

Energy Efficiency and Proton Drivers for ADS



iThEC

INTERNATIONAL THORIUM ENERGY COMMITTEE

Proton Driver Efficiency Workshop
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February 29, 2016

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Accelerators for America's Future



*"Next-generation particle beams represent cheaper, greener alternatives to traditional industrial processes. They can give **us clean energy through safer nuclear power, with far less waste.** They can clean up polluted air and water; deliver targeted cancer treatment with minimal side effects; and contribute to the development of new materials. As tools for inspecting cargo and improving the monitoring of test ban compliance, accelerators can strengthen the nation's security."*

Accelerators for America's Future, DOE Workshop, Washington DC, June 2010

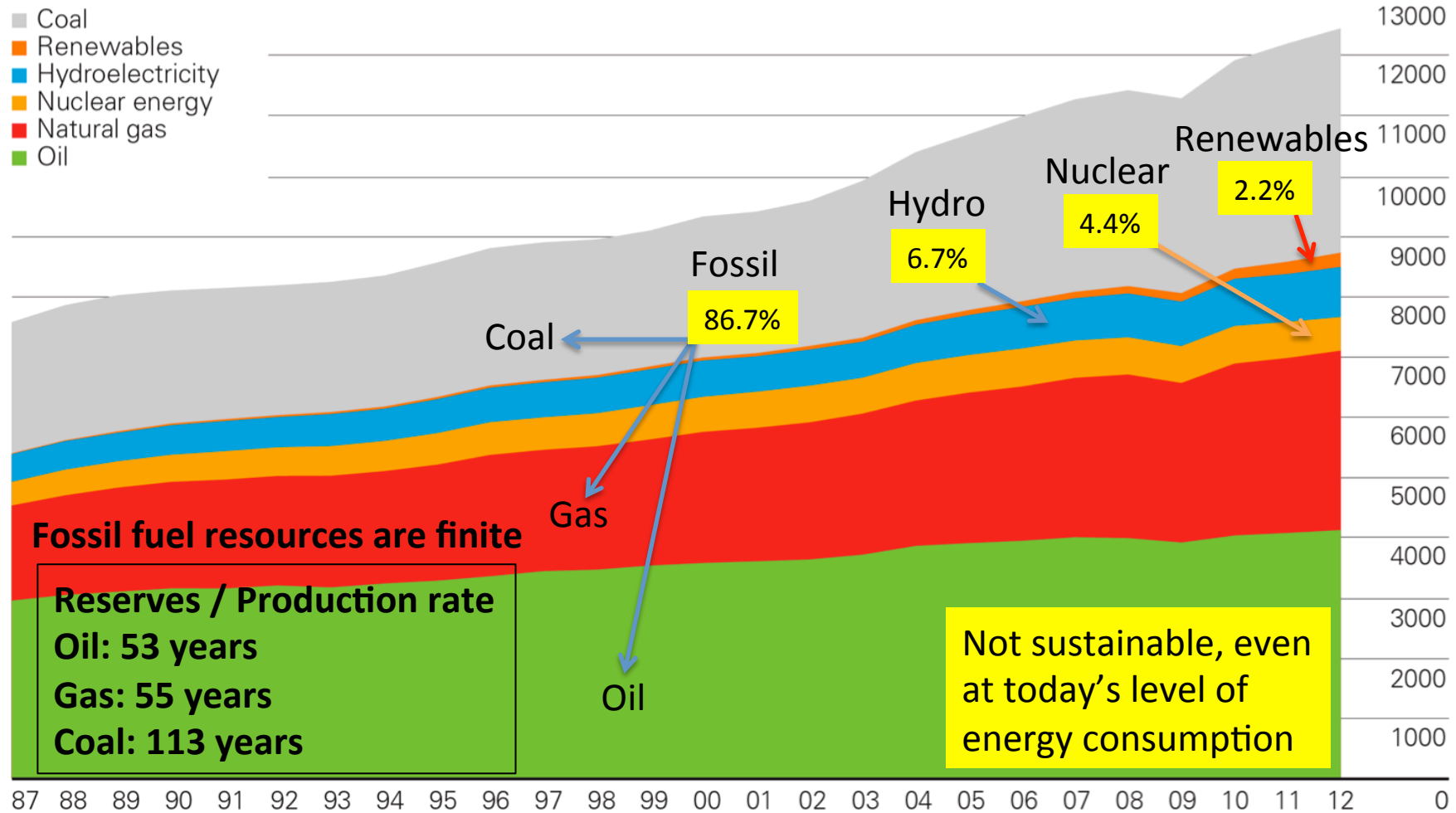
Is high-power accelerator technology ready for industrial application?

Primary energy world consumption

Million tonnes oil equivalent

BP Statistical review of World Energy 2014

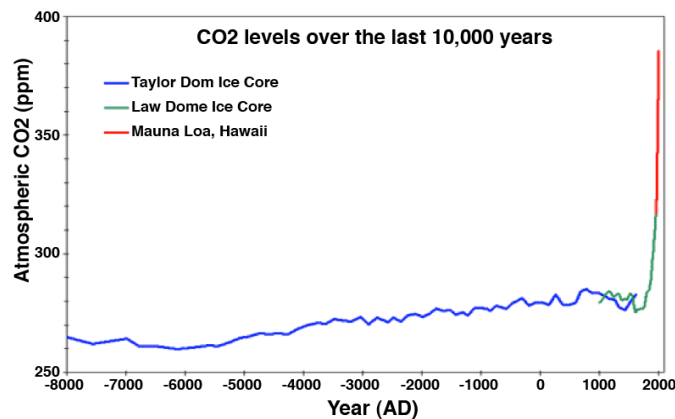
Today, the world behaves as a 15 TW engine ($\approx 2\text{kW/capita}$) +2%/year on average, totally dominated by fossil fuels



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

Burning fossil fuel till the end?

- ❑ **Global warming** Atmospheric CO₂ level higher than ever in the past 15 million years, increasing faster than ever before, with most likely disastrous consequences (IPCC reports)
- ❑ **Air pollution**
 - Burning coal costs Europe alone 40 billion Euros in annual health care expenses
 - The ambient air pollution causes the premature deaths of 0.5 M Chinese annually
 - WHO: 1 in 8 of total global deaths is the result of air pollution exposure
- ❑ **Ocean water pollution** Induced by air pollution (SO₂, NO_x) and CO₂ in the atmosphere



- ❑ But the current tendency is to increase the consumption of fossil fuels! Given the finite supply, obviously this cannot continue for ever
- ❑ Europe not representative of the world. Globally, 1.1 billion people do not have electricity.

COP21: cautious optimism?

195 countries were represented in Paris, last December:

“World Leaders unanimously agree to end the fossil fuel age within a few decades”

Global Footprint Network <http://www.footprintnetwork.org>

“Under US insistence, the agreement was explicitly crafted to EXCLUDE:

1) any binding agreement to emissions reductions;

2) any binding agreement to financing of emissions reductions

3) any binding agreement to fines or penalties of any kind for failure to reduce emissions.

Only one thing was agreed to legally: writing reports every five years.”

John Clark, academic environmentalist

Politicians are stuck for political reasons and because they cannot invent solutions.

It is the responsibility of the scientist to propose new options through R&D followed by innovation

Energy R&D to provide solutions

- ❑ Innovation implies investment in both **fundamental research** and **applied research**
 - **Without fundamental research there is no innovation**, and we would not be today ...
- ❑ **Energy R&D has to be systematic, without prejudice**: Relying entirely on wind and solar energy by the end of the century implies increasing their contribution to the world energy by a factor ≥ 130 (**Not realistic**: fluctuations? storage? space? distribution? cost?)
- ❑ **R&D on nuclear fusion must be pursued but nuclear fission energy must not be left out**:
 - No air pollution: CO₂ and Chemical (SO_x, NO_x, particulate matter, etc.)
 - Abundant and base load type of electric energy production
 - Nuclear fission technology exists and is well understood
 - Breeding can make it essentially “sustainable” on the human time scale
- ❑ **Shortcomings of the PRESENT generation of uranium power plants must be eliminated**:
 - Accidents (Chernobyl, Three Mile Island, Fukushima)
 - Waste management (storage over ≤ 1 million years, the only option developed so far)
 - Proliferation of nuclear weapons (uranium $\approx$ military)
 - Sustainability (< 100 yr at present rate of uranium consumption)

Can this be achieved?

Answer: Yes with thorium!

- ❑ **ThEC13** organized at CERN by the **international Thorium Energy Committee** (iThEC: <http://www.ithec.org>) – **India and China** cited energy issues as their prime motivation



CERN DG



Claude Haegi, Hans Blix

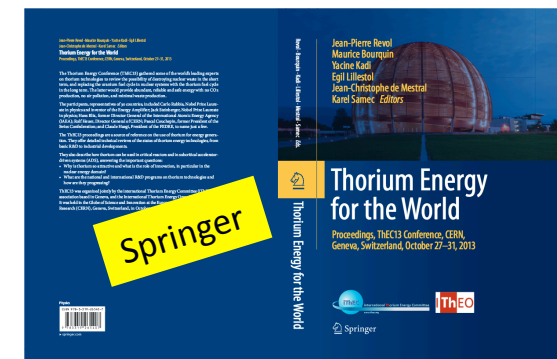


Pascal Couchepin, Carlo Rubbia

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

Luc van den Durpel, CERN, Oct. 29, 2013

- ❑ **ThEC15** organized at BARC in India last October with > 300 participants. A lot of work on thorium!
- ❑ Most developments on thorium nowadays are in India and China, why is Europe not taking the leading role?



