iThEC

INTERNATIONAL THORIUM ENERGY COMMITTEE

iThEC ADS Initiatives

Maurice Bourquin

University of Geneva and iThEC, Switzerland

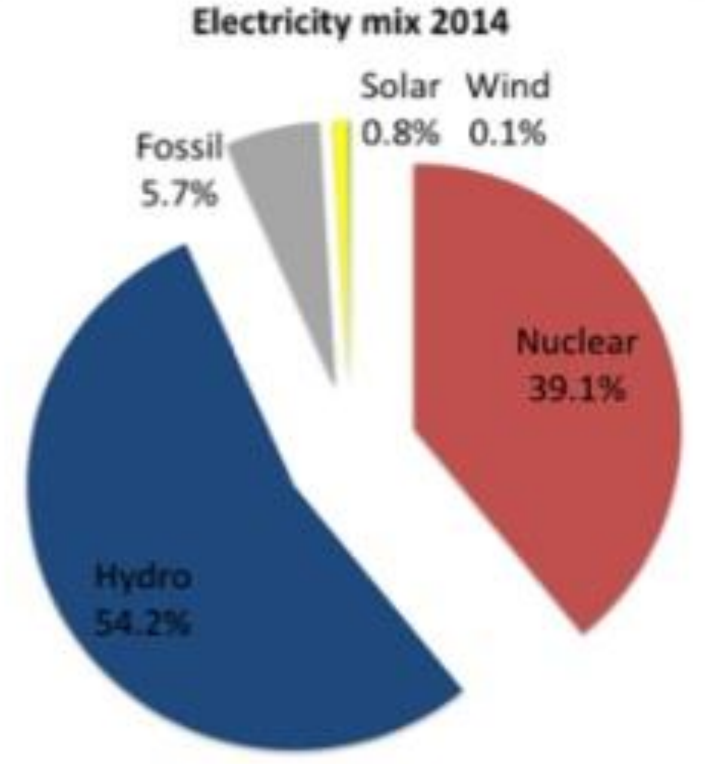
Huddersfield, September 1st, 2016

Our Energy World

- A world where the demand for electricity is increasing and where the use of fossil fuels is threating the environment.
- The massive earthquake and the subsequent tsunami that hit northern Japan and the related nuclear accidents at Fukushima (as did the Chernobyl accident) have triggered a profound reflection about the future of the commercial nuclear energy sector. And the whole energy sector.
- In Switzerland…

Introduction to Swiss electric system: Electricity mix in 2014

- Consumed
  - 56 000 GWh
- Produced
  - 61 500 GWh
- Imported: 28 000 GWh
- Exported: 32 500 GWh

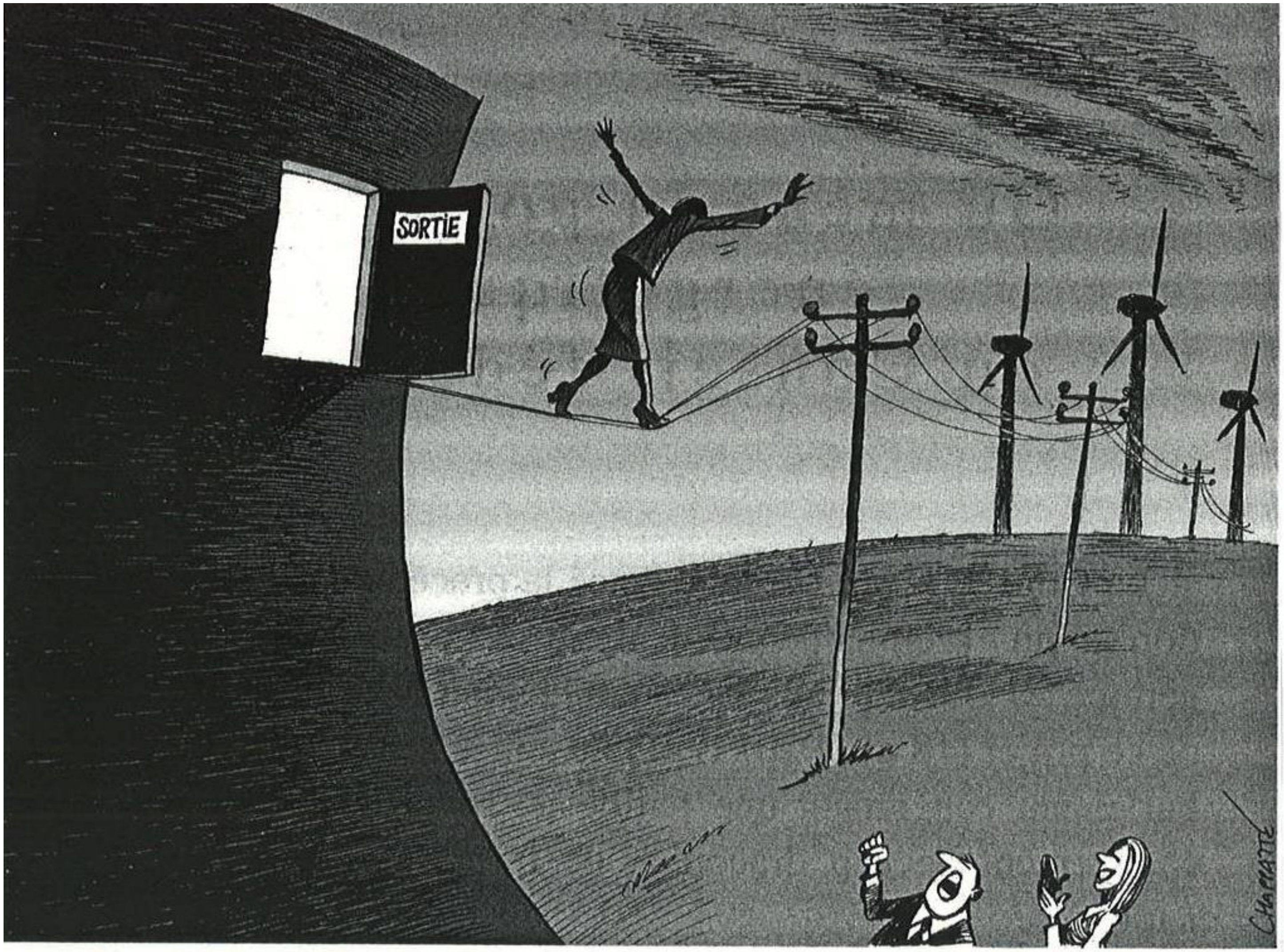


Source: Swissgrid (Energie Uebersicht 2014)

Impact of wholesale electricity market

- The economic attractively of the wholesale market in Europe is visible in Switzerland.
- The Swiss hydroelectric and nuclear installations are thus under pressure, as they cannot anymore cover their costs.
- Should political measures be taken to minimize induced economic biases?

Nuclear power in Switzerland will be phased out (5 plants)



Doris Leuthard et la sortie du nucléaire. *Le Temps*, 27 septembre 2012.

