans Rosling: mailto:http://www.gapminder.org/videos/dont-panic-the-facts-about-population/

If people in developing countries are allowed to live as well as people do in Europe today, by end of 21st century, the world power consumption will have to increase by a factor 3 or more.

Burning fossil fuel till the end?

- **Global warming** Atmospheric CO_2 level higher than ever in the last million years, increasing faster than ever before (IPCC, March 2014 > 2˚C more likely than ≤ 2˚C at end of century)
- **Air pollution**
  - WHO: in 2012 around 7 million people died - 1 in 8 of total global deaths – as a result of air pollution exposure
  - Burning coal cost Europe alone 42.8 billion Euros in annual health care expenses (2013 report by the Health and Environment Alliance)
  - The ambient air pollution caused the premature deaths of > 400,000 Chinese in 2013



- **The current tendency is still to increase usage of fossil fuel: what is the way out?**

Innovation

- Innovation requires both fundamental research and systematic R&D
- There is in principle no lack of funding (only perhaps a lack of vision)
- According to Bloomberg New Energy Finance, between 2005 and 2013 Europe spent **€600 billion on renewable energies**

Global Trends in Renewable Energy Investment 2015

Renewables Re-energized: Green Energy Investments Worldwide Surge 17% to $270 Billion in 2014

According to UNEP's 9th "Global Trends in Renewable Energy Investment 2015", prepared by the Frankfurt School-UNEP Collaborating Centre for Climate & Sustainable Energy Finance and Bloomberg New Energy Finance, the United Nations Environment Programme (UNEP) and Bloomberg New Energy Finance — the past year brought a rebound of green energy investments worldwide with a surge of a solid 17% to $270 Billion. Brushing aside the challenge of sharply lower crude oil prices this sudden increase revereseed the investment dip of the past two years and was mainly driven by investments in solar and wind energy.

MYRRHA ~ 1 billion €, only partially funded

Other potential sources of energy obviously do not receive such colossal investments

iThEC

- Innovation is precisely what iThEC is about **"Promote innovation, more specifically, in the development of thorium technologies"**
  - **September 2012**: creation of iThEC in Geneva Switzerland
  - **October 2013**: Organization of the ThEC13 conference at CERN, in Geneva Switzerland
  - **Spring 2015**: MoU signed with IBeL (industrial partner)
  - **October 2015**: A first concrete step towards the exploitation of thorium – **see later**

ThEC13 at CERN

- iThEC organized ThEC13
  - http://indico.cern.ch/event/thec13 (slides & videos)
- The main world actors were all represented (32 countries)
- ThEC15 well on the way to another great success!

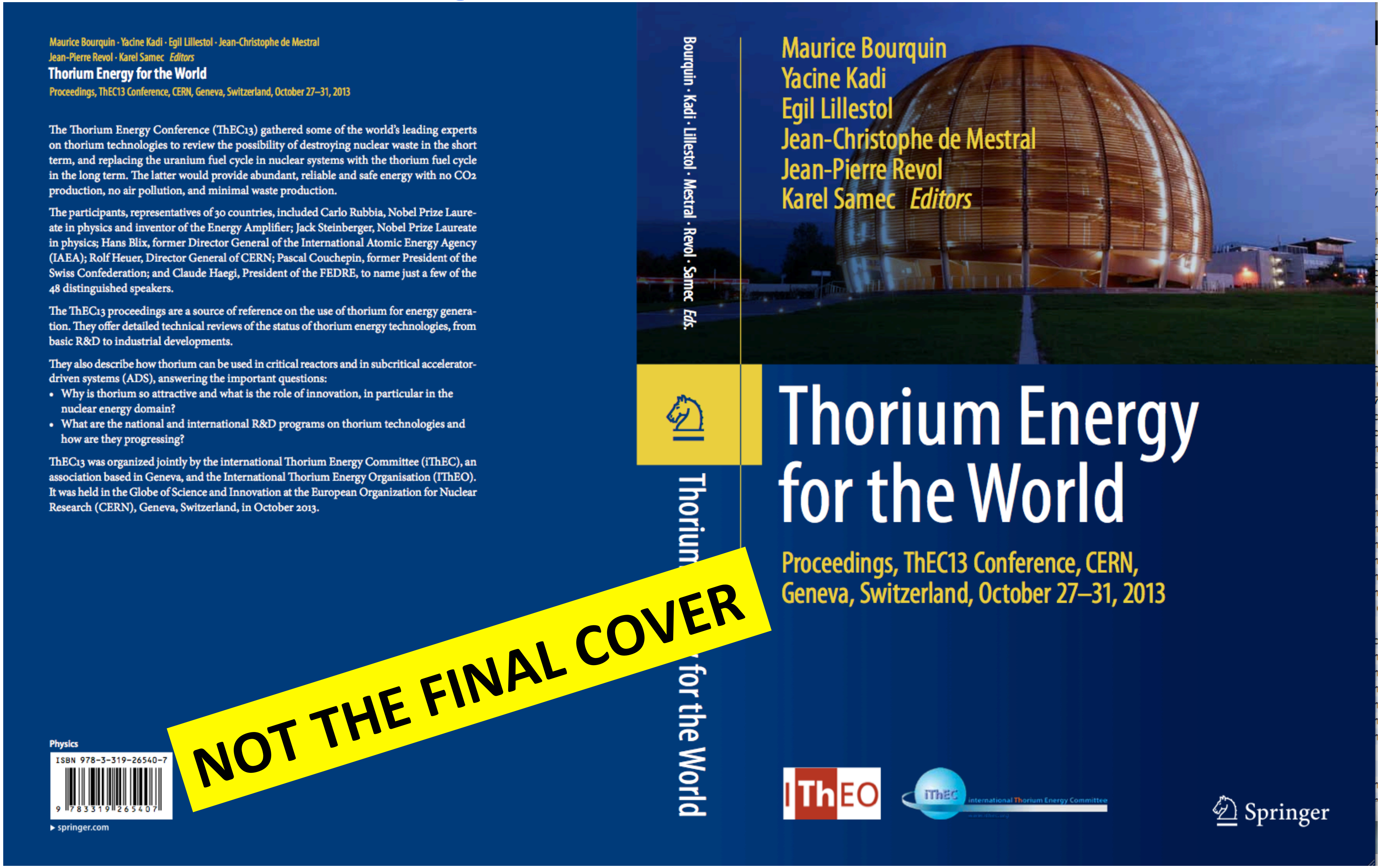
CERN DG

Claude Haegi (President of FEDRE)*
Hans Blix (ex DG of IAEA)

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

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

The next publication on thorium



Why thorium ($^{232}Th_{90}$)?

- *"Thorium is a sustainable source of energy on a human time scale"*

Carlo Rubbia

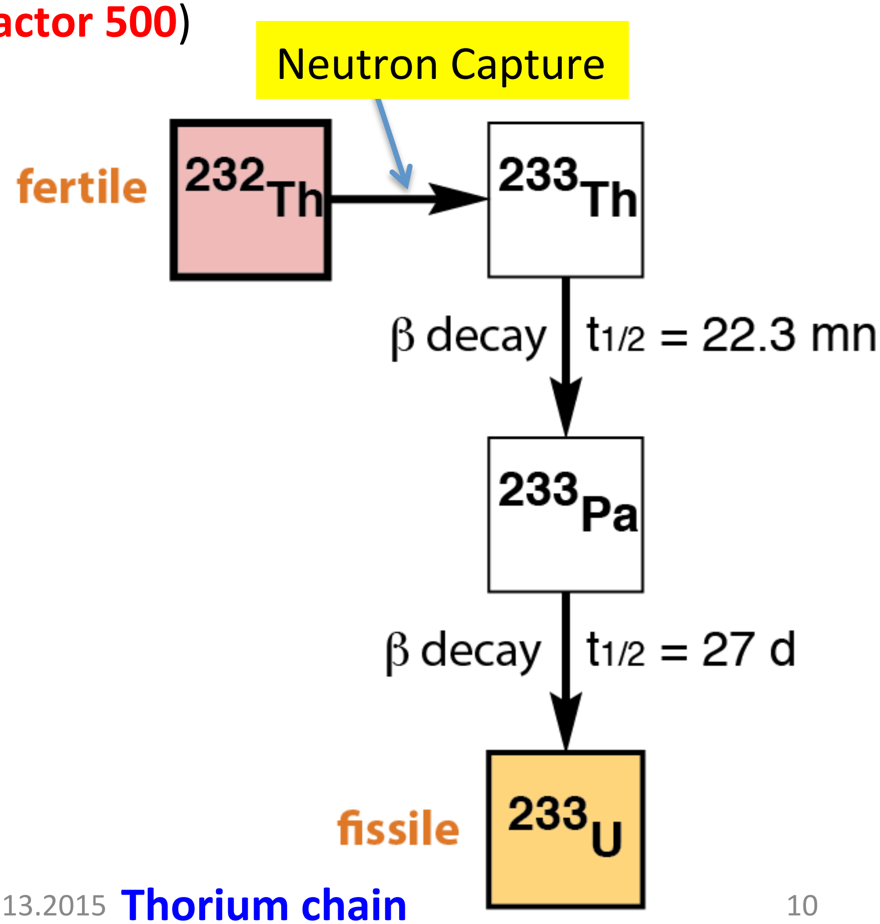
Monazite sample containing 2 to 3% of thorium mixed with rare earths (from the Steenkamp-skraal mine, South Africa – Trevor Blench)