Thorium ($^{232}\text{Th}_{90}$)

- ❑ **Natural thorium is isotopically pure**, α -decay with a half-life of 14 billion years (largest contribution to geothermal power)
- ❑ **Abundant (1.2×10^{14} tons in the Earth's crust)**, as much as lead, and three to four times more than uranium: Recovering only one part per million, that is 1.2×10^8 tons, would provide the present world power consumption of 15 TW, for 18'000 years.
"Thorium is a source of energy essentially sustainable on the human time scale"
- ❑ **Known and estimated resources $\approx 7 \times 10^6$ tons** (IAEA); probably a poor indicator because not searched for systematically (≈ 1000 years)
- ❑ Thorium occurs in several minerals including thorite (ThSiO_4), thorianite ($\text{ThO}_2 + \text{UO}_2$) and monazite (**Ce, La, Nd, Th**) PO_4 . **Often a by-product of mining for rare earths** (lanthanides + scandium and yttrium), tin, coal and uranium tailings
- ❑ **Better thermal conductivity and mechanical properties than uranium**: thorium fuel may be able to operate at considerably higher temperatures than uranium (S. Peterson et al., ORNL-TM-1144)

C. Rubbia @ ThEC13

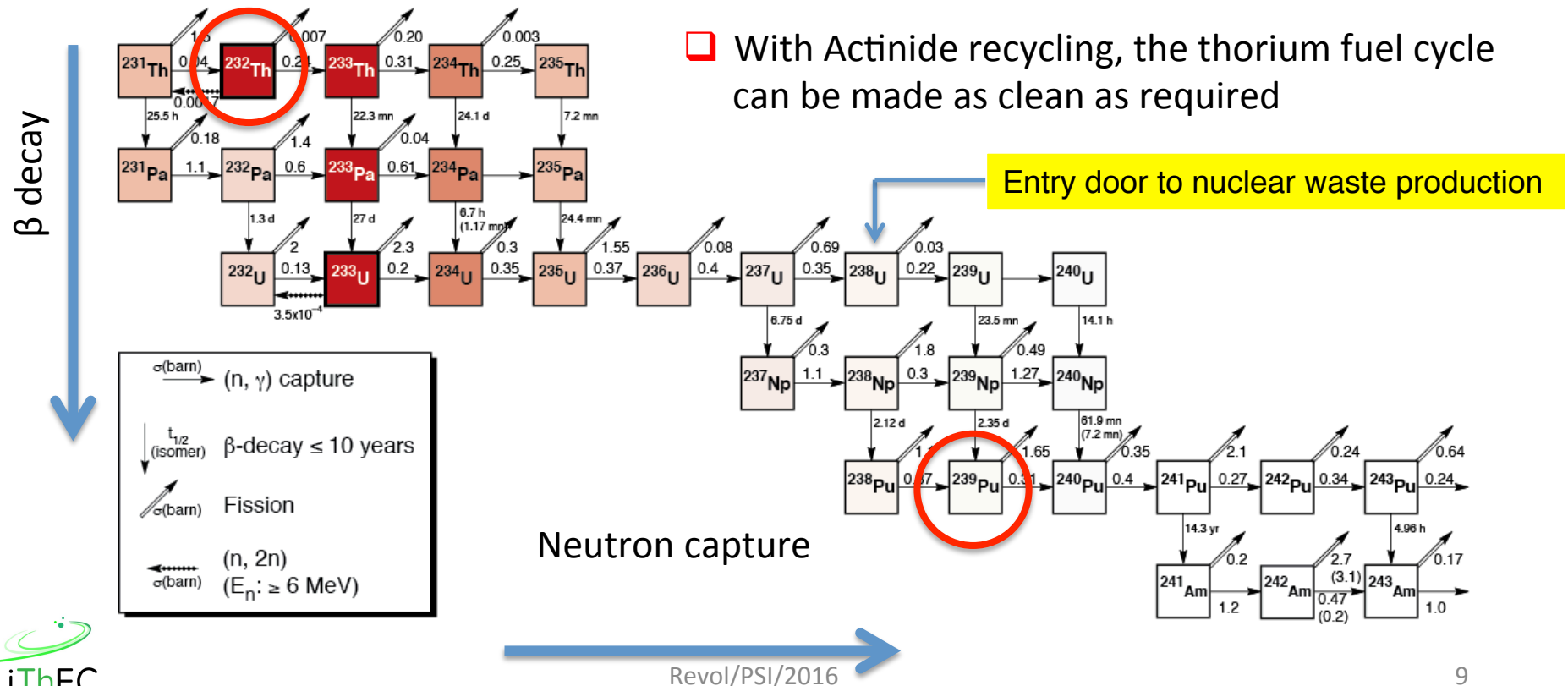


Monazite sample containing 2 to 3% of thorium mixed with rare earths (from the Steenkampskraal mine, South Africa – Trevor Blench)

- ❑ Metallic thorium has a **higher melting point** (1750°C) **than metallic uranium** (1130°C)
- ❑ Thorium dioxide (ThO_2) has the **highest melting point** (3300°C compared to 2865°C for UO_2) **of all oxides** and is one of the best refractory materials

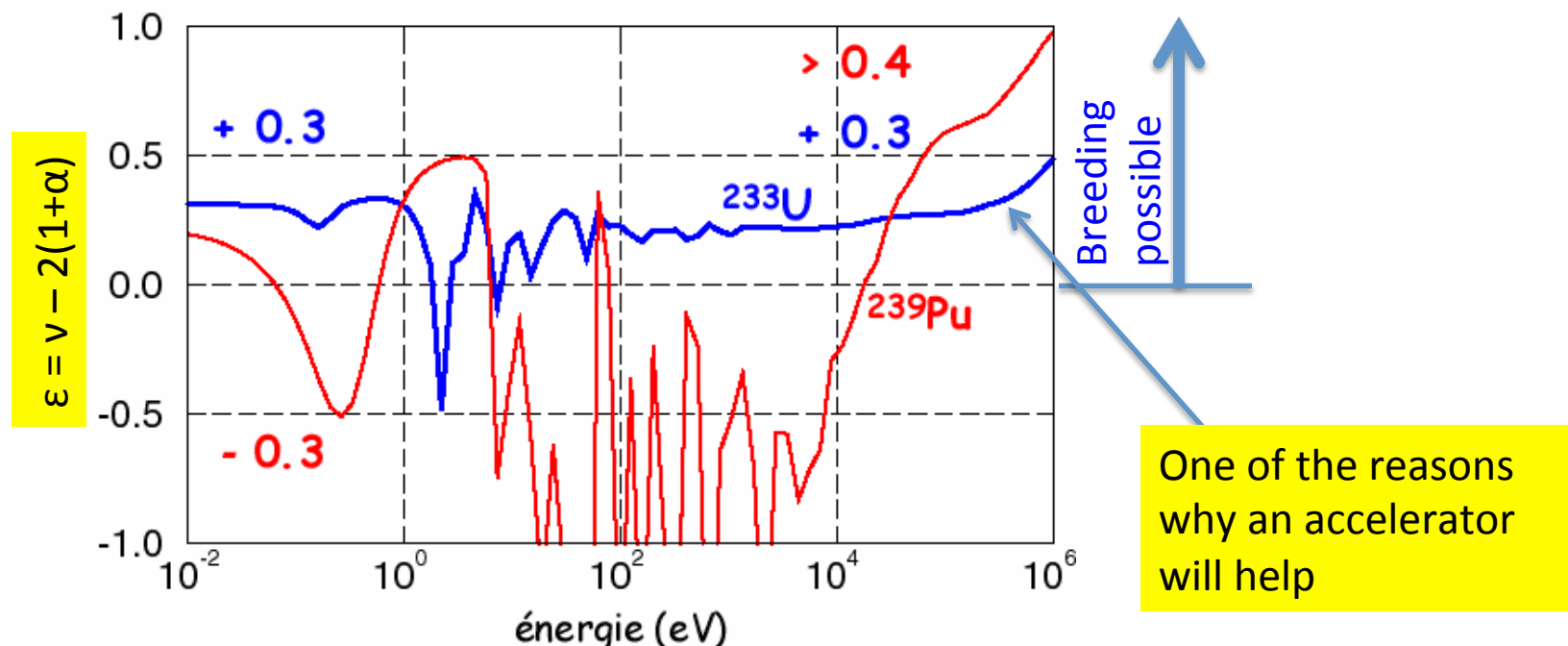
Fission energy from $^{232}\text{Th}_{90}$

- ❑ Thorium is **fertile**, not fissile, so it can **ONLY** be used in breeding mode, to produce ^{233}U , which is fissile. However, this gives a potential factor 140 gain compared to ^{235}U in PWR (in addition to the factor 3 to 4 in abundance on Earth)
- ❑ Minimizes nuclear waste production, as it is 7 neutron captures away from ^{239}Pu . **Can be used to destroy existing nuclear waste, if used in a fast neutron system, which we want to do also for other reasons (Extended burnup, breeding)**



Breeding properties of ^{233}U

- ^{233}U better than ^{239}Pu over most of the neutron energy spectrum, but not where we want to use it, in the fast neutron part. This is where an external neutron source will help.



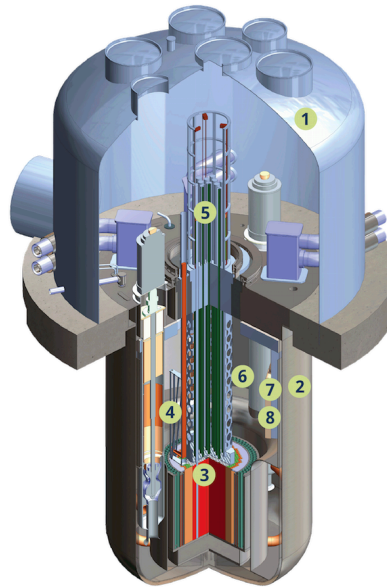
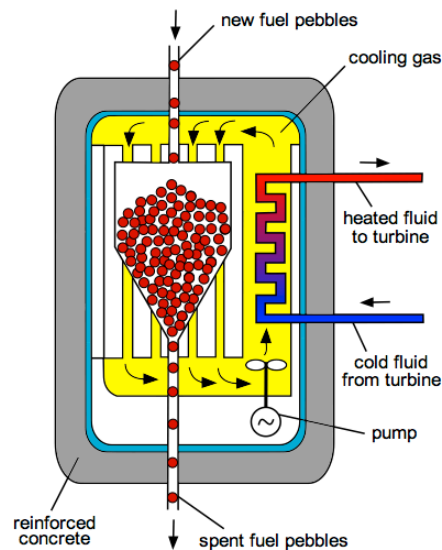
ϵ = Average number of neutrons in excess of the 2 neutrons needed to run the fission chain

- 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 thermal neutron reactors (PWRs).**

How to use thorium in practice?