Energy Strategy 2050 (1/2)

1. **Enhance energy efficiency**
2. **Develop renewable energy production**
   - Hydropower: + 3.2 TWh
     (+ pump storage for integration of new
     Nant de Drance 900 MW renewable energies)
   - New renewable energy: Unlocking sustainable potentials
     (24.2 TWh)
3. **Meet residual demand through:**
   - Electricity production with fossil fuels (combined heat and power, gas and steam turbines)
   - Electricity Imports

Energy Strategy 2050 (2/2)

4. **Electricity Networks**
   - Expansion and Renovation
   - Renovation of distribution grid in direction of smart grids
5. **Strenghtening energy research**
6. **Confederation sets the example**
7. **Encouraging international cooperation in the field of energy**

(from data IAEA-TECDOC-1613, April 2009)

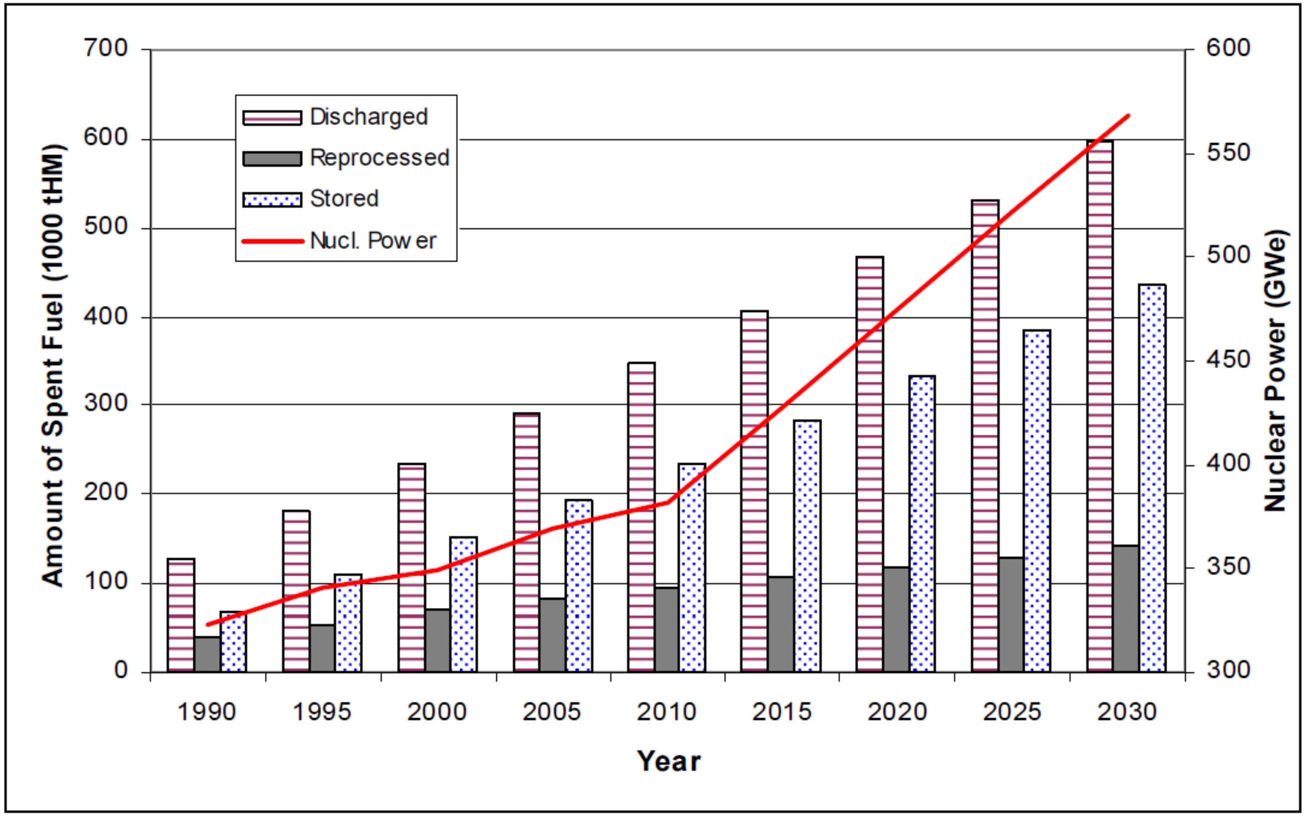
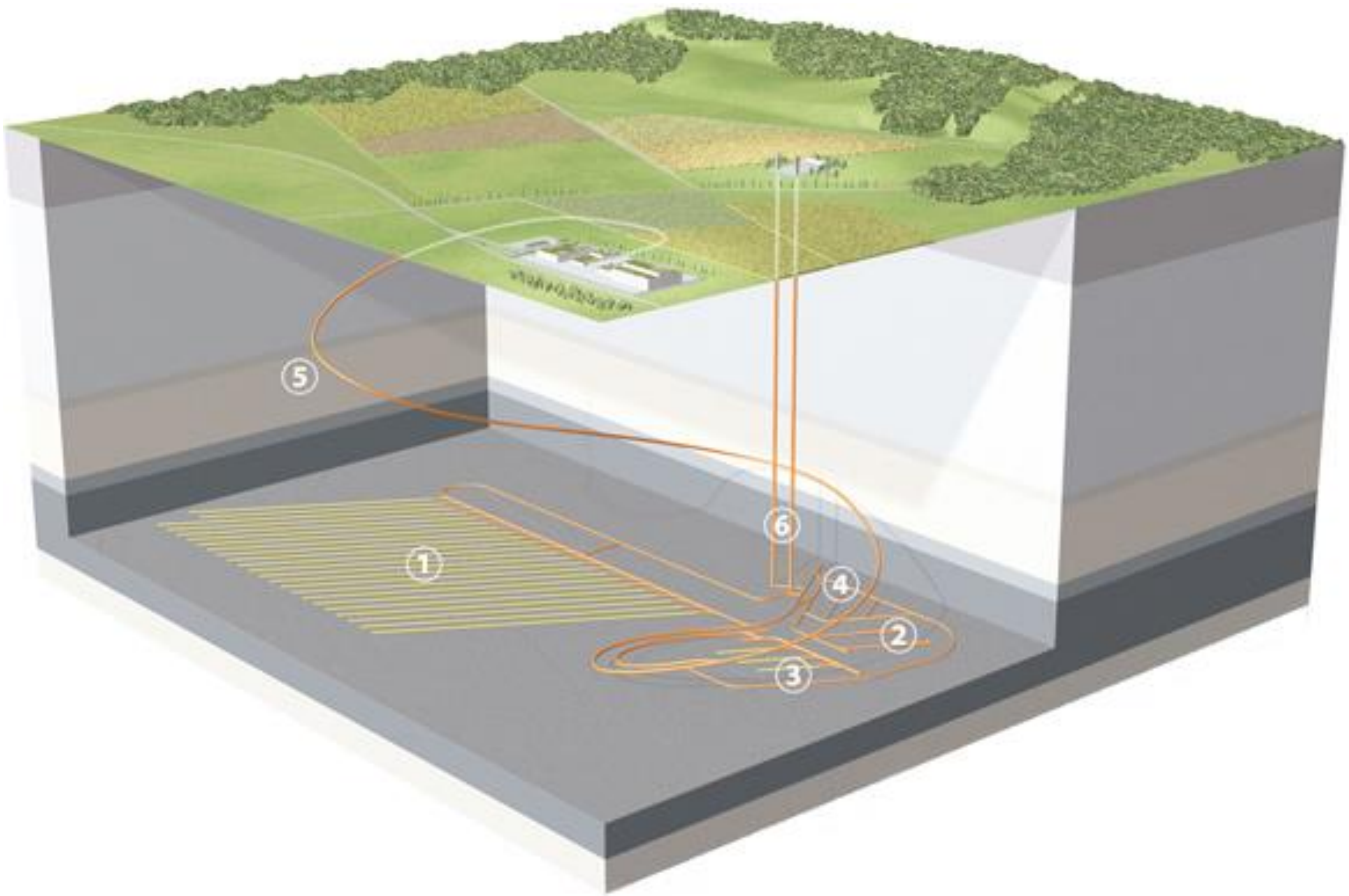


Fig. 14. Cumulative spent fuel discharged, stored and reprocessed from 1990 to 2030.

Even if nuclear energy would be phased-out tomorrow, the world still would need to address the safe, economic and definitive management of all the waste produced in the last 60 years.

Deep Geological Repositories for High-Level Wastes



Swiss example:

Image: Infel AG, Claudio Köppel

1. Main facility SF/HLW
2. ILW repository
3. Pilot facility
4. Test zones
5. Access tunnel
6. Ventilation shaft and construction shaft

Is there an alternative to uranium -fueled power plants?

Can the amount and the lifetimes of radioactive wastes be reduced?