Uranium may also be used in breeding mode, however:

– 4 times smaller supply
– much more waste production
– much more proliferating
– much more dangerous if with sodium-cooled fast breeders

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
- The fact that most of the thorium is used gives a factor 140 gain compared to ^{235}U in PWRs (with the factor 3 to 4 in abundance, **overall factor 500**)



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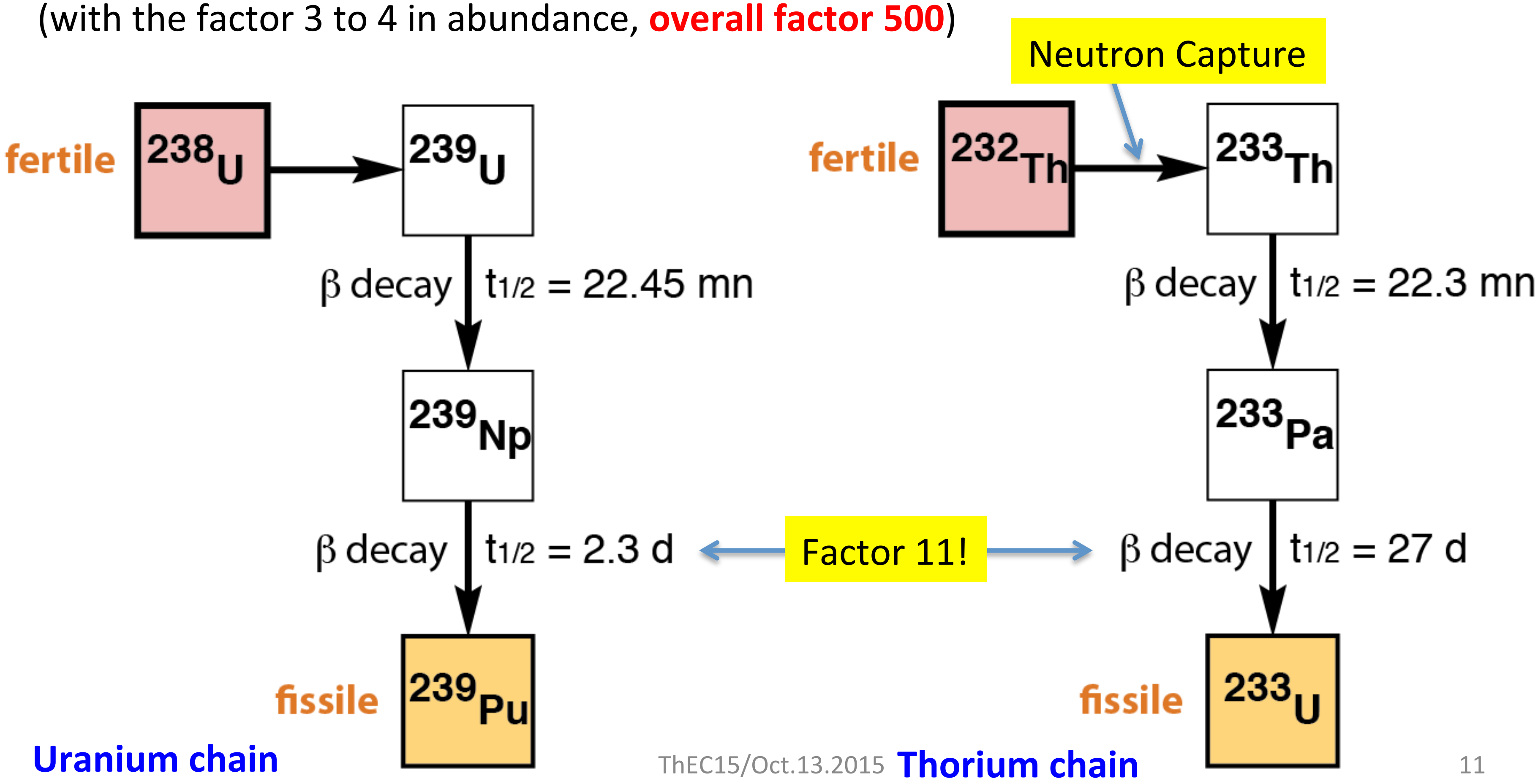
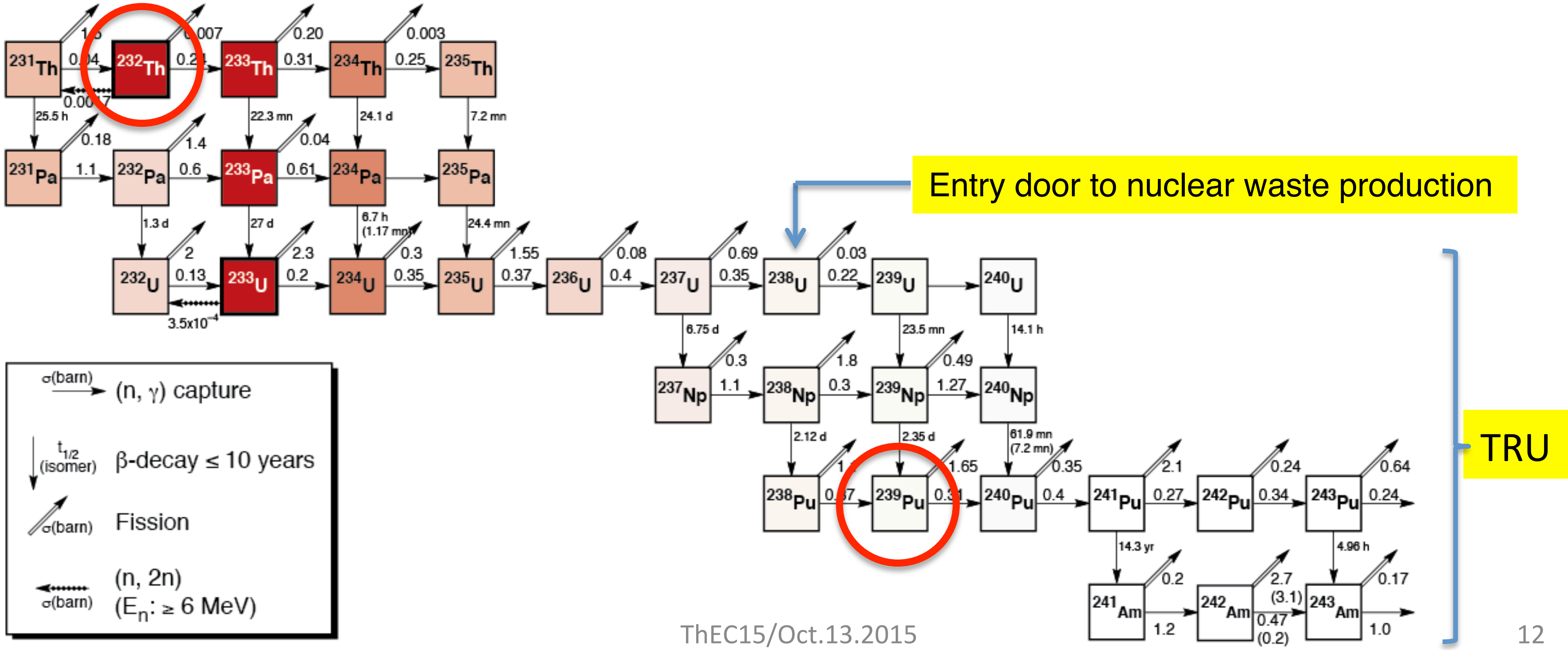