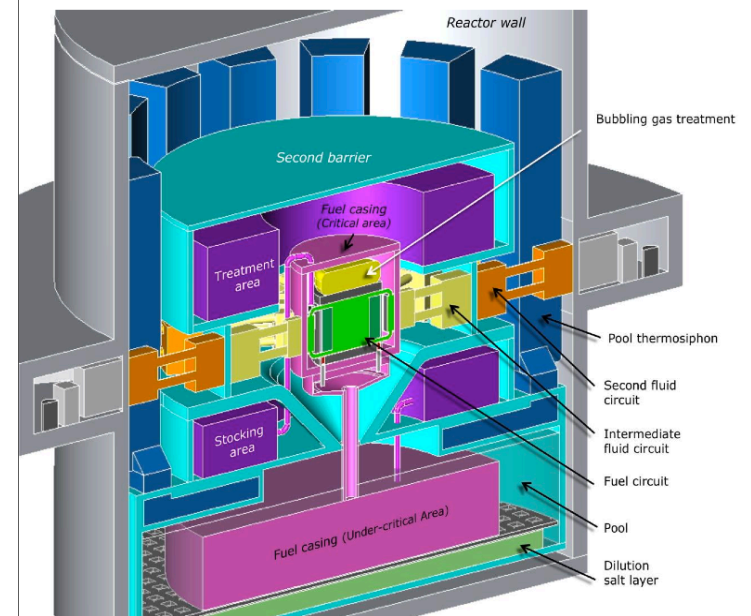
- ❑ First attempts by **mixing Th fuel with U fuel in critical reactors** (Shippingport)
- ❑ **Thorium blankets around fast critical reactors to breed ^{233}U** : the Indian approach, at the cost of maintaining three different nuclear reactor technologies
- ❑ **Continuously circulating fuel to always have fresh fuel in the core**
Pebble Bed or Molten Salt critical Reactors (MSR)
- ❑ **Continuously moving fission reactions toward fresh fuel (fast breeding and fission)**
Travelling Wave Reactors (TWR)
- ➔ ❑ **Provide extra neutrons with an accelerator: ADS**

Pebble-Bed Scheme



TerraPower

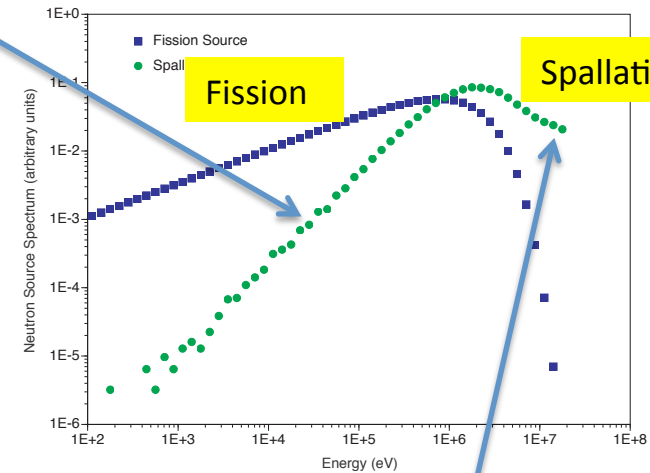
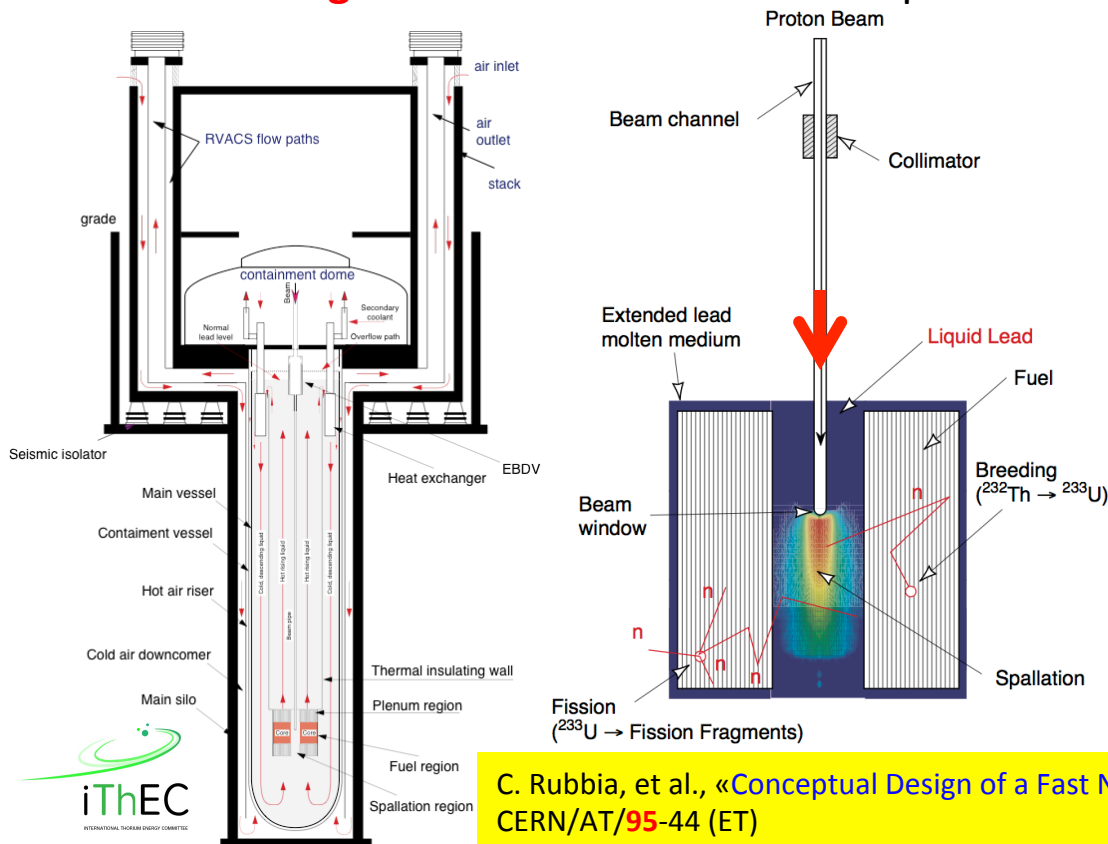
MSR Scheme



China taking the lead

ADS: the subcritical approach

- ❑ A particle **accelerator** to provide an external **neutron source through spallation** and control
- ❑ 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



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

C. Rubbia, et al., «Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier», CERN/AT/95-44 (ET)

Theory of subcritical systems

- ❑ **Physics is very well understood.** Theory of subcritical systems is interesting by itself. Properties are quite different from those of critical systems

C. Rubbia, CERN/AT/ET/Internal Note 94-036

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

Fission

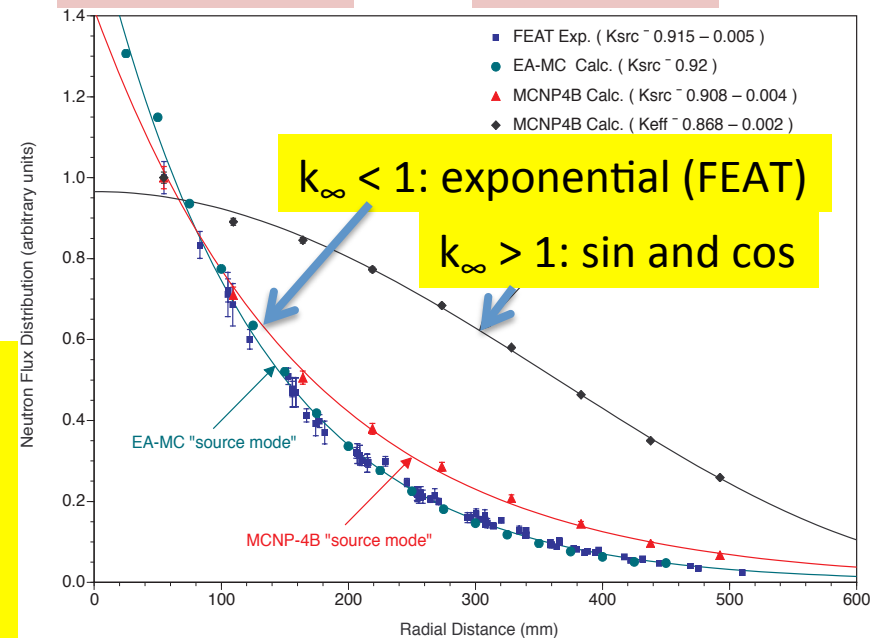
Source

Absorption

Leakage

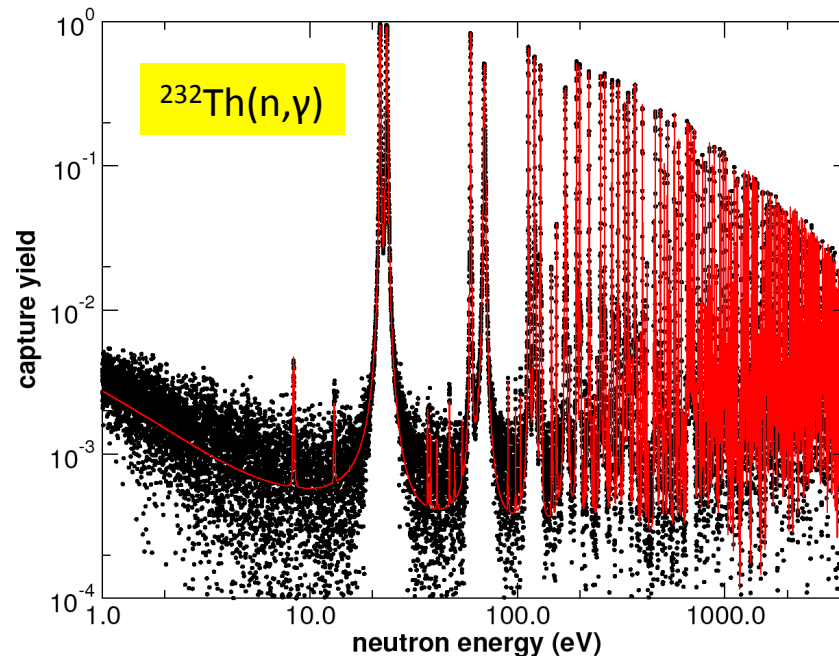
$$k_s \approx \frac{\nu' \sum_f \Phi(\vec{r}, t) + C(\vec{r}, t)}{\sum_a \Phi(\vec{r}, t) - D \nabla^2 \Phi(\vec{r}, t)} > k_{eff}$$

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} . (Y. Kadi et al., Landolt-Börnstein, Accelerators in Energy Research, 2013)



ADS demonstrator

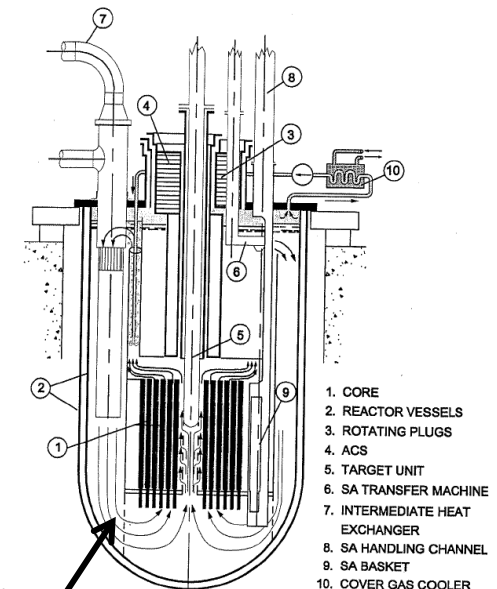
- Simulation available and more and more accurate – Impressive measurements of neutron properties at CERN n_TOF.