Can one make nuclear energy acceptable to Society?

iThEC

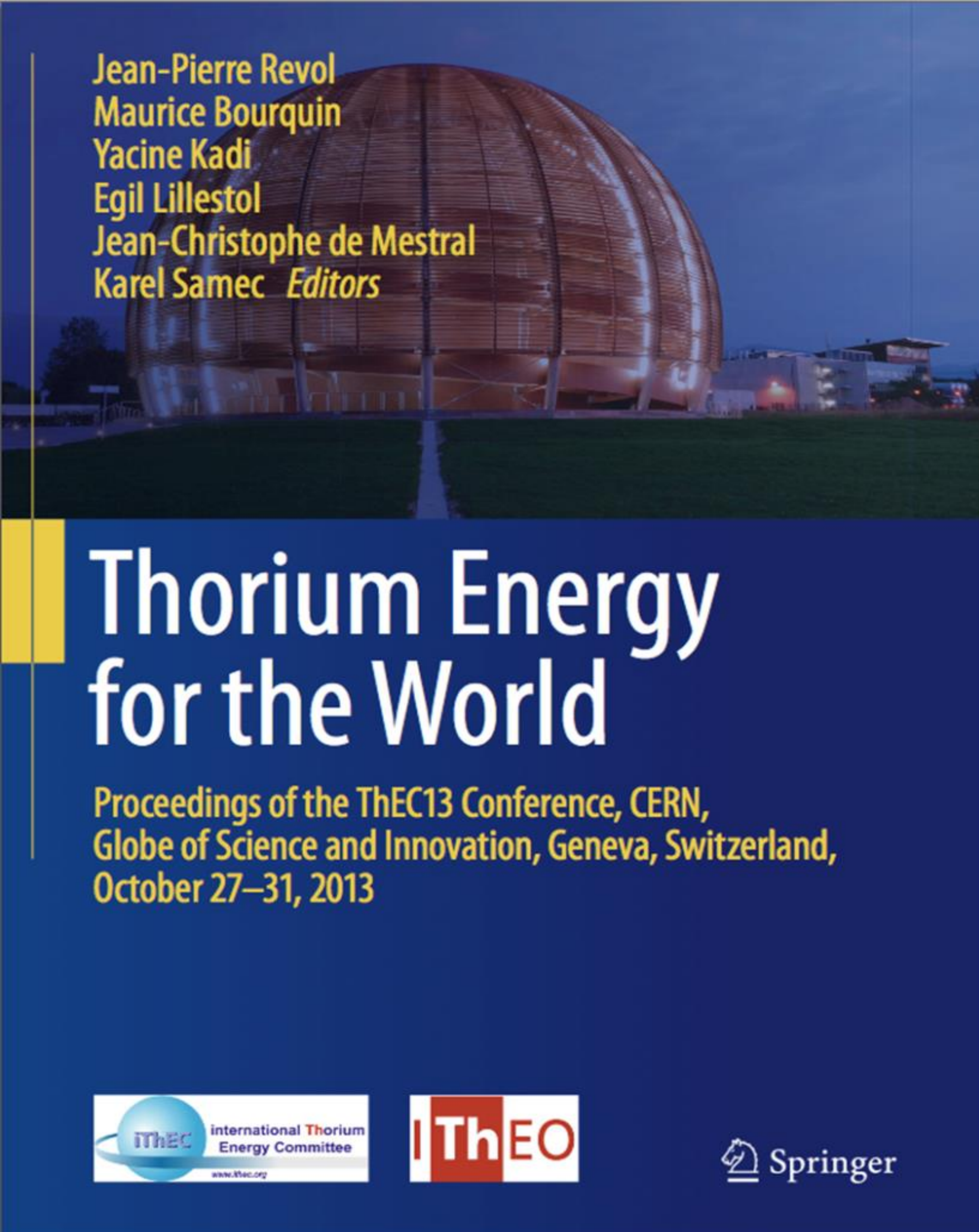
INTERNATIONAL THORIUM ENERGY COMMITTEE

An association aiming at developing thorium energy systems, with a focus on Accelerator-Driven Systems.

international **Th**orium **E**nergy **C**ommittee: **not for profit association, under Swiss law, founded in 2012**: engineers, scholars, politicians and other concerned citizens acting to promote **R&D on the use of thorium in order to**:

Transmute long-lived nuclear waste

Produce safe, clean and abundant energy sources, in particular in view of the huge needs of developing countries



Slides and videos available on CERN indico: http://indico.cern.ch/event/thec13

First task for iThEC: Organize the Thorium Energy Conference 2013 (ThEC13)

The main world actors were all represented (32 countries)

The proceedings contain all the contributions from the conference (more than 80)

A quite complete account of the domain in the world

Anybody with a CERN account can access the proceedings online from the Springer site

TEC13 Opening Talk:

A Future for Thorium Power?

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

Carlo Rubbia

Containers of thorium nitrate in Nevada

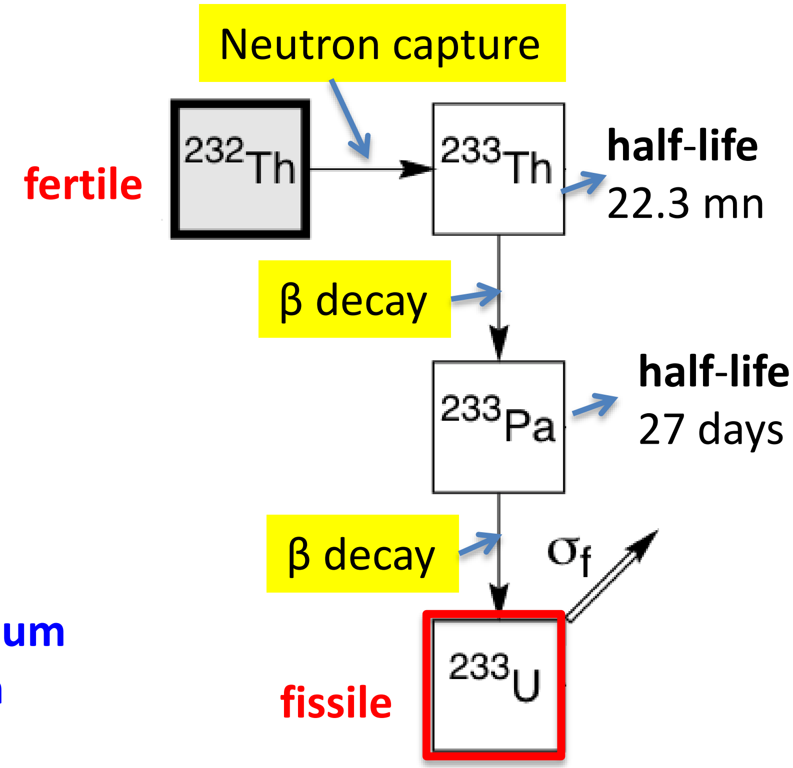
Thorium only used in breeding mode.
In contrast with Uranium (which may also be used in breeding mode):

– 4 times larger supply
– produces less wastes
– less proliferating
– safer

Monazite sample

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

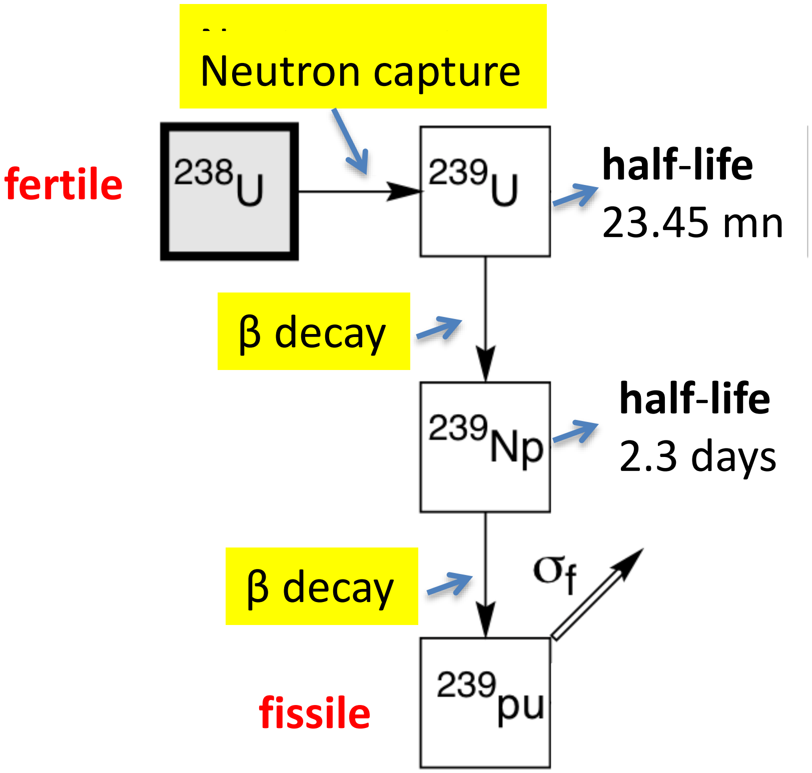
- Thorium is **fertile**, not fissile, so it can **ONLY be used** in breeding mode, by producing ^{233}U which is fissile
- However, this gives a potential factor 140 gain compared to ^{235}U in PWR (in addition to the factor 3 to 4 in abundance)