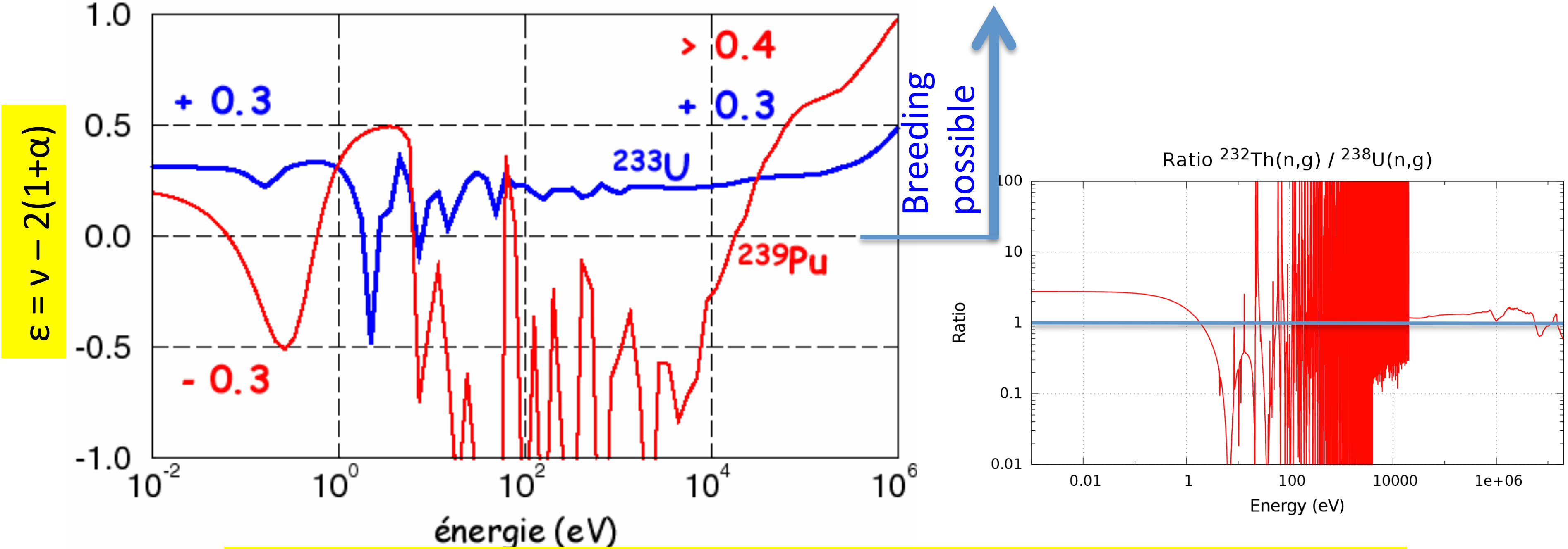
Destroying nuclear waste with $^{232}Th_{90}$

- Thorium minimizes nuclear waste production, as it is 7 neutron captures away from ^{239}Pu
- **For the same reason, it an be used to destroy nuclear waste**
- With **efficient recycling** and a **fast neutron flux**, one can make the TRU inventory as small as wanted



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

- **Breeding potential**: For most of the neutron spectrum ^{233}U is better than ^{239}Pu, However, not for fast neutrons



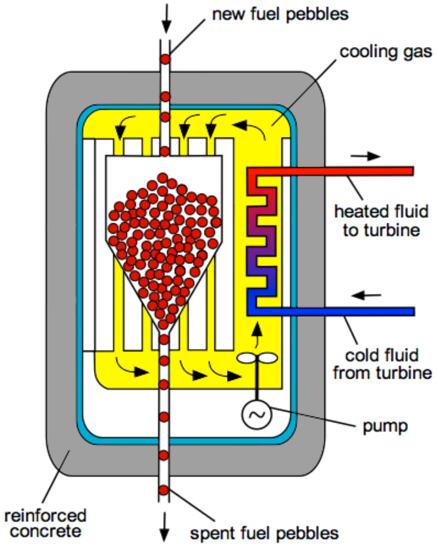
ε = Average number of neutrons in excess of the 2 neutrons needed to run the fission chain

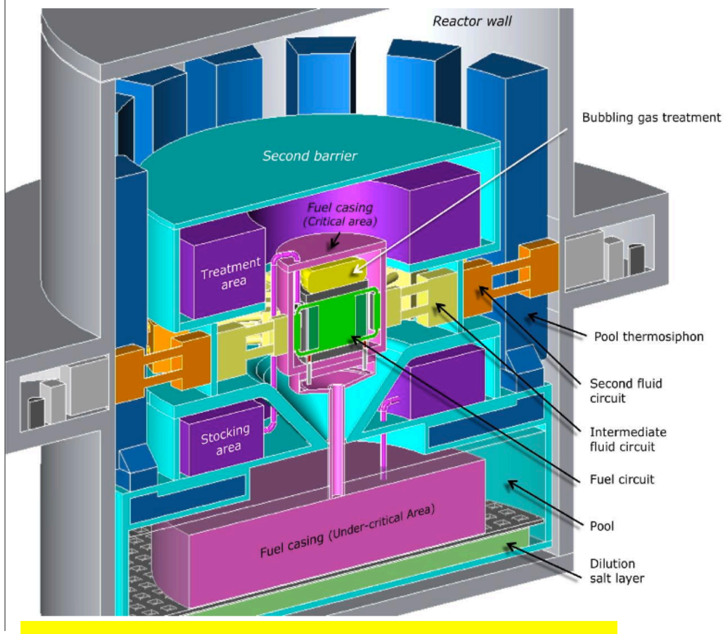
- As thorium has a higher capture cross section than ^{238}U, and it takes much longer to breed the fuel (^{233}U) because of the long half-life of ^{233}Pa), **one cannot simply replace ^{238}U by ^{232}Th in current reactors.**

How to use thorium in practice?

- **Thorium blankets around fast critical reactors to breed ^{233}U**: the Indian approach, most advanced, complicated but it should work
- **Continuously circulating fuel to always have fresh fuel in the core**
  Pebble bed or molten salt critical reactors (MSR)

Pebble-bed Reactor scheme



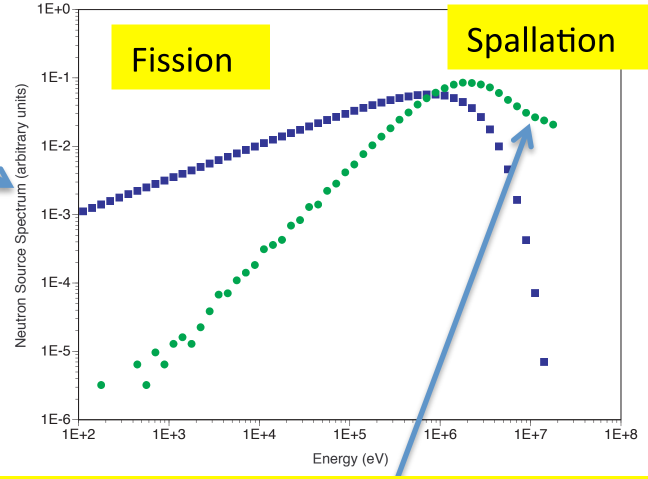


Molten Salt Reactor scheme

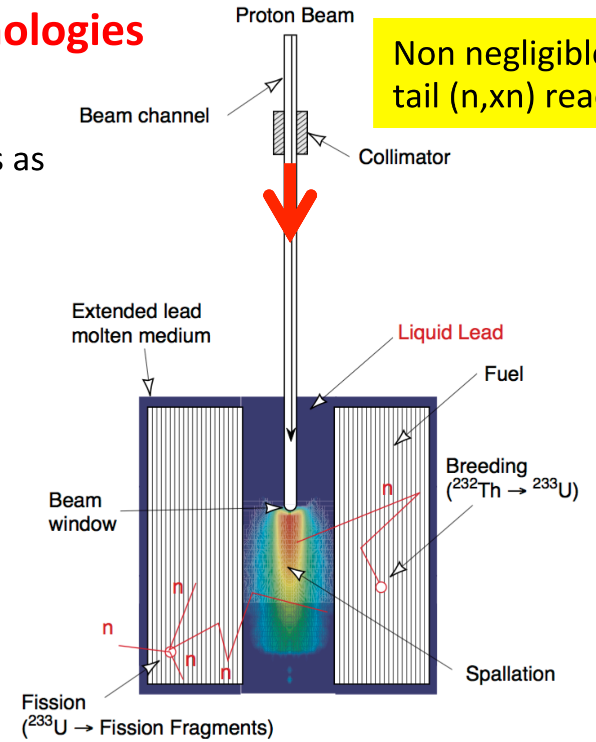
- **Provide extra neutrons with an accelerator: Accelerator-Driven Systems (ADS)**

ADS: iThEC's choice

- A particle **accelerator** to provide a **neutron source through spallation** (Pb, Pb-Bi, U targets)
- A **core** in which both source neutrons and fission neutrons are at work – with a **moderator least moderating** to allow for a fast neutron spectrum
- **Combine with passive processes for heat removal and for safety**
- **Mostly rearranging existing technologies**
- **Can fit in various scenarios:**
  - In combination with U-Pu fast reactors as a dedicated burner of Minor Actinides
  - As a ^{233}U breeder burning TRU