- What remains to be achieved is to couple for the first time a proton beam to a subcritical core **at substantial power** ($P \geq 1$ MW). This is much more a political issue (funding) than a scientific one.

First attempt by C. Rubbia et al., in 1999

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



Forced convection

Europe ADS: MYRRHA

Hamid Aït Abderrahim

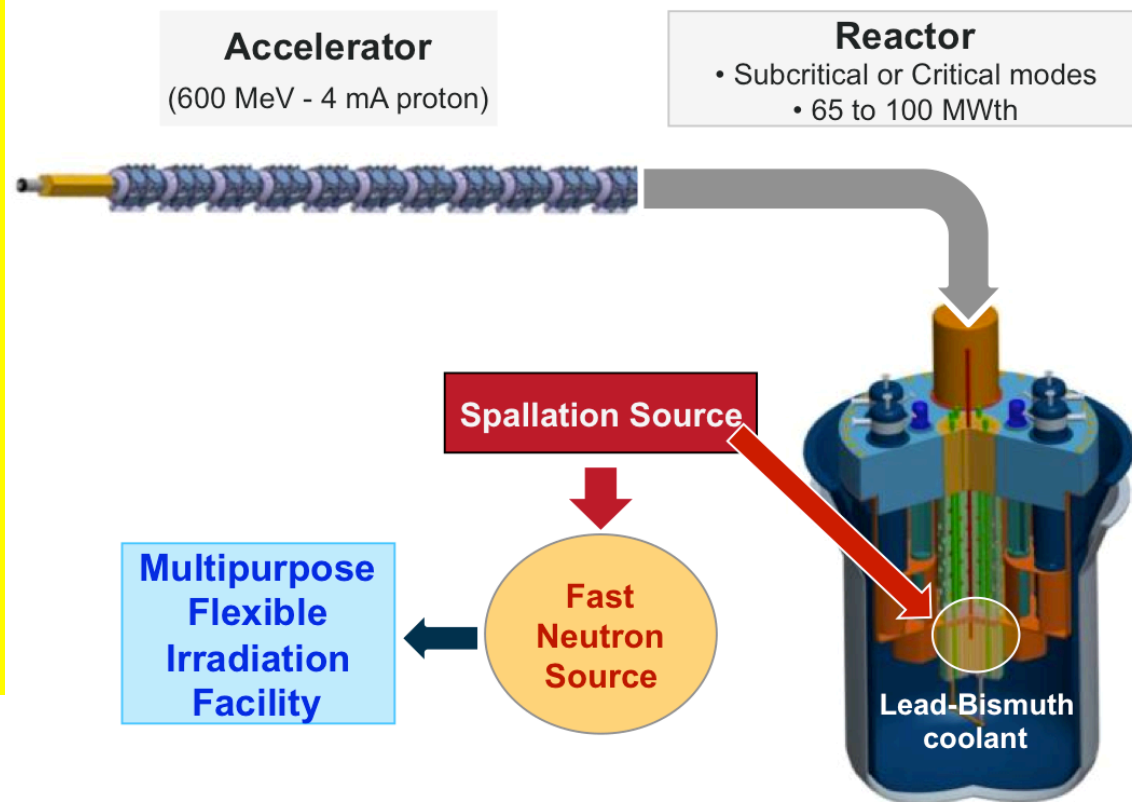
SCK•CEN, Boeretang 200, 2400 Mol, Belgium

MYRRHA - Accelerator Driven System

In principle MYRRHA should be the flagship of ADS projects.

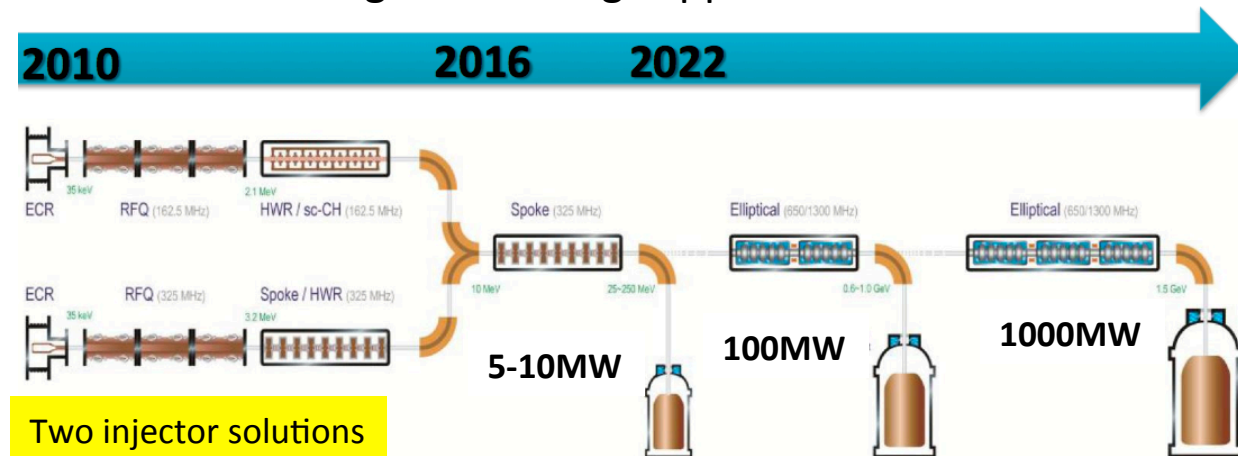
Strong support from the Belgian government, however:

- several challenges faced at the same time: the accelerator, the subcritical core and their coupling
- no thorium in the plans
- will not remain an ADS, and will turn into a critical reactor
- only partially funded
- not before 2025?



China ADS: ADANES

- ❑ Wenlong Zhan, Vice President of the Chinese Academy of Sciences
- ❑ The Chinese Accelerator-Driven System (ADS) project started 5 years ago, including the accelerator, the target and the blanket. The idea of Accelerator-Driven Advanced Nuclear Energy System (ADANES) is proposed as a complete energy system, integrating nuclear waste transmutation, nuclear fuel multiplication and energy production. ADANES has the potential to reach the requirements of sustainable development, safety, economic competitiveness, and nuclear weapon non-proliferation.
- ❑ Innovative spallation target, aiming at 1000 MWe, aggressive schedule, backed through the strong support for R&D within China



Two injector solutions developed in parallel

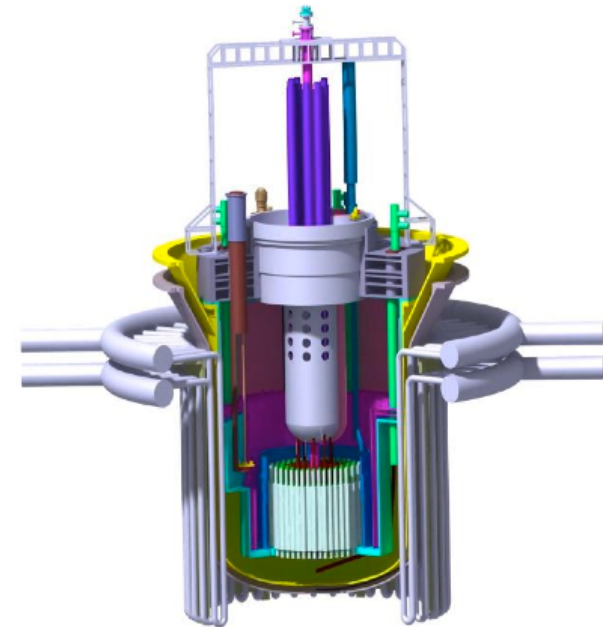
CIADS: INITIAL FACILITY

250MeV@10mA
5-10MW in 2022

RESEARCH FACILITY

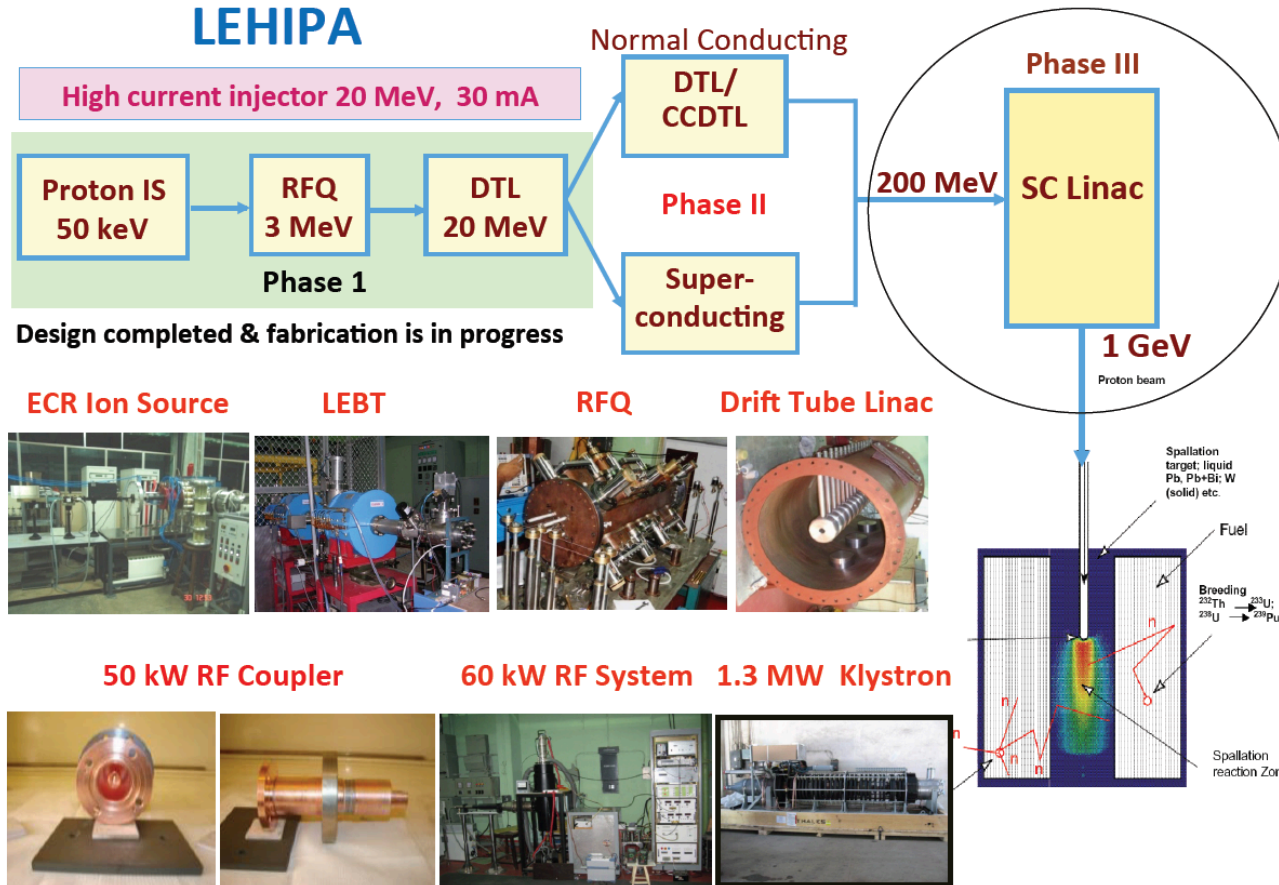
Revol/PSI/2016

DEMO FACILITY



India ADS: at BARC

LEHIPA



Study of a high-current, high-energy proton accelerator (1 GeV and 30 mA), in collaboration with the USA (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.