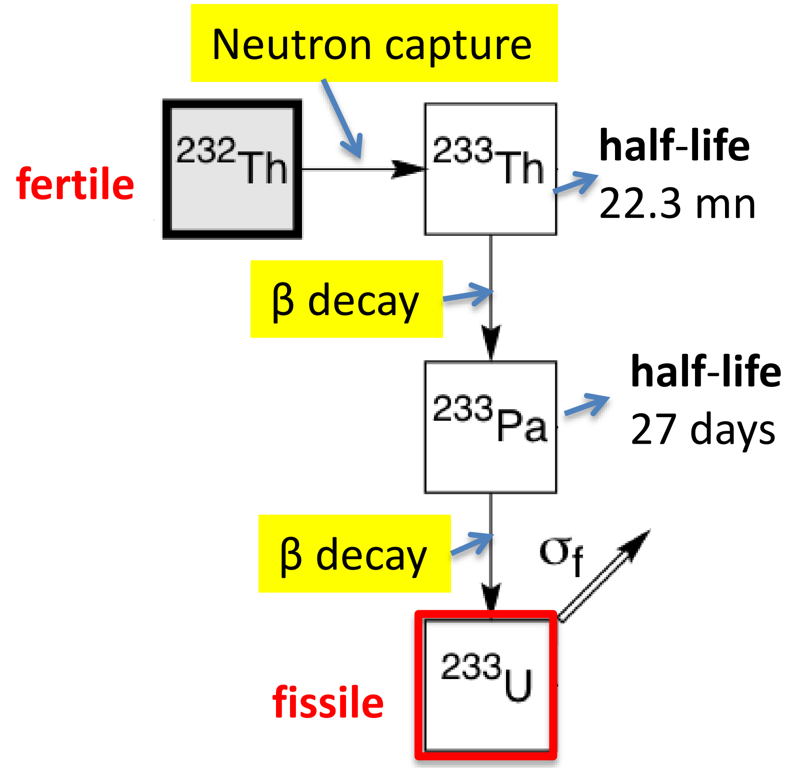
Thorium chain

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
- However, this gives a potential factor 140 gain compared to ^{235}U in PWR (in addition to the factor 3 to 4 in abundance)



Uranium chain



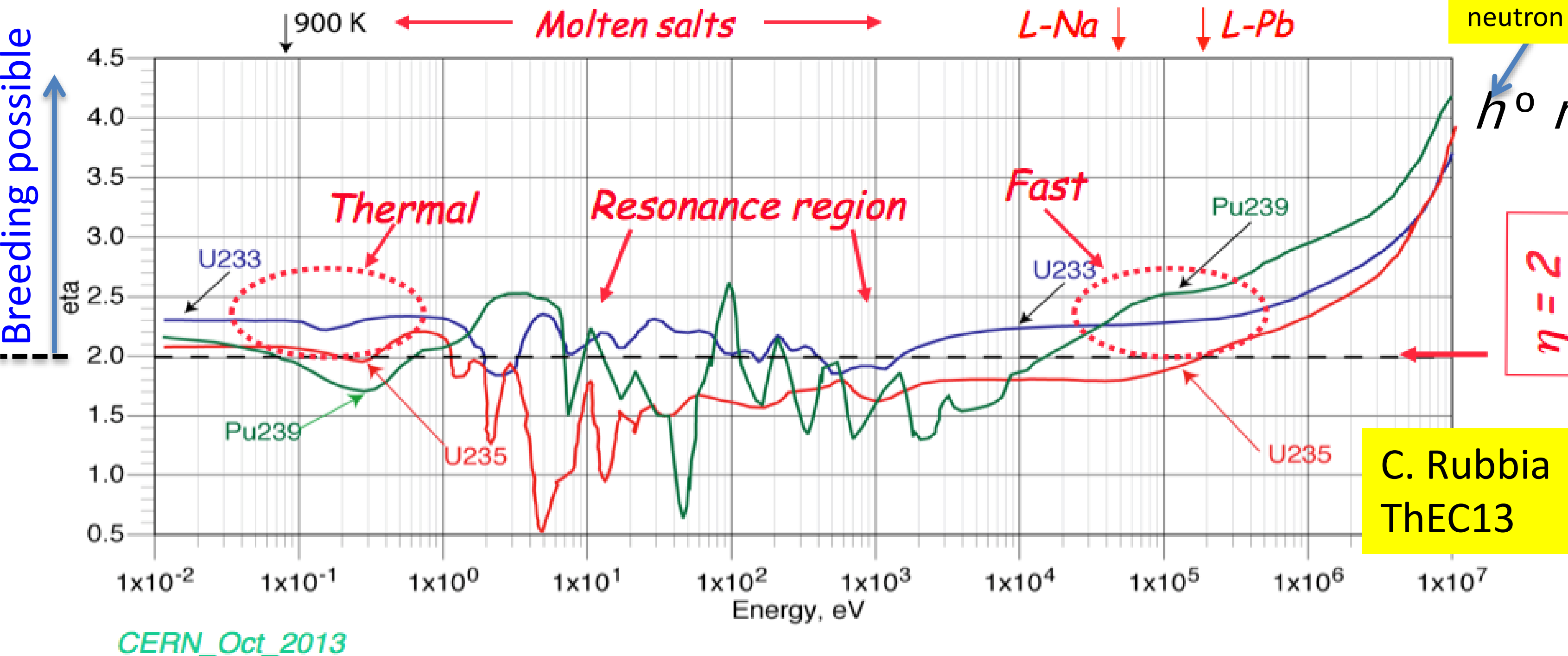
Thorium chain

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

- ^{233}U is an excellent fuel for a breeder system, especially with fast neutrons