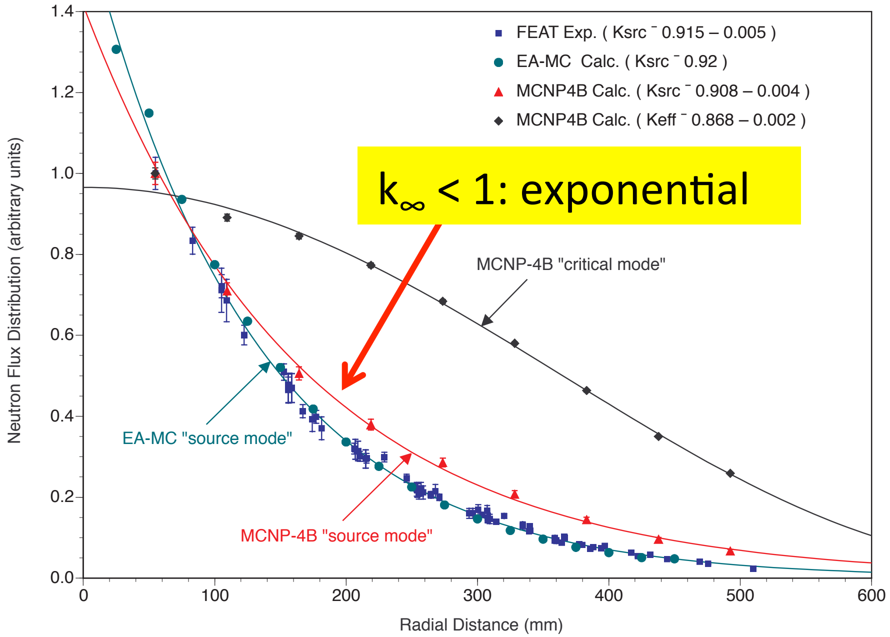


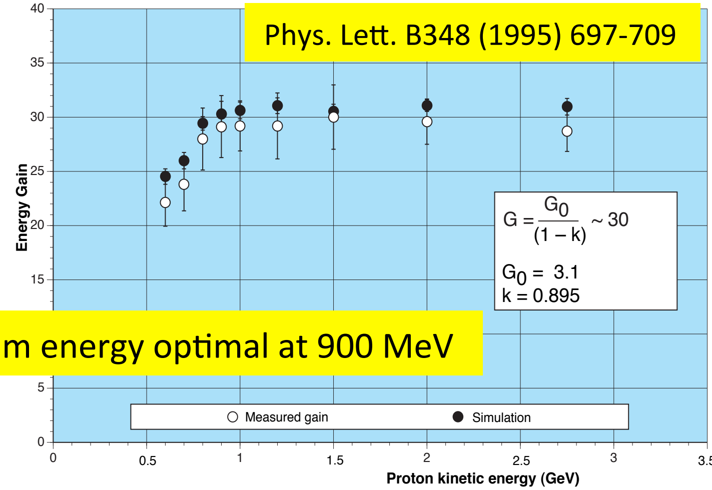
Non negligible contribution from the high energy tail (n,xn) reactions on Pb.

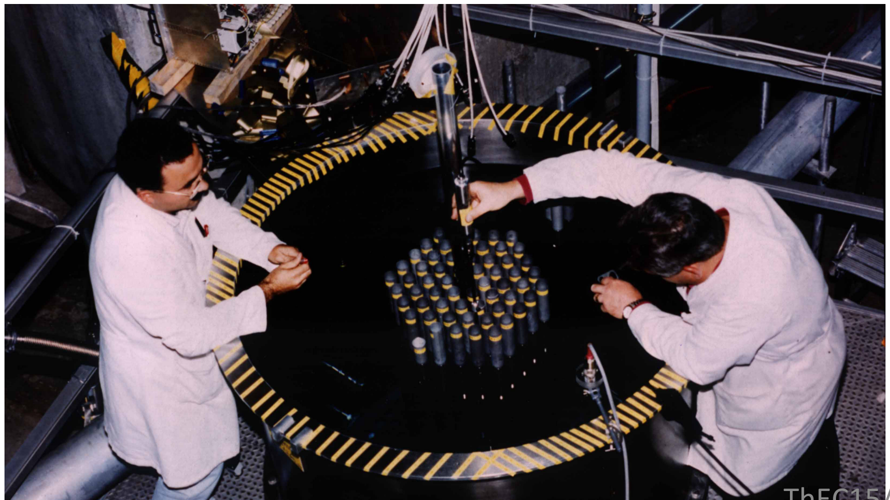


– In addition, the accelerator allows to modulate the power (complementarity with renewable energies)