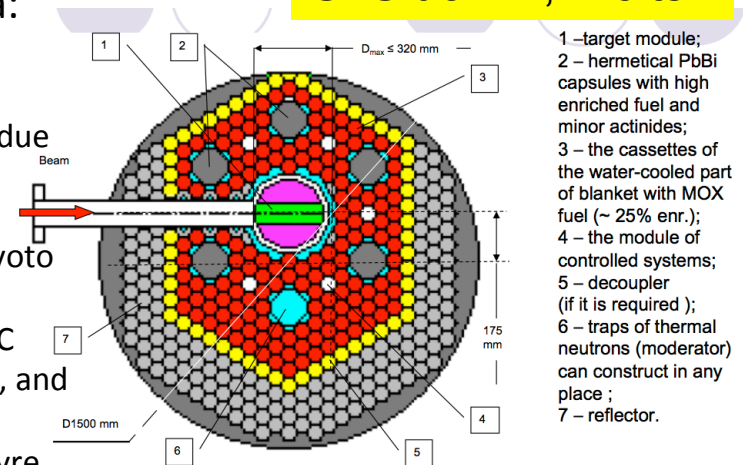
Shashikant Degweker

Other ADS projects and activities

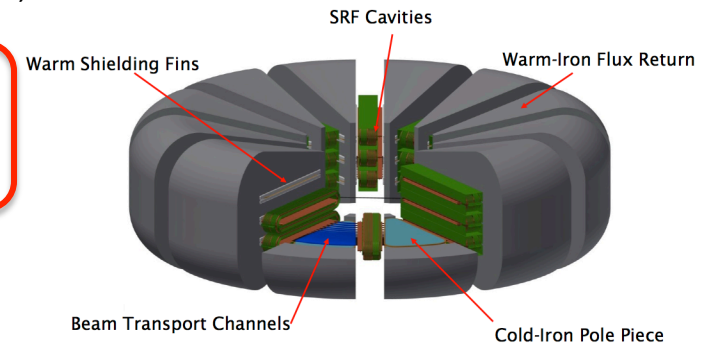
S. Sidorkin, Troitsk

UK, Ukraine, Japan, Korea, Russia, USA, Turkey, Venezuela:

- Complete engineering design by **Aker Solutions** for the 1500MWth/600MWe Rubbia Energy Amplifier
- 200 kW uranium-based ADS prototype, driven by an electron beam, due for completion in 2014 at the Karkhov Institute of Physics and Technology (**KIPT**). **Should be in the commissioning phase!**
- **KURRI** irradiation studies of a Thorium--loaded ADS Experiment at Kyoto University, in Japan (see Cheolho Pyeon @ ThEC13)
- ADS research at **KAERI**: HYbrid Power Extraction Reactor now KOMAC only an accelerator at 100 MeV, Sungkyunkwan University, in Suwon, and Seoul Nat. U., Korea (see Jong-Seo Chai @ ThEC13)
- Strong focussing cyclotron developed at **Texas A&M**, by Peter McIntyre et al., for ADS in a molten salt core (290 MWth).
- A study of ADS within **Turkic Accelerator Complex** (TAC) Project (Arik et al.)
- A study of **AD-MSR** with 1 GeV protons, 1 to 4 MW, by Laszlo Sajo-Bohus, in Caracas
- 1-3 MW **TROITSK** ADS, 90 kW proton beam, rearranging existing elements (accelerator, neutron source, etc.). Has the potential of becoming the next significant step in ADS, reaching for the first time the MW thermal energy range.



P. McIntyre, Texas A&M

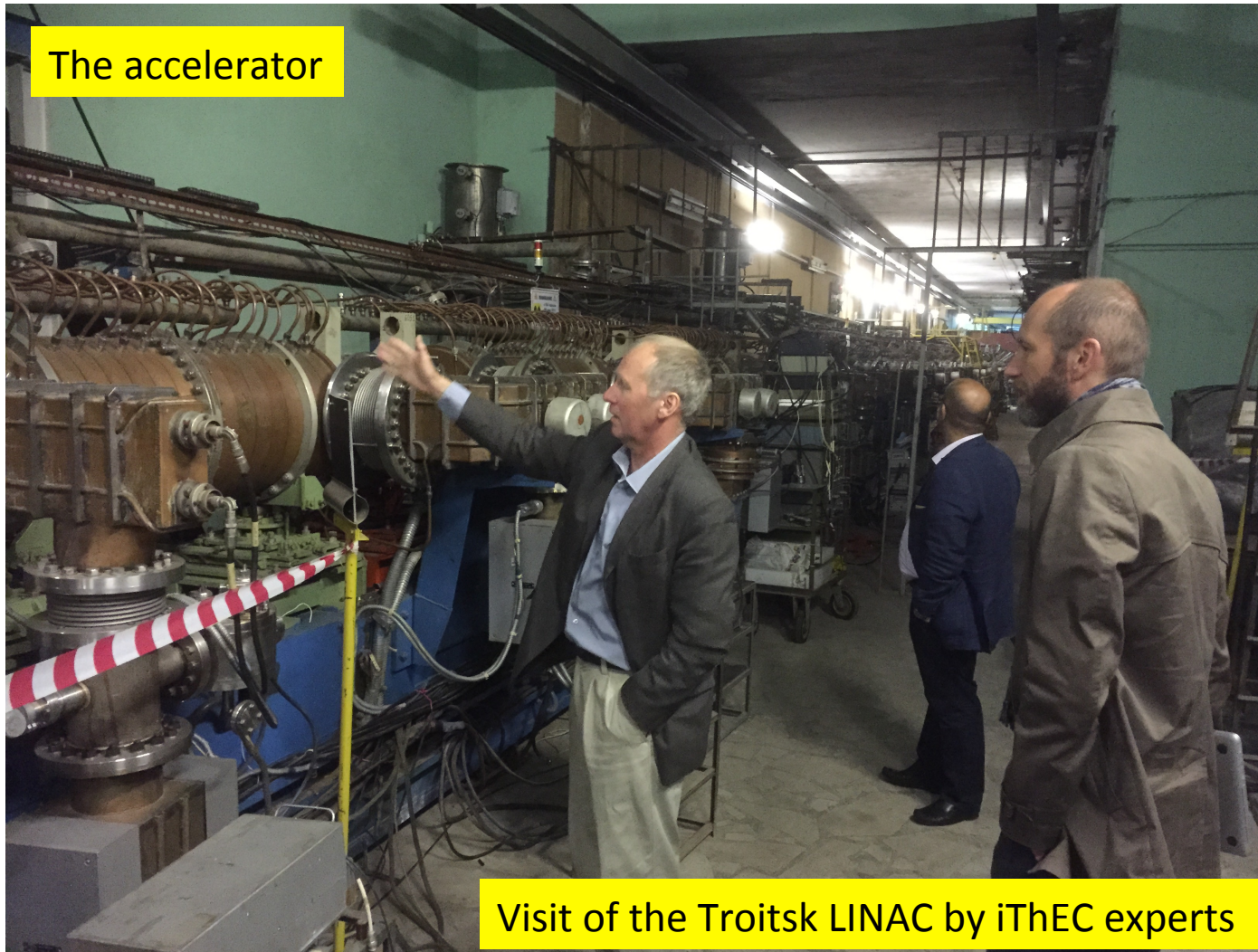


- ❑ Many scattered projects, representing national interests. Some kind of coordination should be activated. IAEA?