Neutrons produced per neutron absorbed

$$\eta \equiv \nu \frac{\sigma_f}{\sigma_f + \sigma_c}$$

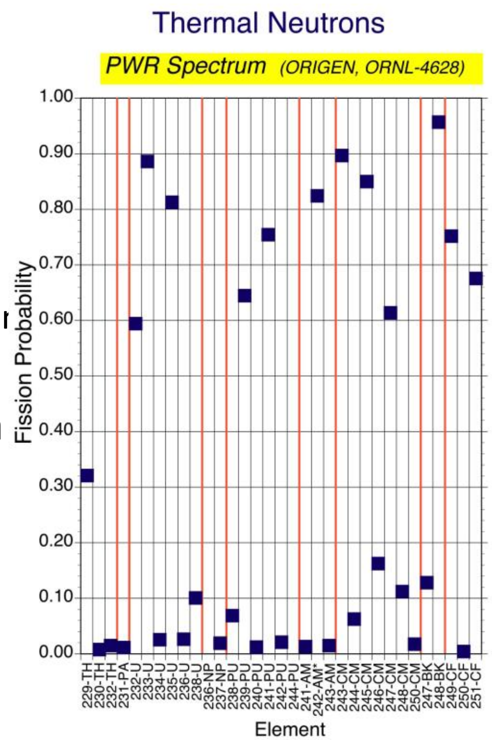


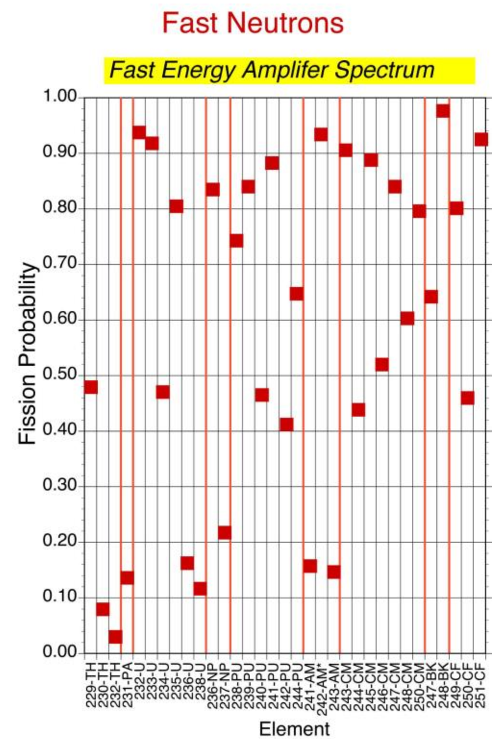
C. Rubbia ThEC13

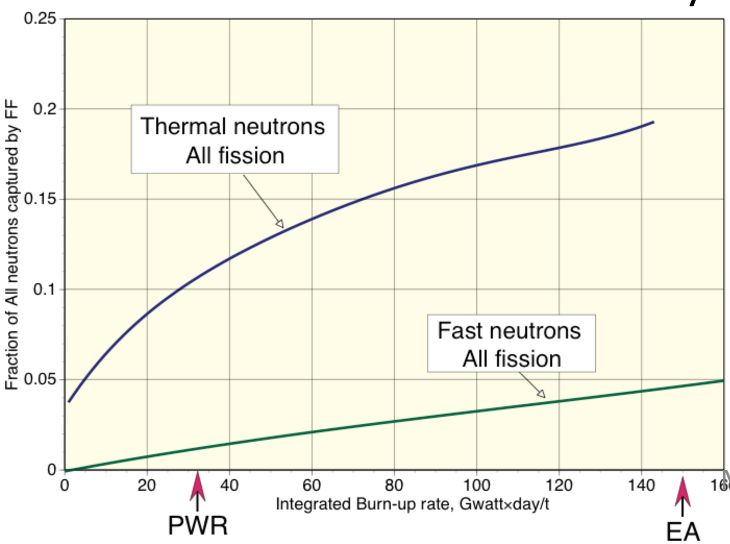
- But the environment has to be taken into account (^{232}Th, ^{238}U). Thorium + ^{233}U cannot be substituted simply to PWR fuel because of neutron inventory issues (capture rate on thorium and long half-life of ^{233}Pa)

Fast neutrons are needed anyway

- **Advantages of fast neutrons**:
  - Favorable to breeding
  - Enhanced TRU fission probability
  - Simplified reprocessing
    - No need to separate out Pu! (Pyro-Electro reprocessing?)
  - Extended burnup
    - Reduced captures on FF, (120 GW.day/t achieved in fast electro-breeder at Argo N.L., and in EA simulation)
  - Better proliferation control (System could be sealed for 5 to 10 years)







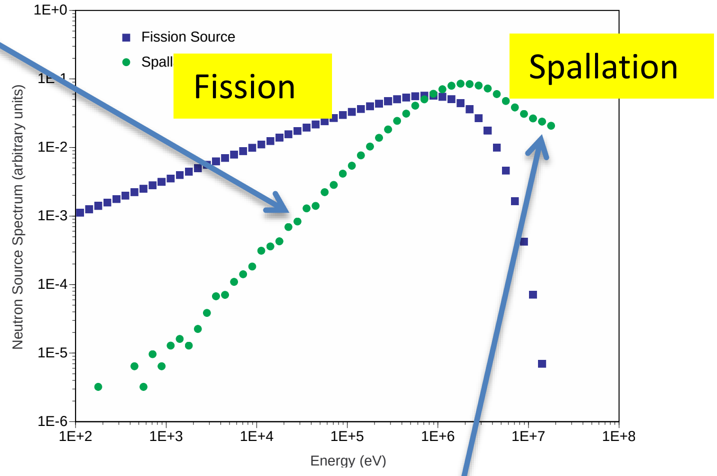
Using Thorium

What are the options?

- Use **thorium blankets** around reactors, to breed ^{233}U and introduce ^{233}U in fuel
  (n + $^{232}Th \rightarrow {}^{233}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$)
- **Continuously move the fuel out**, such as to always have fresh fuel
  - Pebble bed reactors (once through)
  - Molten salt reactors (reprocessing on-line)
  - Traveling wave reactor (Encouraged by Bill Gates in Terra Power)
- **Provide an external neutron source** – Accelerator Driven Systems (**ADS**): this is the solution proposed by C. Rubbia at CERN in the 1990's and promoted by iThEC

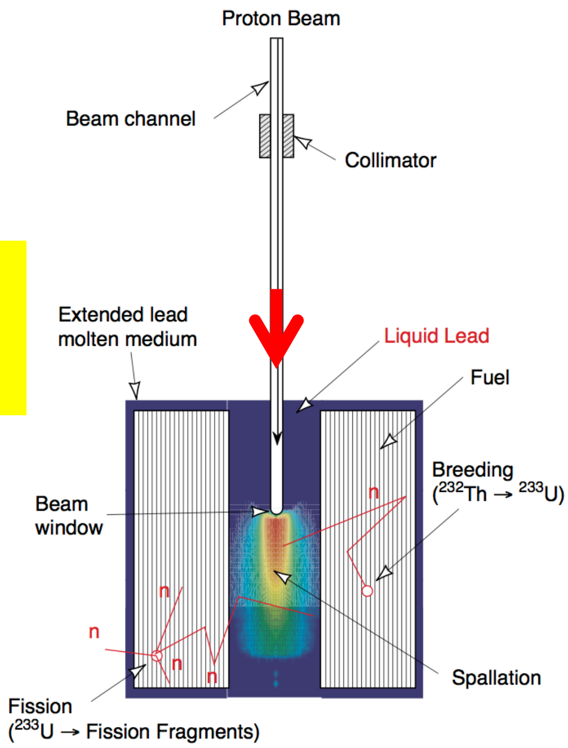
ADS: the subcritical approach

- 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.

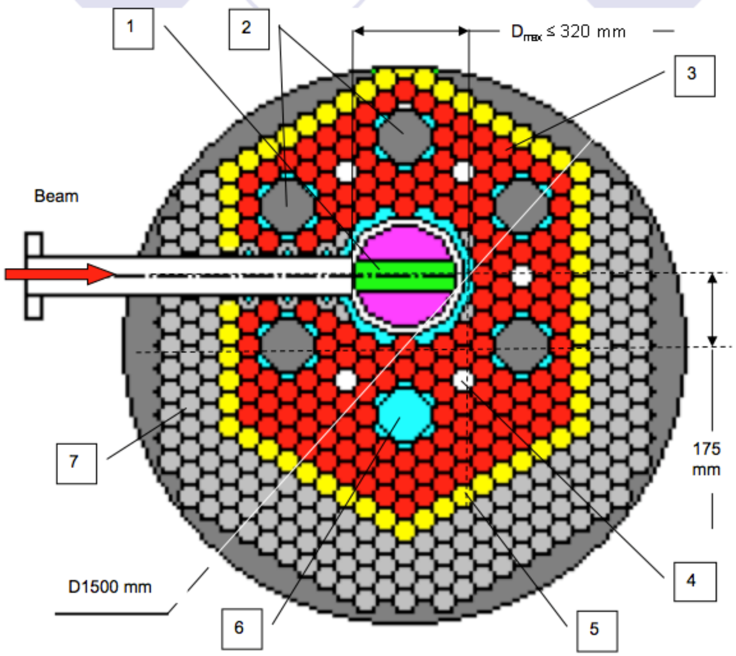
C. Rubbia, et al., «Conceptual Design of a Fast Neutron Operated High Power **Energy Amplifier**», CERN/AT/95-44 (ET)



Example in TEC13: An ADS Experiment at INR Troitsk

- At ThEC13 Stanislav Sidorkin presented a proposal of an ADS experiment at Troitsk, using the Moscow Meson Factory, at the Institute for Nuclear Research (INR)