FEAT and TARC experiments at CERN



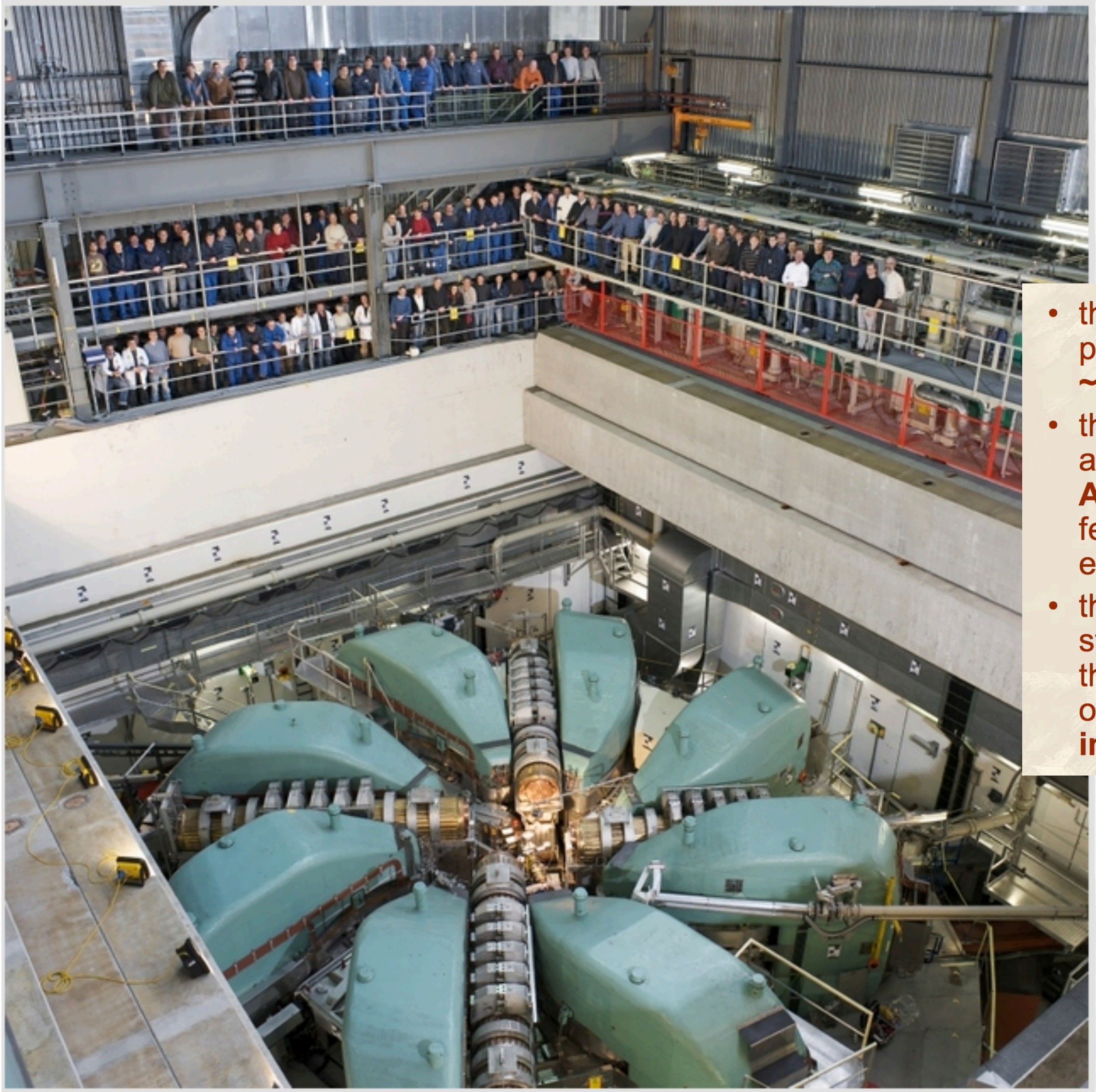




3.62 t of natural uranium at CERN PS; k_{eff} ~ 0.9

Nucl. Instr. Methods Phys. Res., A478 (2002) 577-730

The PSI Cyclotron



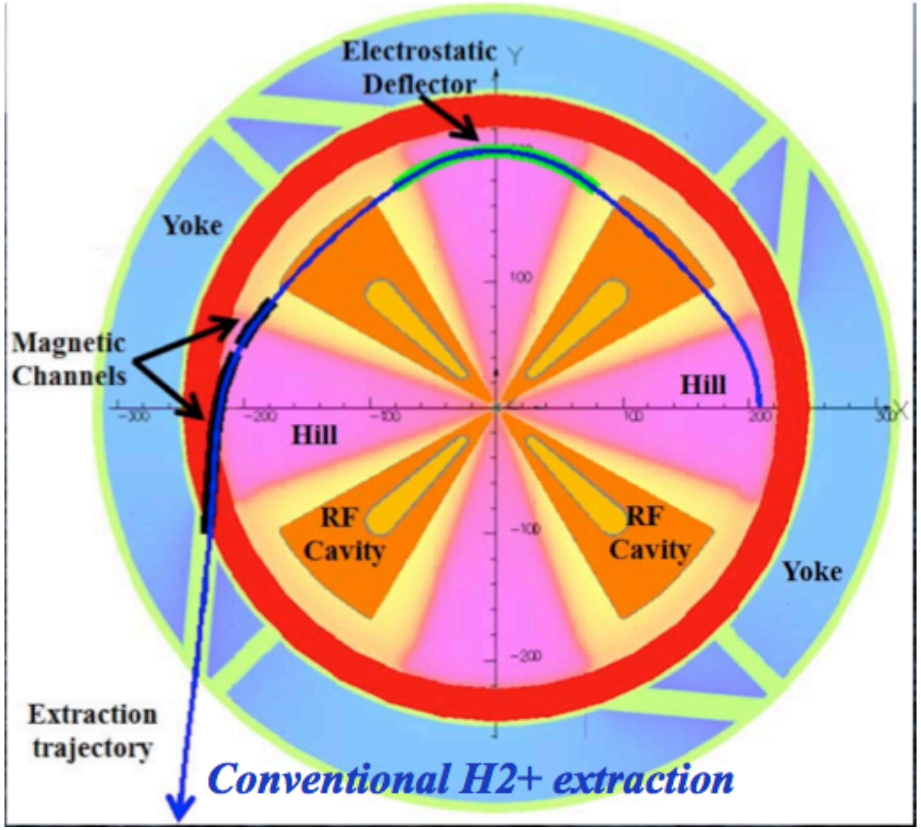
- the PSI accelerator delivers at max. **1.3MW** beam power in CW mode; average reliability is **90-94%**; **~25 trips** per day (2008)
- the cyclotron concept presents an effective alternative **to generate a high power beam for ADS** applications; **1GeV/10MW cyclotron** seems feasible in next step; fundamental limit at 1GeV energy – no obvious limit for power
- the reliability statistics at PSI is o.k. for today's standards but still **3 orders of magnitude below** the claimed requirements for ADS → development of **failure tolerant systems**, but also **improvements on the reactor side desirable!**

1.3MW@0.59GeV, 94% reliability

Mike Seidel

Next generation of cyclotrons

Separate turn Cyclotron



H_2^+ Cyclotron with reverse bend and multiple (3) injections, 1.6 MW at 800 MeV should bring the number of trips within the ADS requirement

At the same time progress on core configuration should make it more tolerant to trips

P. Mandrillon (AIMA)

MEGAPIE TARGET

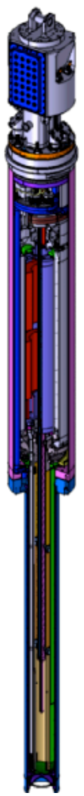
Heat Exchanger (Oil)
10 i/s, 5.5 m/s
140-175°C inside

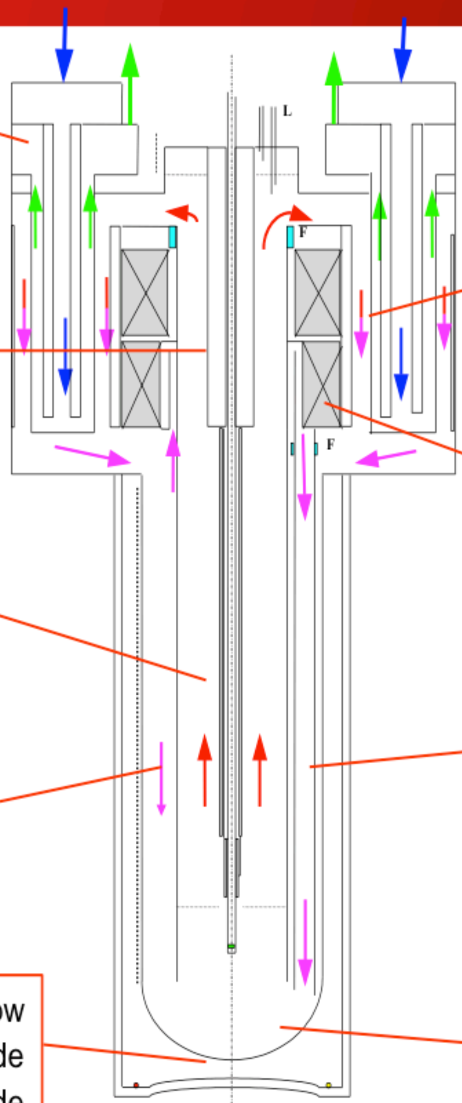
Main Pump
4 l/s, 1.2 m/s
380°C

Guide Tube
4 l/s, 0.33 m/s
380°C

Downcomer
3.75 l/s, 0.33 m/s
230-240°C

Beam Window
380°C outside
330°C inside





Heat Exchanger
4 l/s, 0.33 l/s/pin
0.46 m/s
380-230°C inside

Bypass Pump
0.25 l/s, 0.2 m/s
230°C

Bypass Tube
0.25 l/s, 1m/s
230-240°C

Nozzle 1.2 m/s
Beam Window 1 m/s

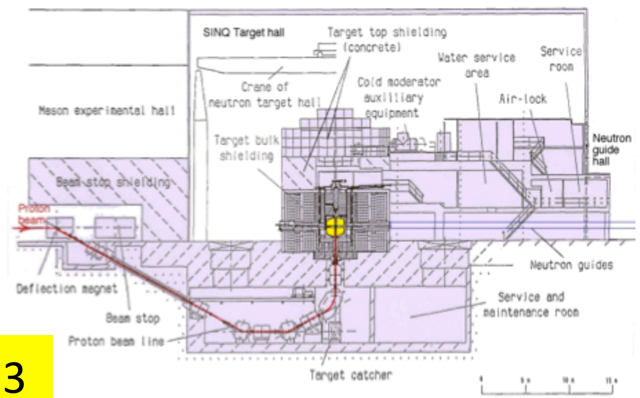
Design parameters

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



Ch. Latge (CEA) France @ ThEC13

High Level Baseline Parameters for the SNS

Proton beam energy on target	**1.0**	**GeV**
Proton beam current on target	**1.4**	**mA**
Power on target	**1.4**	**MW**
Pulse repetition rate	60	Hz
Beam macropulse duty factor	6.0	%
Ave. current in macro-pulse	26	mA
H^- peak current front end	38	mA
Chopper beam-on duty factor	68	%
RFQ output energy	2.5	MeV
FE + Linac length	335	m
DTL output energy	87	MeV
CCL output energy	185	MeV

SC linac output energy	1.0	GeV
HEBT length	170	m
Accumulator ring circ.	248	m
Ring fill time	1.0	ms
Ring beam extraction gap	250	ns
RF systems	h=1 +h=2	
RTBT length	150	m
Protons per pulse on target	1.5×10^{14}	
Proton pulse width on target	695	ns
Target material	Hg	

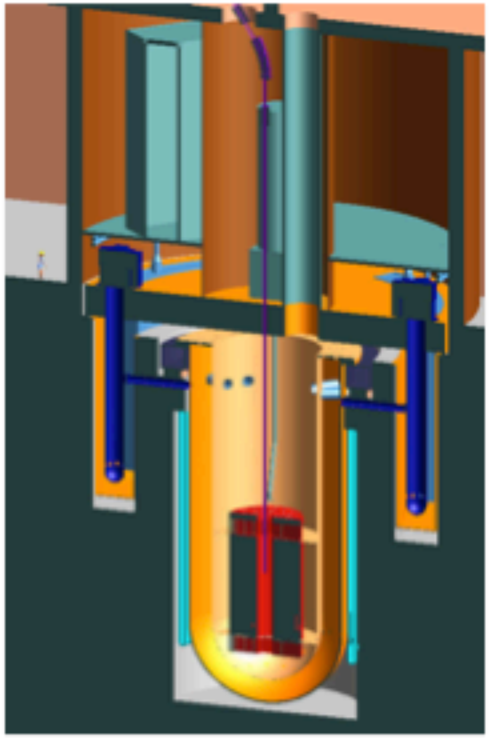
Industrialized ADS

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

AkerSolutions

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

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



A Thorium fuelled reactor for power generation

Jacobs Engineering Group Inc.