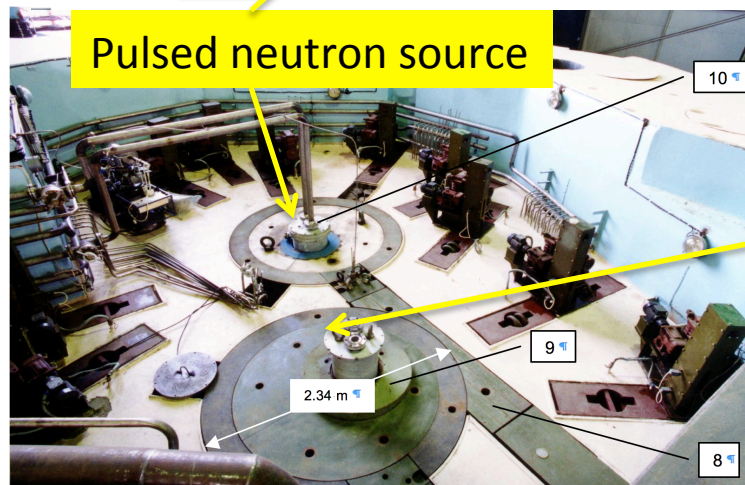
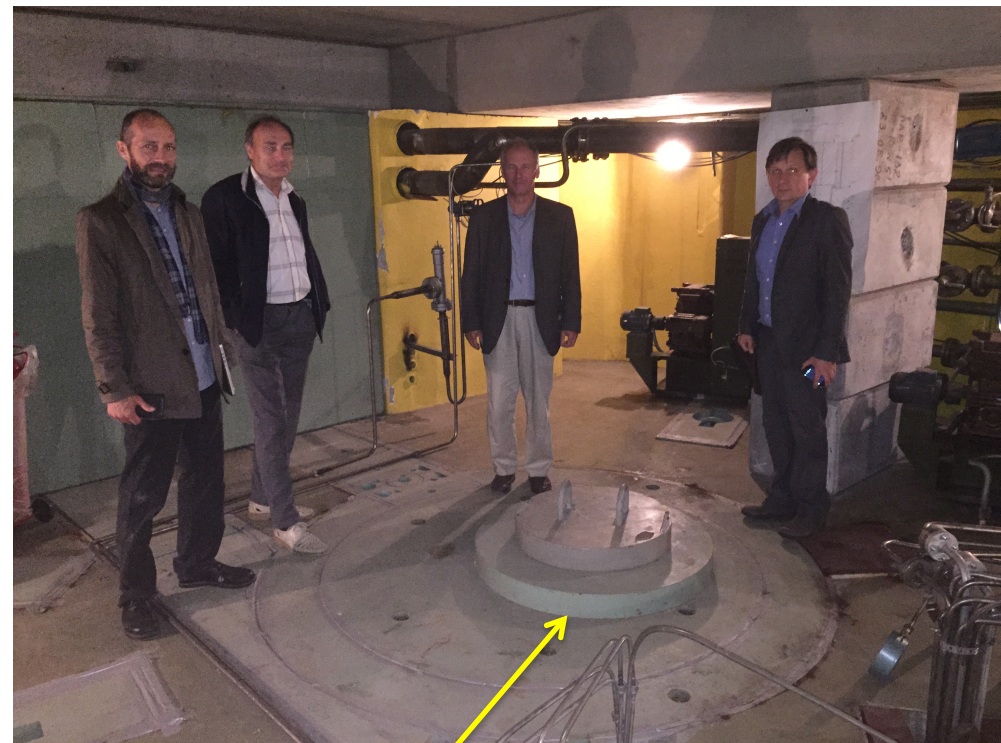
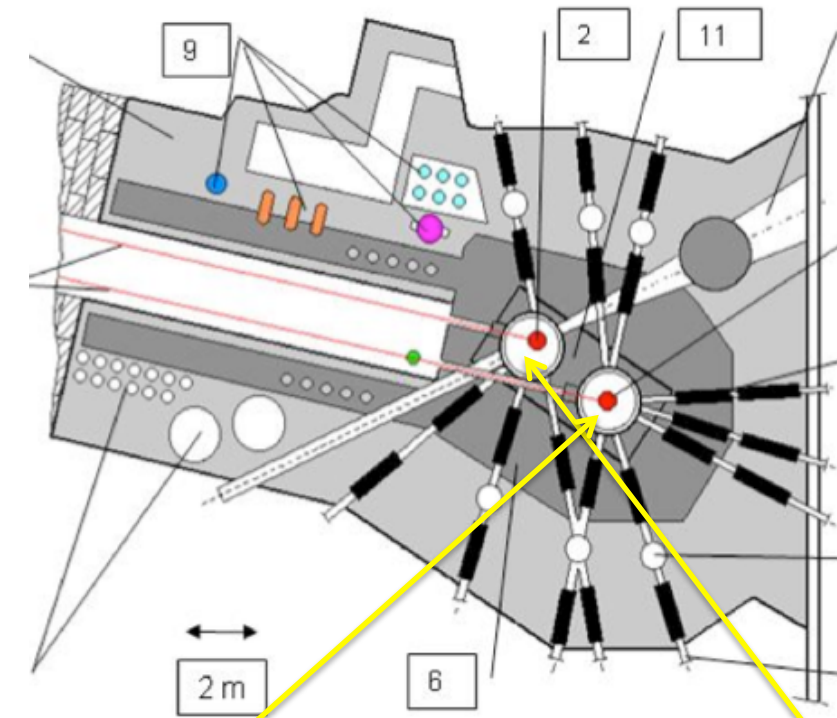
History of ADS projects

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 ($k \approx 0.9$) 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
EADF (Europe)	Proton (0.6 GeV)	Fast (80 MW)	Energy Amplifier Demonstration Facility, proposed in 1999 – Not approved
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 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 – reactivated => 2020
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 => 2020
MYRRHA (Belgium)	Proton (600 MeV) + Pb-Bi (1.8 MW)	Fast (60 MW)	Experimental ADS – under design – 2025
CADS (China)	Protons (0.6 – 1.5 GeV) + Gravity-driven granular W	Fast (100– >1000 MW)	Four phase project: 2011 – 2031
U-ADS (Ukraine)	Electrons (100 MeV, 100 kW) + U / W	Thermal (131-192 kW)	Uranium-based ADS prototype (KIPT), sponsored by the USA: in commissioning stage?
→ ADS (Russia)	Protons (250-300 MeV, ≤ 100 kW) + W	Fast 1-3 MW	First beam-core coupling at significant power and MA transmutation tests – Troitsk – core under design, proposal in preparation – 2021 (5 years)

Using an existing facility at Troitsk



Using an existing facility at Troitsk

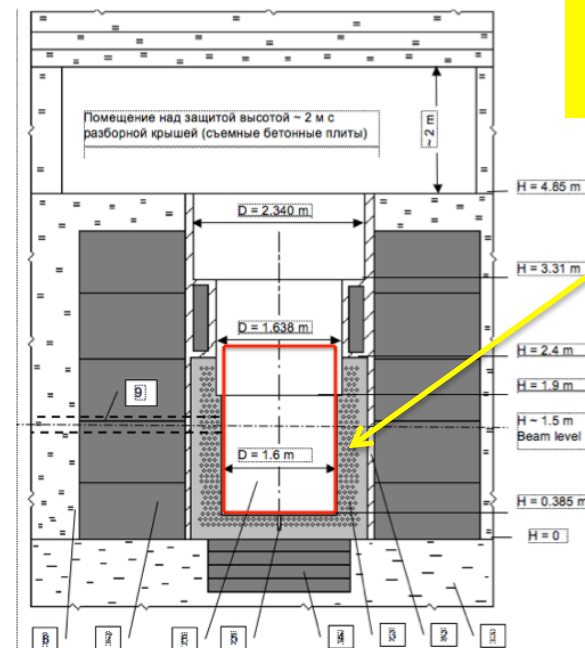
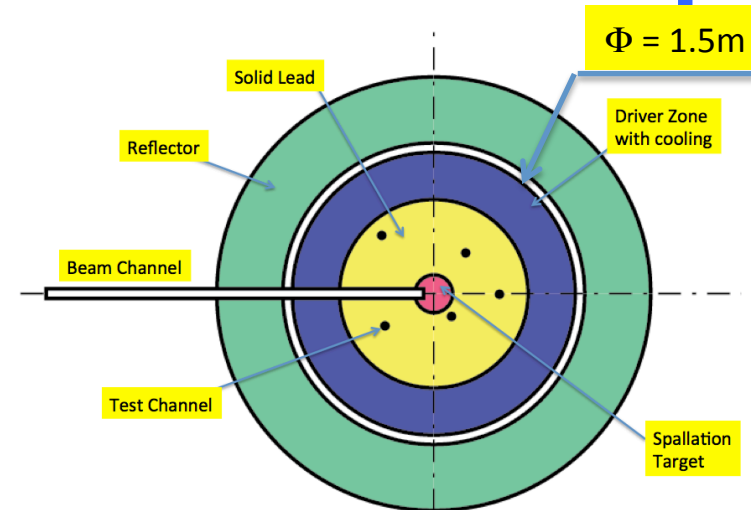


Pulsed neutron source

ADS experimental cell

Troitsk simplified core concept

- ❑ Both an **ADS experiment and a fast neutron test facility**
- ❑ INR Moscow, in cooperation with iThEC, and a few other institutes in Russia and abroad (under discussion with EPFL, PSI, Řež, and CERN to form a collaboration)
- ❑ **Goal:** Study for the first time the coupling of a proton beam to a subcritical fast neutron core at substantial power (1 to 3 MWth). **Demonstrate safety and minor actinide destruction.**
- ❑ Control and protection system (CPS) and the physical and technical parameters of the ADS must comply with regulations of the Russian Federation:
Core to be designed and submitted for approval to Russian safety authorities by ROSATOM specialized Agencies
- ❑ Conceptual design in preparation



Principle of the new core

Reflector, already in place

ADS accelerator power

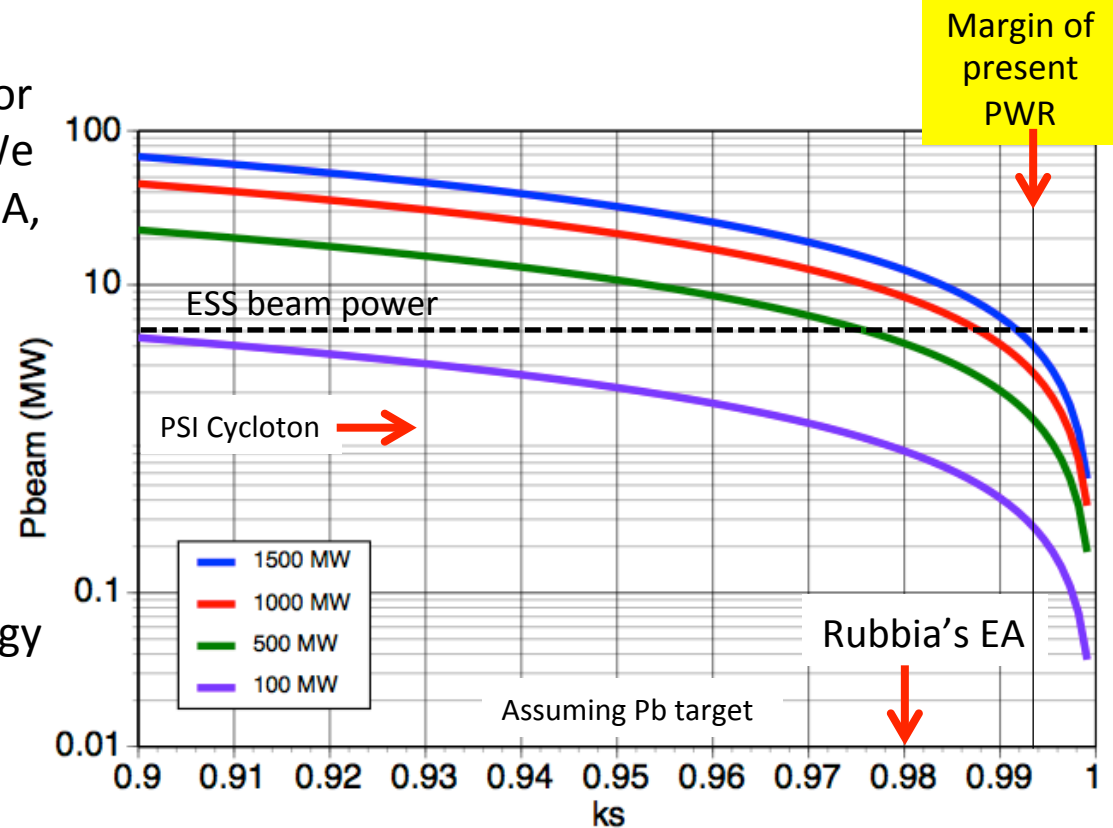
- Applications range from 50 MW_{th} for sea water desalination to 1000 MWe for electricity production. In the USA, SMR ≤ 300 MWe. Economics optimisation of ADS needed.