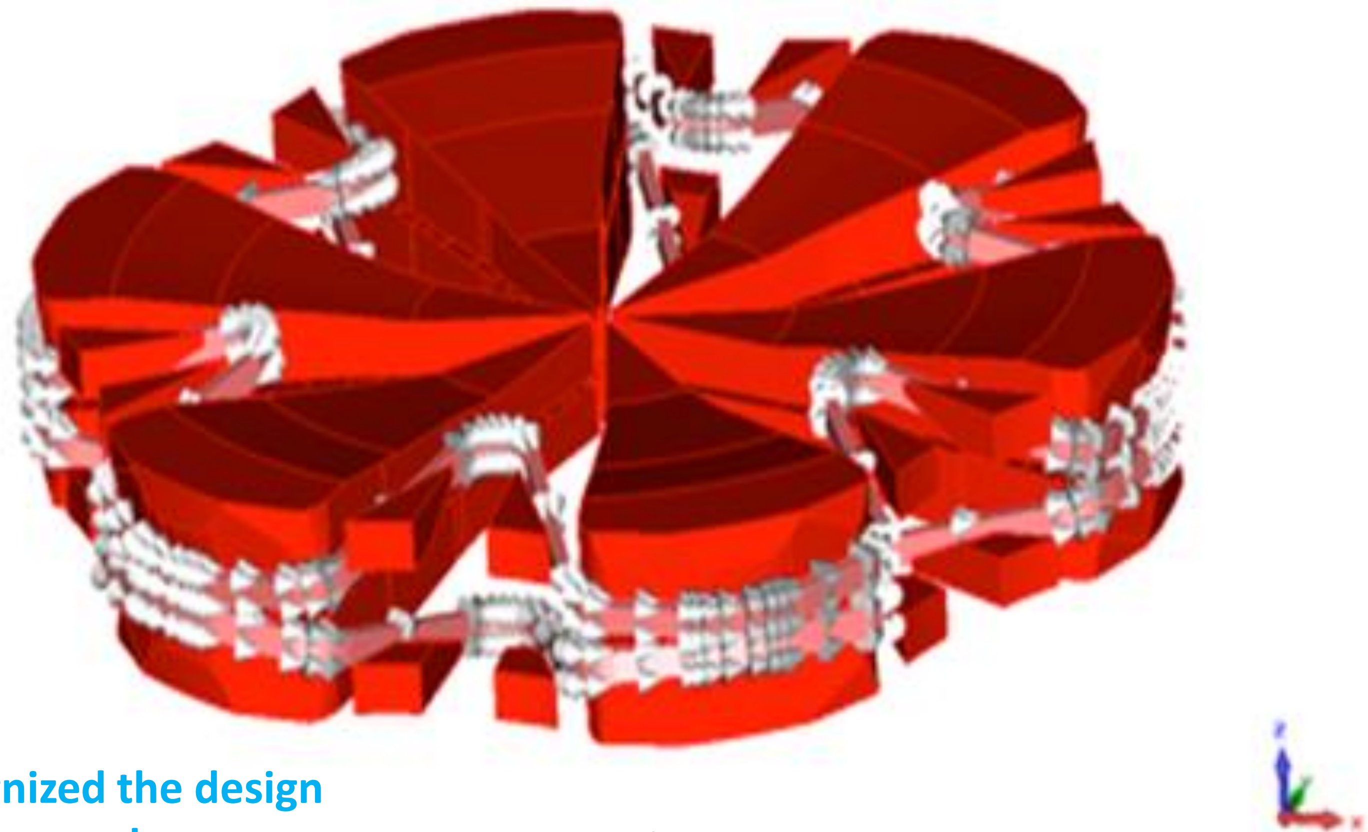
Conceptual scheme of research ADS



1 –target module;
2 – hermetical PbBi capsules with high enriched fuel and minor actinides;
3 – the cassettes of the water-cooled part of blanket with MOX fuel (~ 25% enr.);
4 – the module of controlled systems;
5 – decoupler (if it is required);
6 – traps of thermal neutrons (moderator) can construct in any place ;
7 – reflector.

iThEC recognized that it could be a realistic possibility of having an ADS experiment

Examples: cyclotron drivers for ADS (P. Mandrillon et al.)



iThEC recognized the design could be proposed to HORIZON 2020 FET

3D view of the 6-sector single-staged AIMA DEVELOPMENT cyclotron with reversed valley B-field

20 Years History of ADS

√ – ***Phase 1:*** ADS basic concepts were developed at CERN [FEAT, TARC/CERN patent), neutron cross section data (n_TOF), simulation tools (FLUKA, **EA-MC,** GEANT4]

√ – ***Phase 2:*** All basic elements of ADS have now been tested separately – (spallation neutron source (MEGAPIE/1MW at PSI), development of high power targets (EURISOL DS/5MW at CERN), SNS, ESS, R&D on high-power accelerators (IPHI, SPL, LINAC4, high-power superconducting RF structures (SRF), etc.)

The next steps for ADS

- **Phase 3**:
  - **Coupling** of a beam to a subcritical core at significant power (≥ 1 MW) to characterise the properties of ADS, demonstrate safety and learn how to operate the system;
  - Development of a high-power proton beam **adapted** to ADS
- **Phase 4**:
  - Design and construction of an industrial prototype
  - Development of appropriate thorium fuel cycle