Carlo Rubbia

CERN_Oct_2013

Simplified reprocessing (U & Pu by fluorination)

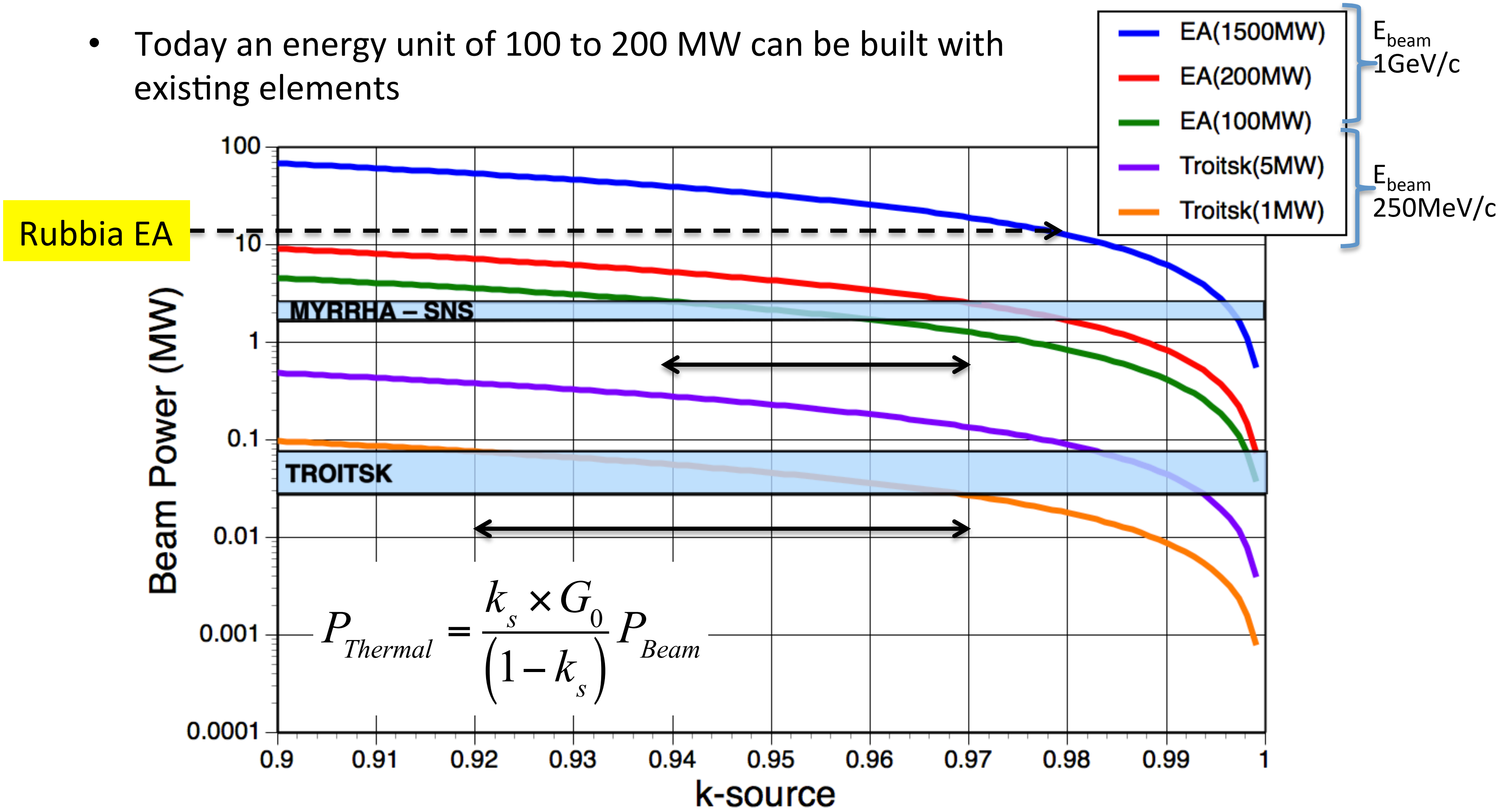
lide# : 23

ADS demo projects

Project	Neutron Source	Core	Purpose
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 2.75 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 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, $\sim 10^{12}$n/s)	Fast (< 1 kW)	Coupling of fast subcritical system with spallation source including MA fuelled configuration - **postponed**
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 - **postponed**
MYRRHA (Belgium)	Proton (600 MeV) + Pb-Bi (1.8 MW)	Fast (60 MW)	Experimental ADS – **under design**
CADS (China)	Protons (0.6 – 1.5 GeV)	Fast (100–>1000MW)	**Four phase project: 2011 – 2031**
U-ADS (Ukraine)	Electrons	200 kW	Uranium-based ADS prototype (KIPT)
ADS (Russia)	Protons (250-500 MeV)	1-5 MW	**Using an existing facility at Troitsk**

What can be done today?

- Today an energy unit of 100 to 200 MW can be built with existing elements

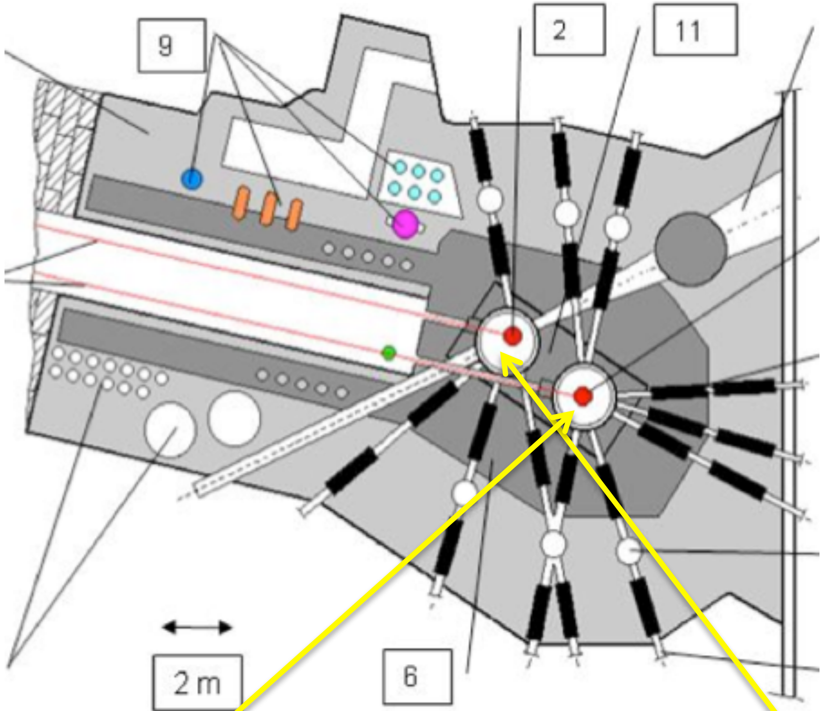


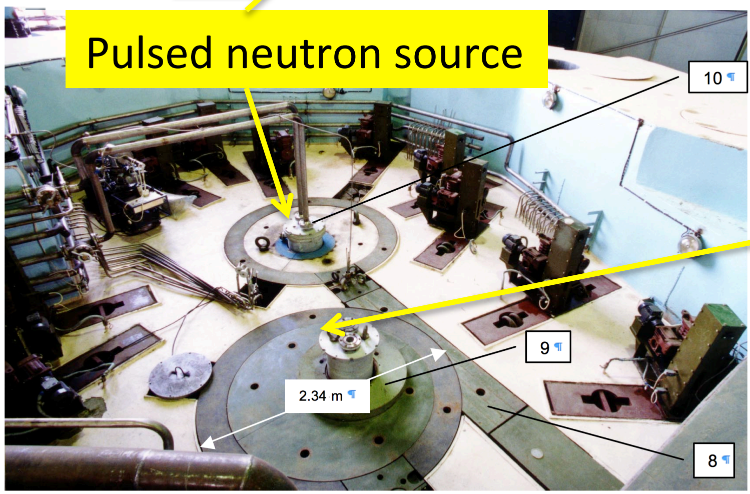
The Troitsk ADS demonstrator

- **A demonstrator of significant power is a necessary step**
- **Strategy: Building on an existing facility at Troitsk**
  - The accelerator exists but needs to be refurbished (250-300 MeV perhaps 550 MeV, 25 to 75kW of beam power (a few MW of thermal power)
  - The spallation source exists (pulse source in operation)
  - There is a design of the core which needs to be optimized
- A cost estimate puts the project at 5% of the cost of MYRRHA
- The project can be completed in 5 years