- The application defines the power output P_{ADS} :

$$P_{ADS} = G \times P_{beam} = \frac{G_0 k_s}{1 - k_s} \times P_{beam}$$

- For a given power output, the energy gain G (choice of k_s and G_0) determines the accelerator power.

Trade-off between accelerator power and criticality margin



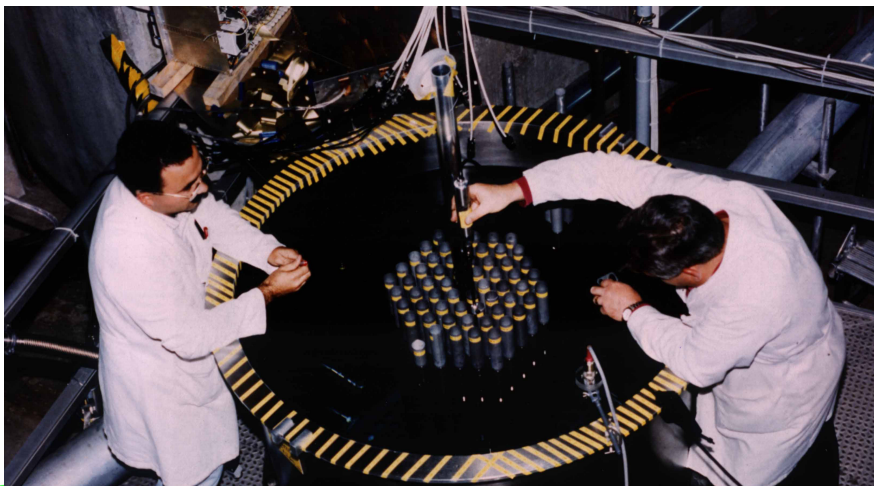
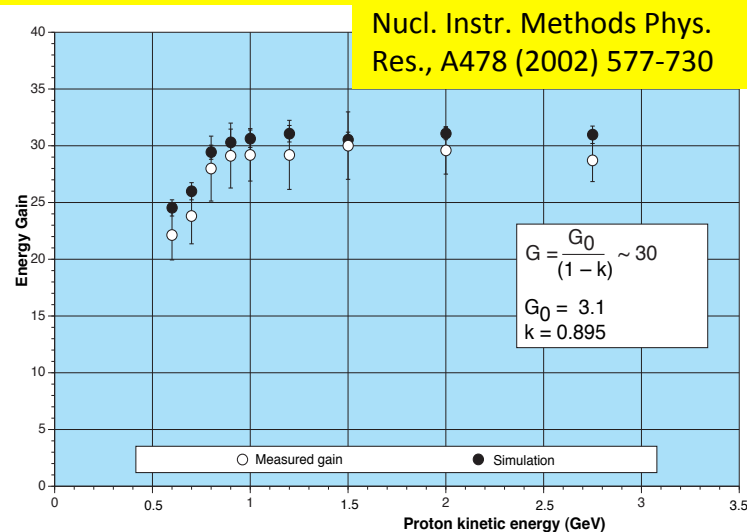
$$P_{beam} = \frac{(1 - k_s)}{k_s G_0} P_{ADS}$$

Accelerator requirements

- ❑ In principle, it does not matter how the external neutron source is provided. In practice, for industrial applications, there are many requirements which makes the accelerator challenging:
 - **Beam particle: proton**
 - **Beam Energy:** ideally $E_{\text{beam}} \geq 900 \text{ MeV}$ (See FEAT experiment), but lower energy can be compensated by higher current
 - **Beam power: a few to $\approx 10 \text{ MW}$** depending on required application. Large operational range desirable to follow fluctuating demand, if associated to wind or solar energies (factor 10?)
 - **Beam spot size (footprint):** large on impact on window
Studies at JAEA $\rightarrow$ OK $\leq 0.1\text{-}0.2 \text{ mA/cm}^2$, MYRRHA has 0.07 mA/cm^2
 - **Beam losses:** minimize irradiation of the accelerator and of the environment (main issue for any high power beam, not only for ADS); impact on accelerator maintenance (figure of merit $\leq 1 \text{ W/m}$ for LINACS, for cyclotrons losses are localized, at injection and extraction)

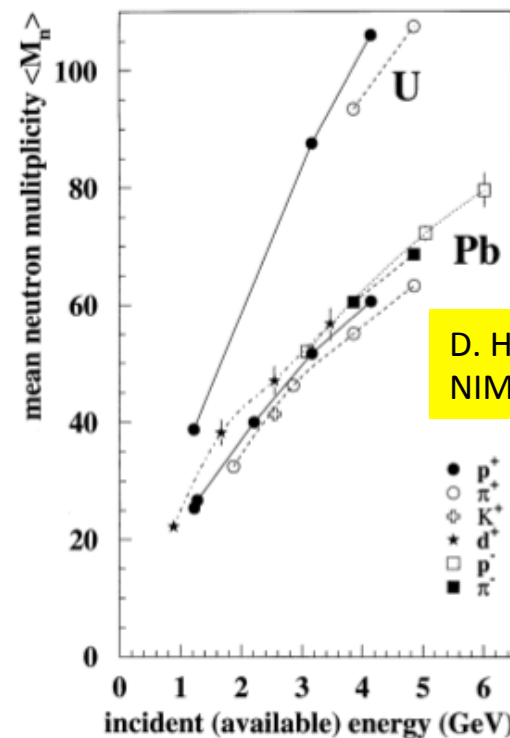
Accelerator requirements (cont.)

FEAT: optimum energy gain from the point of view of the spallation process reached at 900 MeV



3.62 t of natural uranium at CERN PS; $k_{\text{eff}} \sim 0.9$

Spallation target optimization: maximize neutron production, with at the same time adequate mechanical properties (U, Pb, W, Pb-Bi) – **contributes to the energy efficiency**



D. Hilschler et al.,
NIM A 414 (1998)

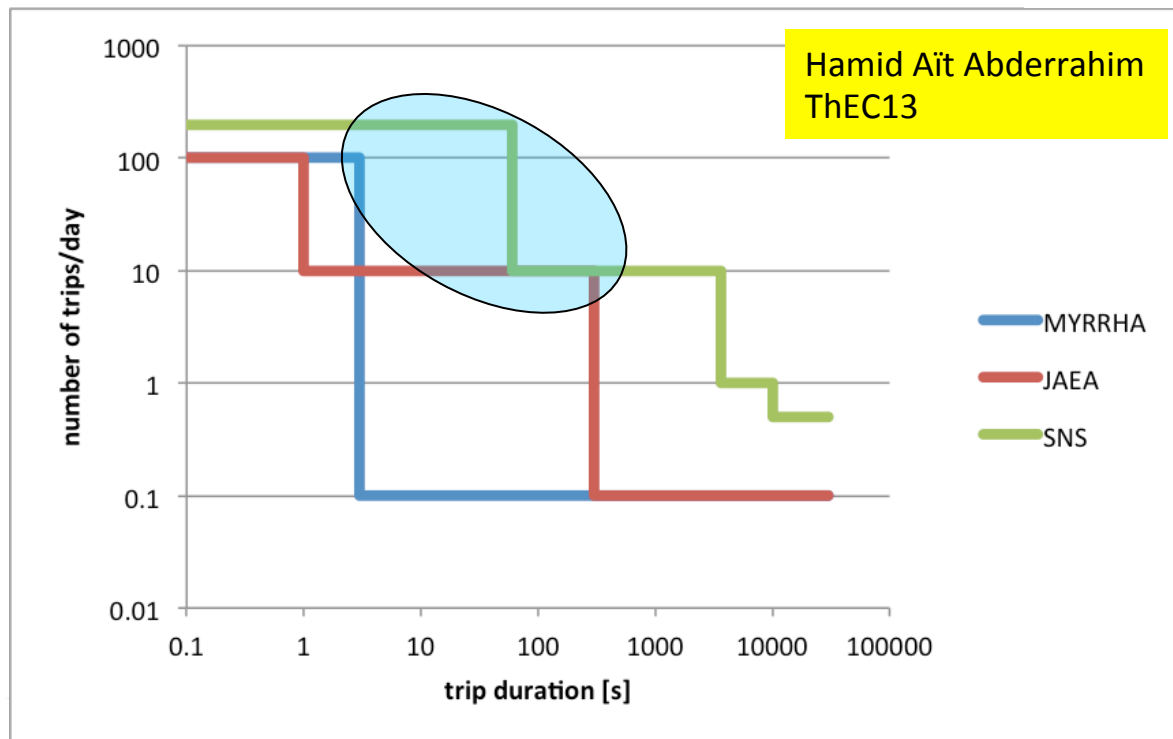
Accelerator requirements

- **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 (JAEA limitations not as stringent):

- No limit for trips for $T_{\text{trip}} < 0.1$ s
- Not more than 100 trips per day $0.1 \text{ s} < T_{\text{trip}} < 3$ s
- Not more than 10 in three months for $T_{\text{trip}} > 3$ s
- Administrative limit if SCRAM event

Hayanori
Takei et al.