iThEC activities are presently centered on phase 3

– iThEC identified unique opportunities to contribute to phase 3

Phase 3 should provide invaluable input for phase 4

iThEC

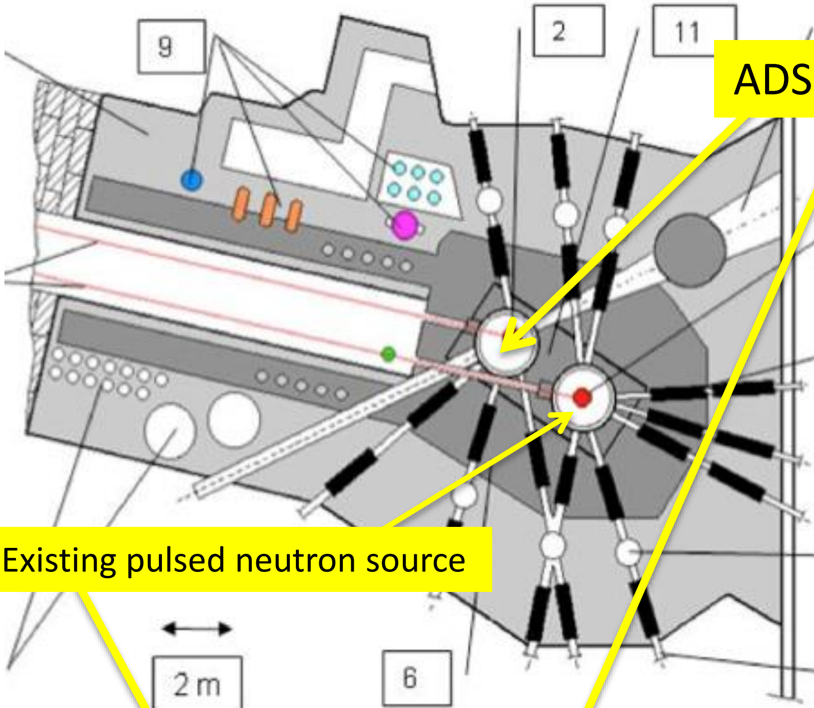
INTERNATIONAL THORIUM ENERGY COMMITTEE

Guidelines for ADS parameter choice

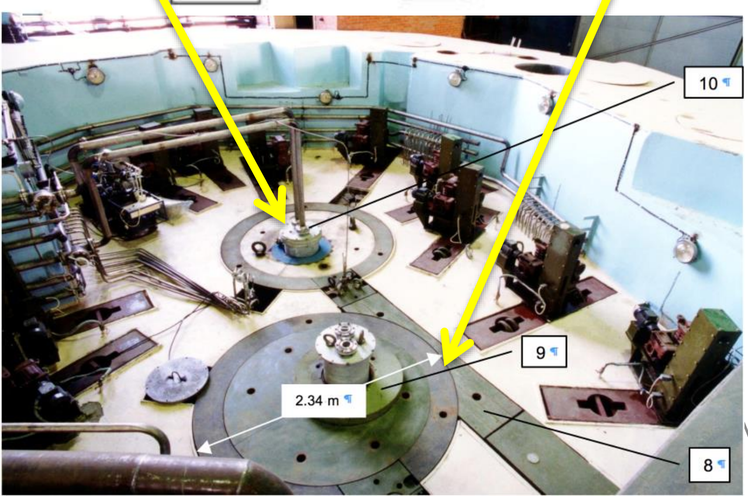
- **Safety**:
  - Eliminate criticality accidents by making the system subcritical (void coef., T coef., β_{eff} no longer "critical" parameters)
    This requires an external proton source!
  - Operate system with passive safety elements to avoid core melting or limit its consequences, borrowing features from US advanced fast critical reactor designs;
  - Avoid dangerous coolants such as liquid sodium (use lead) Generation IV?
- **Waste management**:
  - Use (1) fast neutrons, (2) thorium fuel, and (3) recycle long-lived transuranic actinides (TRU) to minimize waste.
- **Military proliferation**:
  - Use thorium fuel (small Pu prod., ^{233}U very difficult mixture)
  - Avoid Pu separation (Purex), use pyroelectro reprocessing instead (developed for uranium at Argone N.L.)

The INR/iThEC ADS Project at Troitsk

Using an existing facility at Troitsk



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



The existing INR Infrastructure

– proton linac (≤600 MeV, ≤ 300kW)

– Spallation neutron source

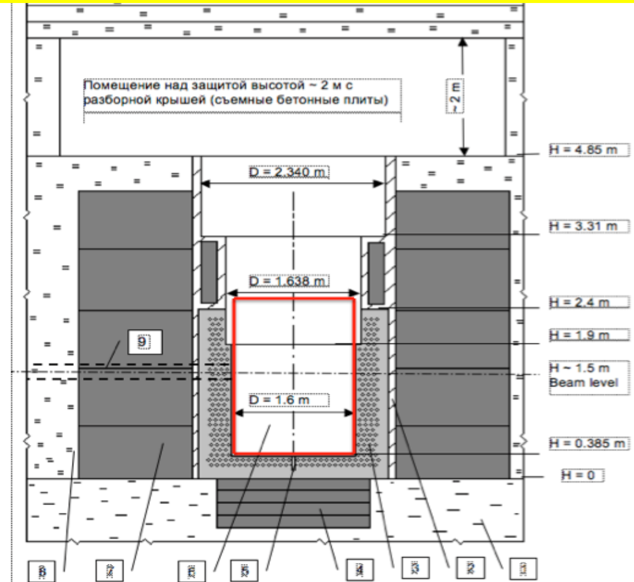
– Pit on a beam line to receive a **subcritical core**

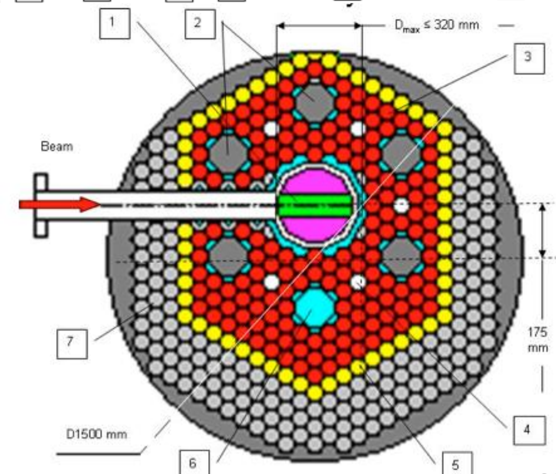
– Infrastructure (shielding, handling devices) to manipulate highly radioactive material)

Existing infrastructure at INR Troitsk

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

Faster and cheaper than current projects





Initial core design

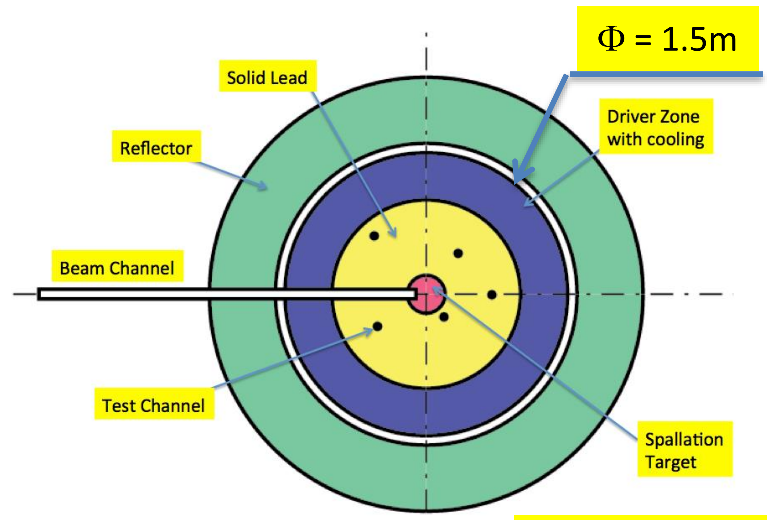
ADS experiment goals:

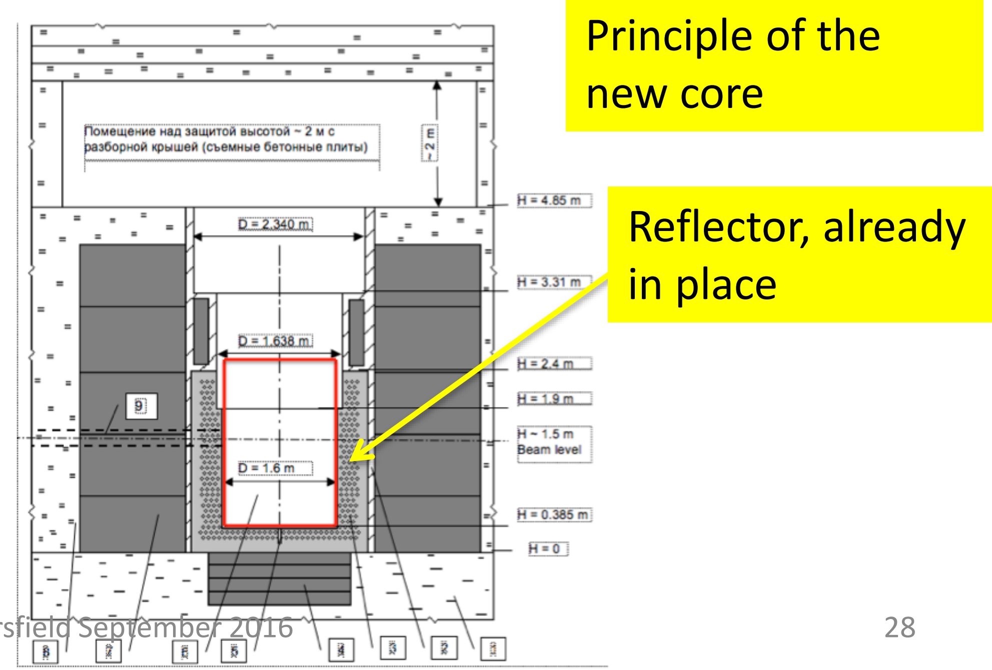
1) Measure physical properties of a 1 to 3 MW ADS (coupling accelerator to core; demonstrate safety; develop operational procedures)
2) Demonstrate transmutation of nuclear waste (MA & LLFP/TARC)
3) Provide unique fast neutron test facility, test the production of specific radioisotopes