The LINAC

The target area

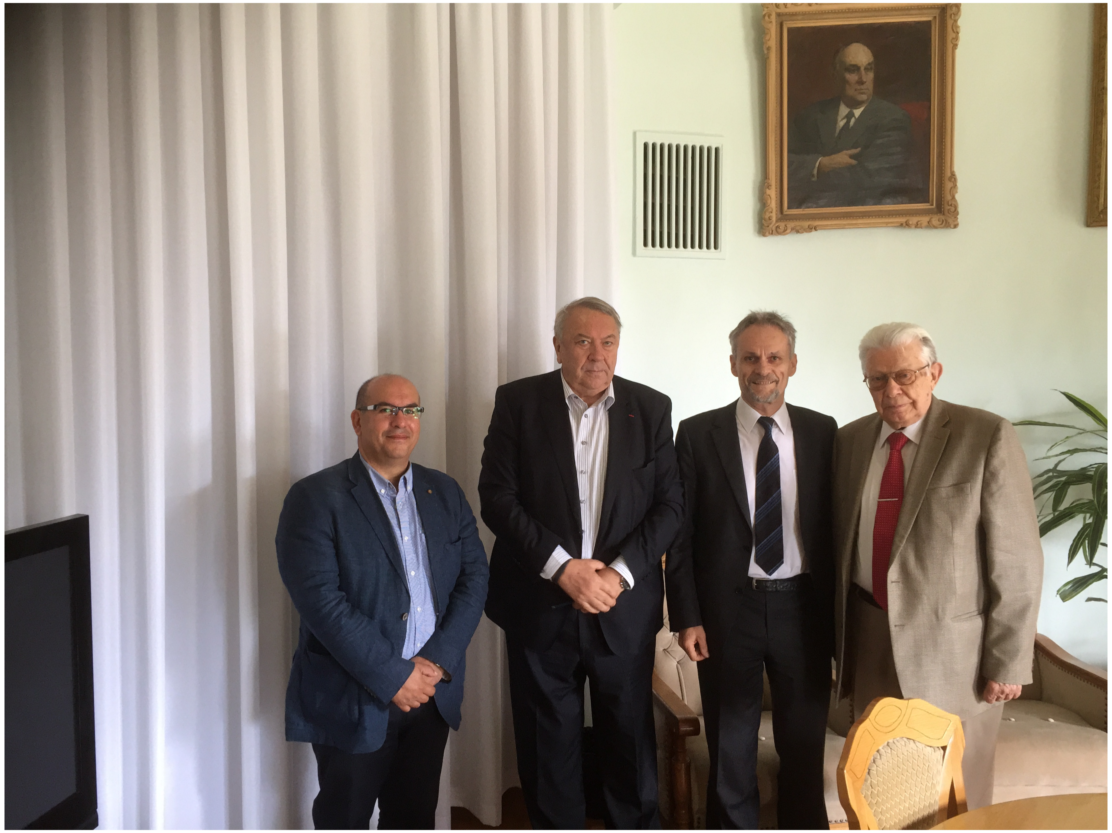




Pulsed neutron source

ADS experimental cell

iThEC's strategy



**Yacine Kadi, Vladimir E. Fortov (President of RAS),
Jean-Pierre Revol (President of iThEC),
Boris F. Myasoedov (In charge of Thorium at RAS)**

Evaluation of the Troitsk facility in Russia (done)

Discussions with partners in Russia:
– Troitsk management
– Russian Academy of Sciences
– ROSATOM

MoU signed with IBeL, an industrial partner, with international connections

Decision by iThEC last week to start a feasibility study, and at the same time form an international collaboration

iThEC international Thorium Energy Committee
www.ithec.org

CONCLUSION

- **Thorium should play a major role in future energy production** because it is a sustainable energy source on a human time scale
- ADS with a fast neutron flux is a most efficient way of using thorium that can complement other nuclear scenarios
- With existing accelerator and neutron spallation source technologies, it is already possible to build modular energy sources of order 100 to 200 MW
- iThEC has decided to invest in a feasibility study for Troitsk: a first demonstrator of significant thermal power, **faster and cheaper than current projects**
- The community is welcome to join a collaboration that should be put together in the next months

RESERVE

Table of contents

A fossil fuel free economy?

- Achieving a fossil fuel free economy is a tremendous challenge, **the first global challenge for humankind**.
- **Solutions can only come from innovation**.
- Nowadays, countries such as China and India seem to have a better understanding of the global situation than the western world – they are more active developing new ways to exploit nuclear energy.
- Innovation implies vigorous and systematic R&D in the energy domain, without prejudice, and **thorium represents clearly one of the most promising new options. It requires appropriate funding.**

Theory of subcritical systems

- **Theory of subcritical systems** well known. Properties are quite different from those of critical systems (*C. Rubbia, CERN/AT/ET/Internal Note 94-036*)
- MC simulations are needed for quantitive properties. Neutron flux geometry important to determine the generated power distribution and the uniformity of fuel burnup
- Analytical approach interesting to get insight into the physics. The basic equation similar to that of a critical reactor, but **with an external neutron source term in addition,** and obtain the qualitative properties of the system:

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

Fission — **Source** — Absorption — Leakage

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

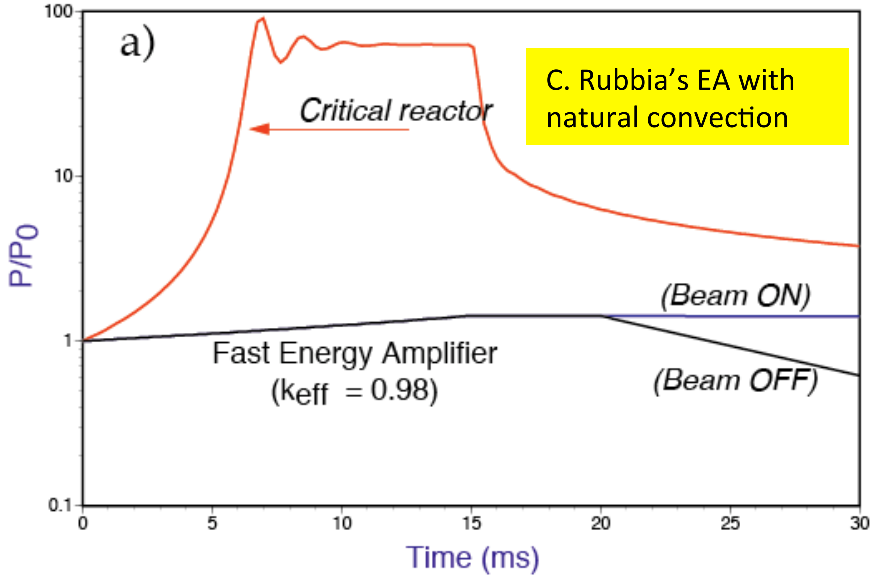
Switching off the neutron source not only stops the main power generation, but also moves the system further away from prompt criticality, k_s to k_{eff}.

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!

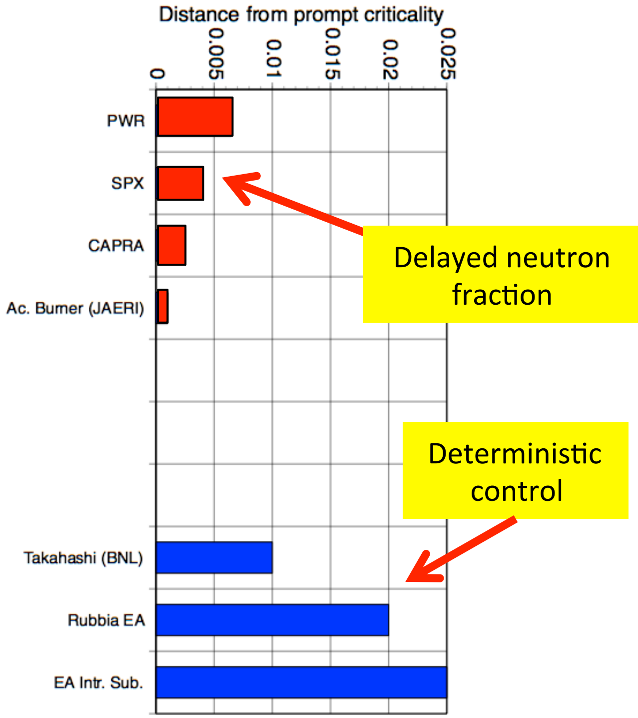
- The reactivity changes only very slowly; the beam can be switched off very quickly, reducing k_s to k_{eff}. It is possible to choose a higher k_s in order to reduce the load on the accelerator (Takahashi at BNL, k_s = 0.99)