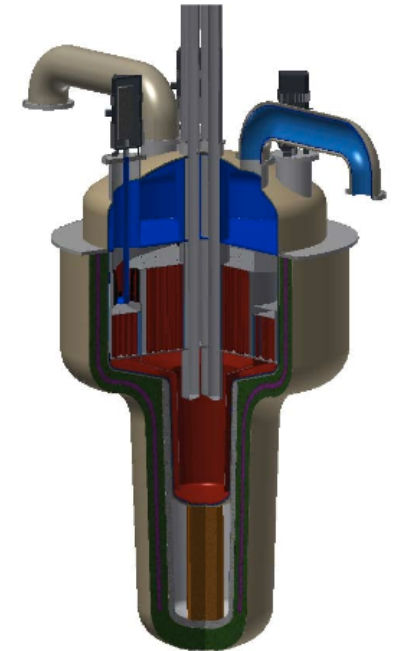
Criteria	Acceptable value (times/year)	Component or condition that imposed limits
$0 \text{ sec.} \leq T \leq 10 \text{ sec.}$	25,000	Inner barrel
$10 \text{ sec.} < T \leq 5 \text{ min.}$	2,500	Inner barrel, Reactor vessel
$T > 5 \text{ min.}$	43	system availability



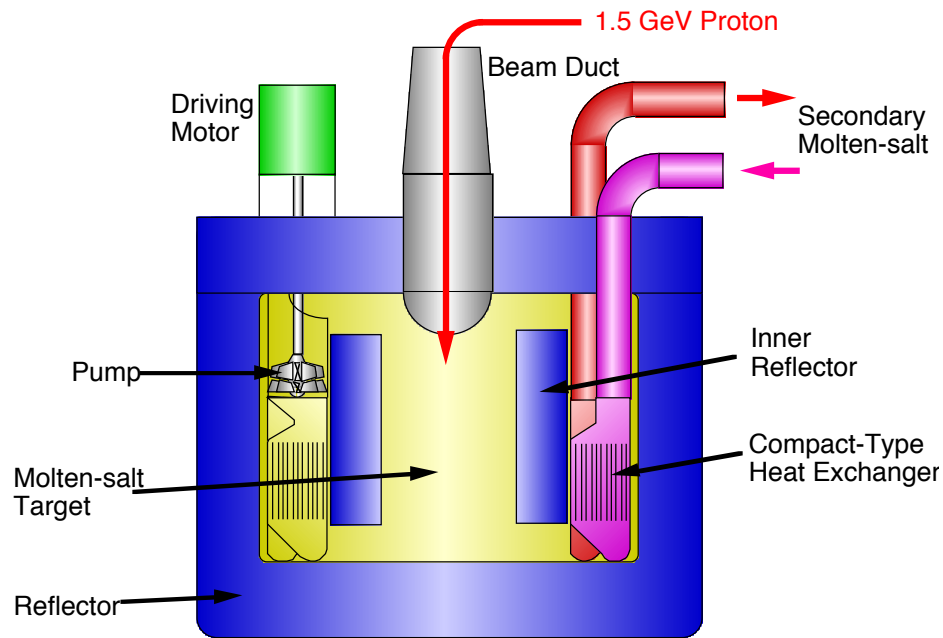
- 1) Make the accelerator more reliable: Redundancy (several sources, several accelerators, etc.)
- 2) Improvements in materials, maintenance and operation (Beznau nuclear reactor (KKB) in Switzerland, running for 40 years: they were initially counting on 10 trips per year, and nowadays, they hardly get one trip per year.)
- 3) Relax the demands from ADS (Molten Salt-ADS)

Molten salt ADS

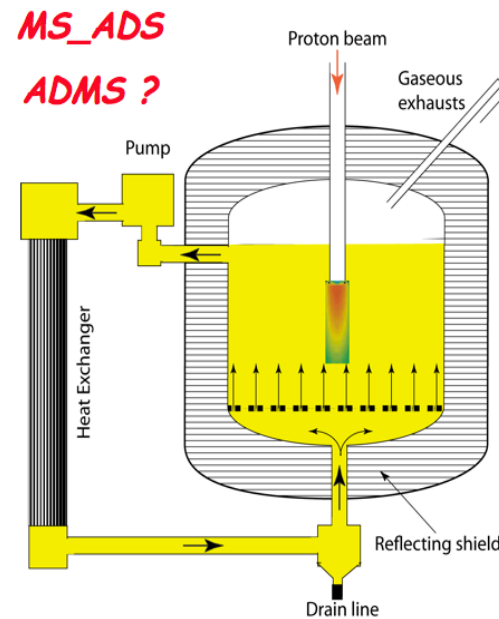
- Several **Molten Salt ADS concepts** exist which have reduced constraints on beam trips, and other advantages
- Only the beam window remains affected by beam trips ($\leq 6 \times 10^4$ trip per year stress analysis of tungsten window target by Y. Wu et al.)



Peter McIntyre
@ Texas A&M



Toshinobu Sasa @ ThEC13



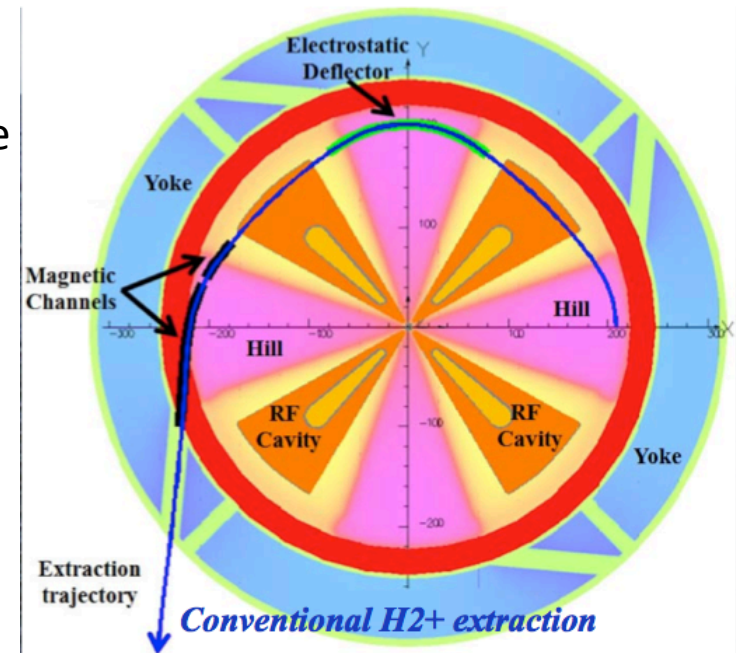
Carlo Rubbia @ ThEC13

Accelerator requirements

- **Energy efficiency:** maximize fraction of electric grid power stored in the beam. Relevant to overall energy efficiency of system
- **Size of accelerator:** for waste elimination, people might want to fit it on the site of a standard nuclear power plant – depends on application
- **Cost:** This is obviously most important for industrial applications.

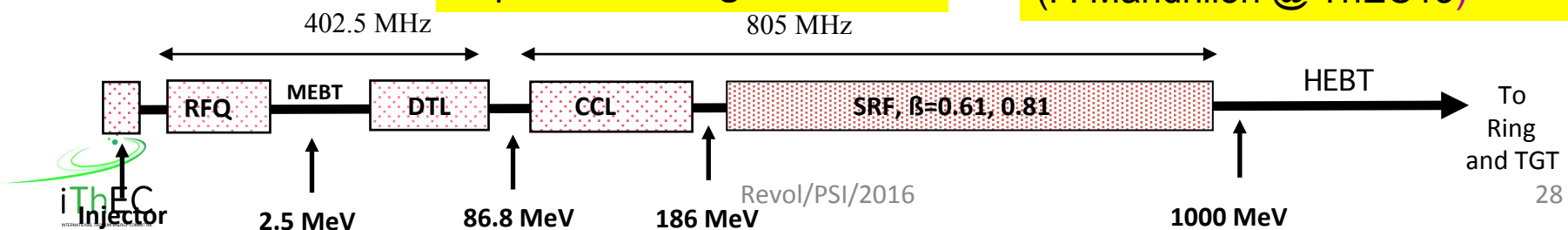
- ❑ In the end, the solution chosen among LINAC or Cyclotron will be the one best fulfilling all the above requirements
- ❑ The optimum technological solution likely to depend on the type of application

One stage cyclotron

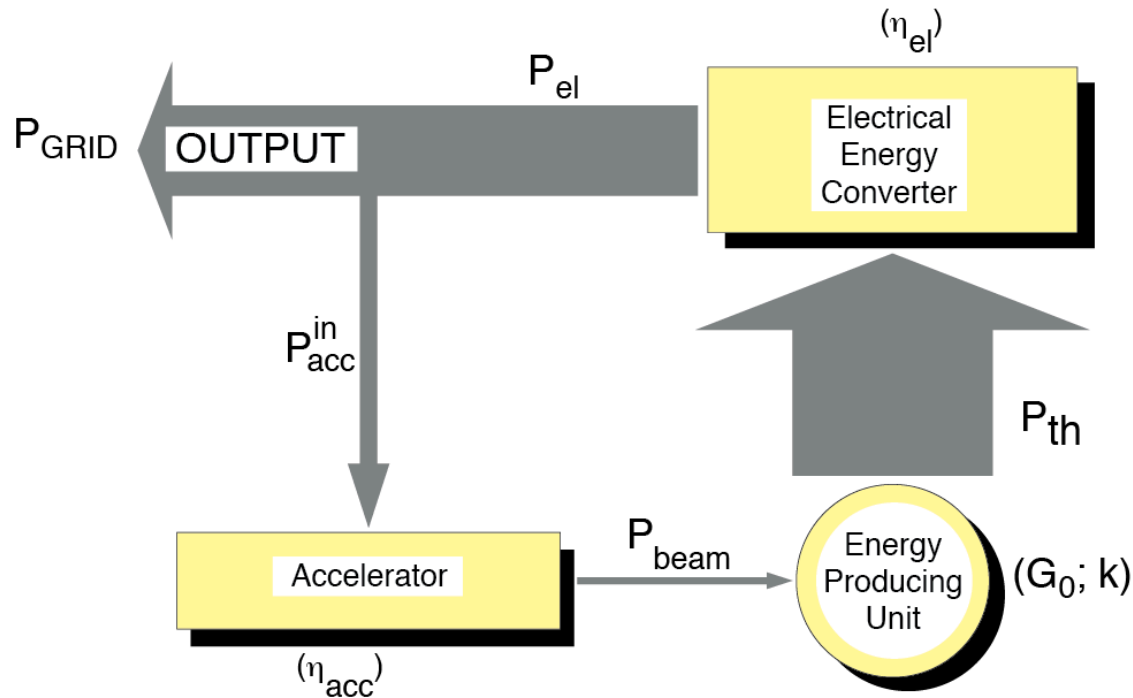


H₂⁺ AIMA Cyclotron w reverse bend and 3 injections, 600 MeV, 6 mA (P. Mandrillon @ ThEC13)

Superconducting SNS LINAC



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:

$$\frac{1}{\eta_{acc}} \ll 50 \Rightarrow \eta_{acc} \gg 0.02$$

- ❑ Minimum is $\eta_{acc} = 0.2$, but $\eta_{acc} = 0.4$ should be 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.)

Conclusion

- ❑ Energy consumption in developing countries will determine the ecological future of the Earth. Why are developed countries which possess the know-how not leading a global coordinated R&D effort?
- ❑ ADS physics is well understood, conceptual designs exist. The next step is the coupling a proton beam to a subcritical core, at significant power. Troitsk proposes to do it at the 1 to 3 MW level, in 5 years, at minimum cost (55 M\$).
- ❑ Today, with existing beams (for example PSI cyclotron @ 600 MeV, 1.4 MW), ADS could already be demonstrated up to the 100 MW level.
- ❑ This would give time for the accelerator technology to get to the power and quality required for an industrial demo of a thermal power of several 100 MW.
- ❑ The following step would be a ≥ 10 MW beam for an industrial system. Only a factor 2 in power from ESS, however, quality requirements may be challenging (reliability, beam losses, cost, etc.).
- ❑ With ADS the accelerator community has a very interesting and important challenge, which certainly appears to be achievable.