Comparative response to reactivity insertion



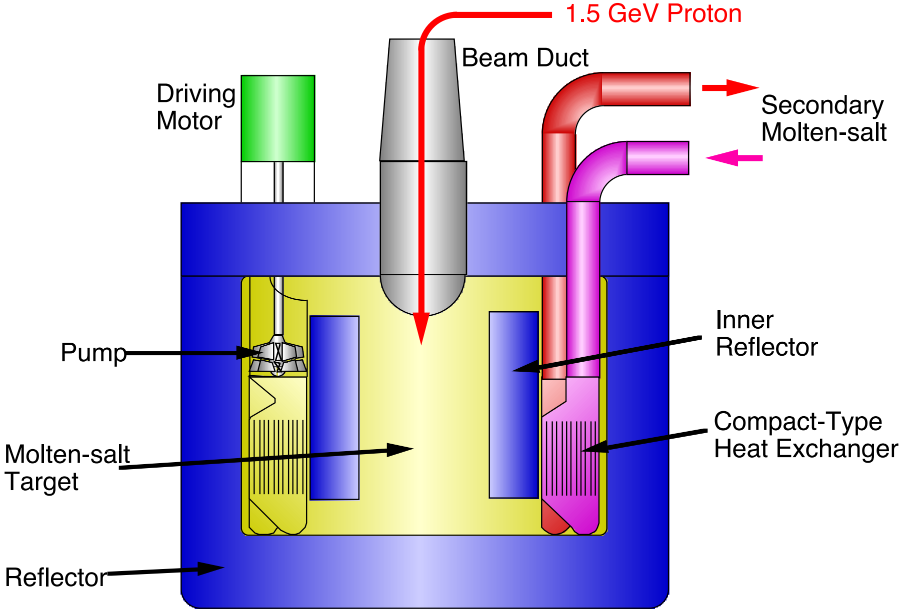
There is enough time for the natural convection to adapt

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.



Other ADS concepts

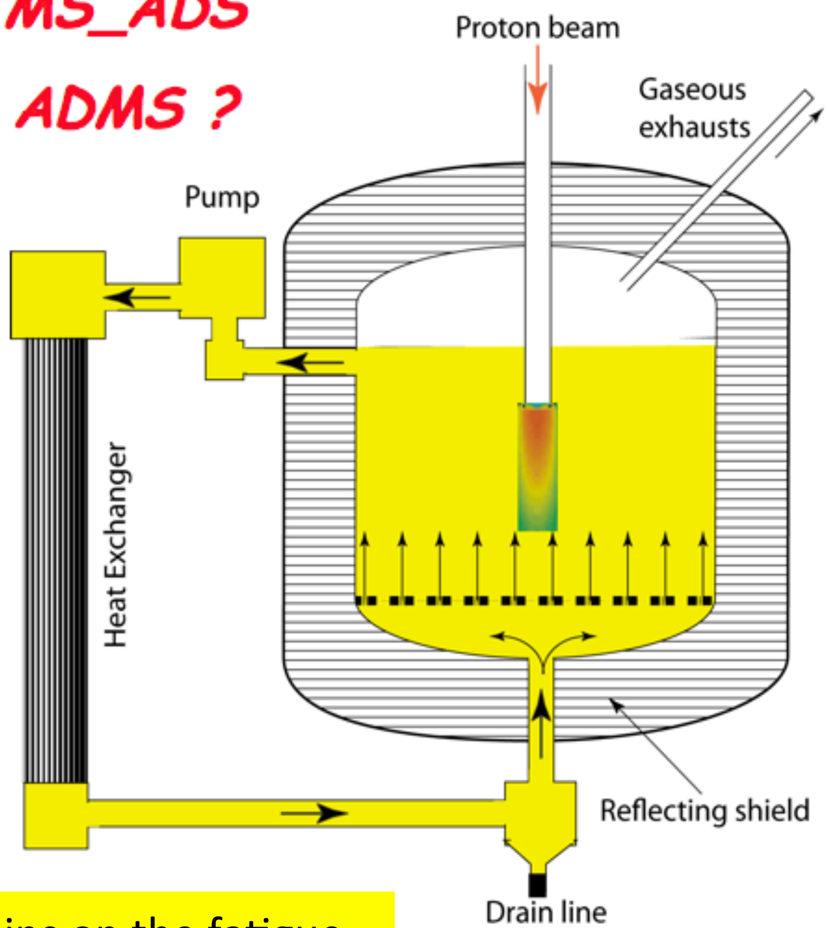
- Several **Molten Salt ADS concepts** are being studied: Carlo Rubbia, Toshinobu Sasa and Laszlo Sajo-Bohus, presented such possibilities at ThEC13.



Toshinobu Sasa

MS_ADS

ADMS ?



This relaxes the constrains on the fatigue induced in the fuel structure by the accelerator trips

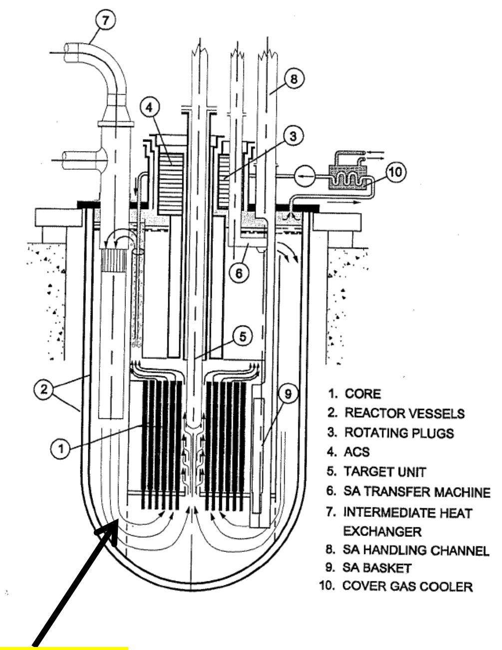
Carlo Rubbia

ADS demonstrator

- **The next step for ADS must be a demonstrator of significant power** (≥ 1 MW minimum to study the behaviour of an industrial system).
- What must be achieved with a system of a few MW:
  - Demonstrate ADS at a substantial power (≥ 1 MW thermal) the coupling of an accelerator with a subcritical core;
  - Learn how to operate an ADS of substantial power, in particular define and demonstrate the safety features for a future industrial prototype;
  - Demonstrate the destruction of Minor Actinides;
  - Prepare the design of a prototype of an energy producing unit of industrial power (a few hundred MW).
- **All this can be achieved with the Troitsk project** presented by Stanislav Sidorkin at ThEC13

This the project that iThEC decided to support

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



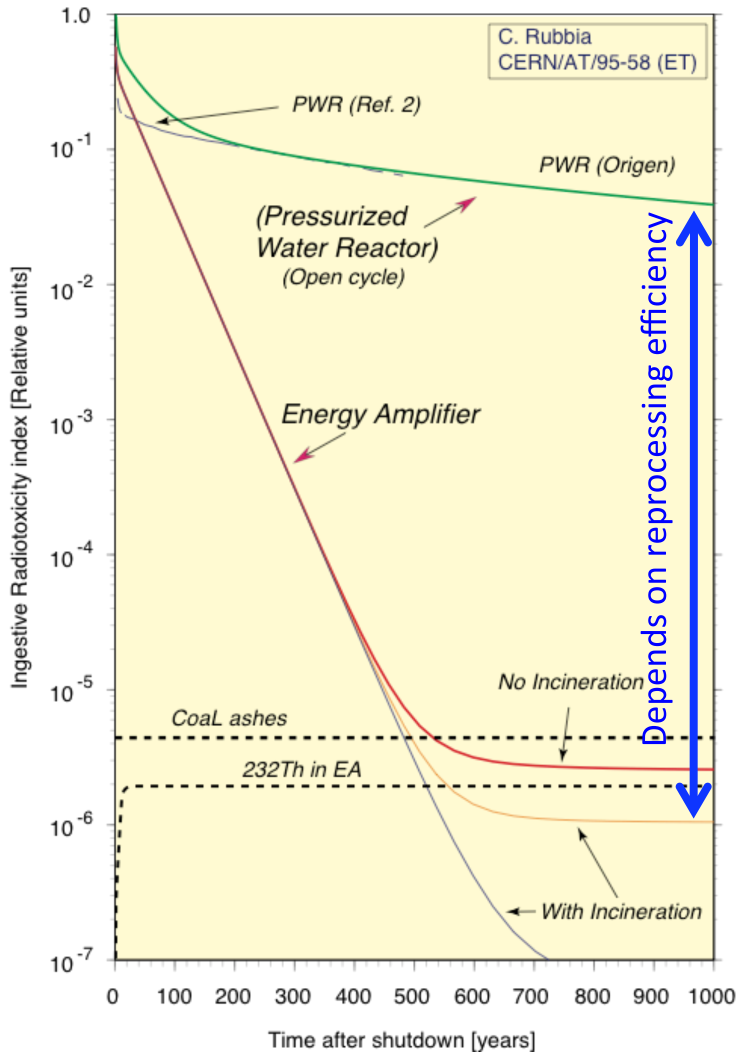
Transmutation performance of ADS

- **C. Rubbia's EA can destroy** 36 kg of TRU/TW_{th}.h (A PWR **produces** 14 kg of TRU/TW_{th}.h)

- Calculations of specific transmutation rates (Y. Kadi)

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

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



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