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**

Optimizing the subcritical core concept

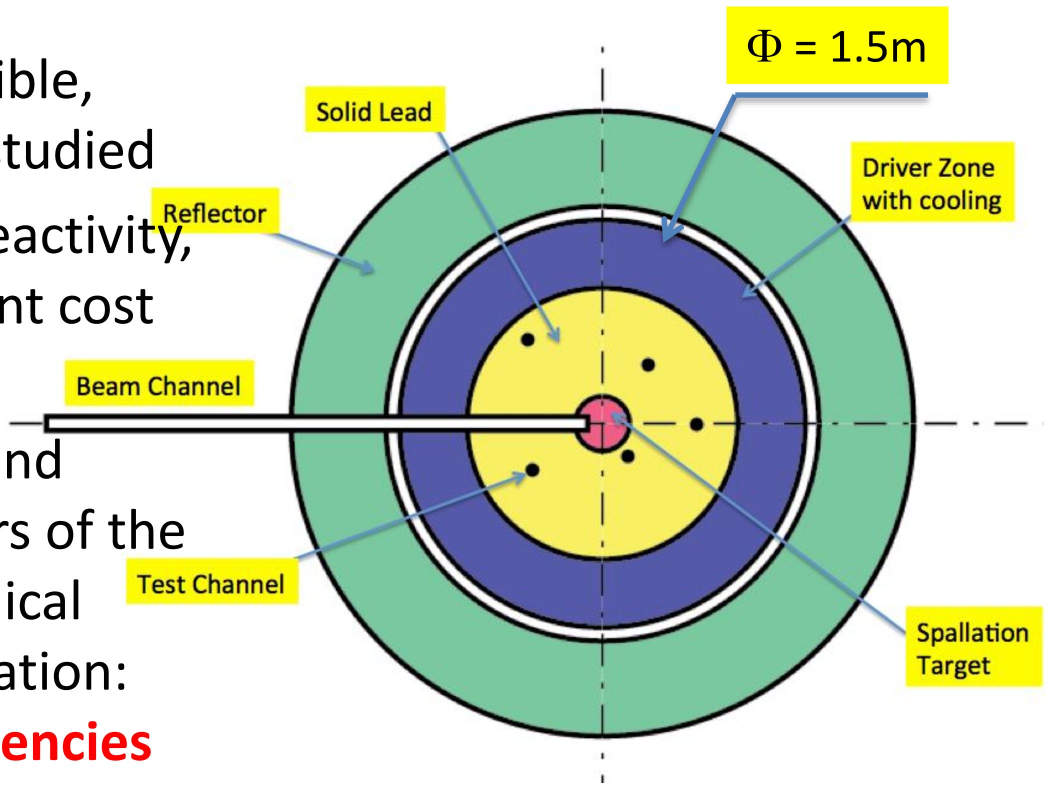
- Both an **ADS experiment and a fast neutron test facility**
- Control and protection system (CPS) and the physical and technical parameters of the ADS must comply with regulations of the Russian Federation:
  Core to be designed and submitted for approval to Russian safety authorities by ROSATOM specialized Agencies
- Road map prepared jointly by INR and iThEC
- Optimized conceptual design in preparation:
  - Ensure that all the goals can be fulfilled;
  - Simplify the structure in order to reduce the cost significantly
- INR Moscow, in cooperation with iThEC, other institutes in Russia and abroad (under discussion with EPFL, PSI, Řež, and CERN to form a collaboration)





Main principles of the core concept

- A fast neutron flux similar to a fast reactor/ADS flux (10^{14} n/cm^2/s?)
- Minimize the inventory of fuel
- Thermal drive zone may be possible, but fast driver zone will also be studied
- Simplify cooling and control of reactivity, which should result in a significant cost reduction
- Control and protection system and physical and technical parameters of the ADS must comply with the technical regulations of the Russian Federation: **To be designed by ROSATOM Agencies**



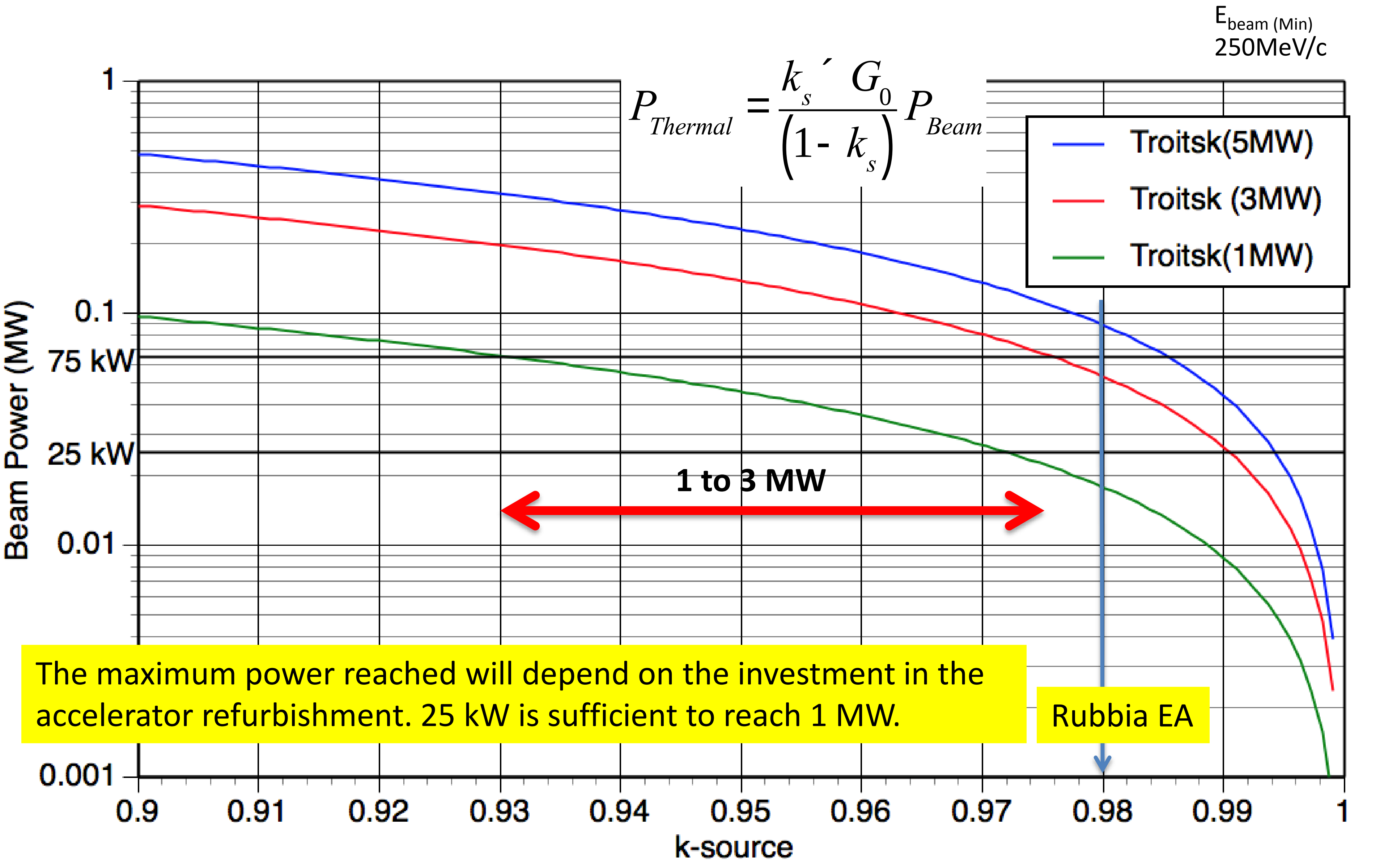
Technical assumptions

- **Minimum guaranteed beam power: 25 kW**, average beam power 50 kW, and maximum beam power 90 kW, all at a beam energy between 247 MeV and 300 MeV;
- In order to guarantee that a thermal power of 1 MW can be reached, k will have to reach 0.972, and in general during operation **k will be varied up to a maximum value of 0.98**, to characterize the core to accelerator coupling over the largest k range;
- As the beam power is relatively small, the target will be **a solid target, most likely tungsten, water-cooled**. This is a simplification and a significant saving on the cost;
- **The maximum thermal power could reach 3MW** (at 75 kW beam power), therefore the cooling of the core should allow for this.

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

The above assumes G_0 = 1.15, which will have to be refined for the specific tungsten target to be used

What can be done at Troitsk?



The maximum power reached will depend on the investment in the accelerator refurbishment. 25 kW is sufficient to reach 1 MW.

Troitsk ADS scientific program

- The scientific program is similar to what was for foreseen for TRADE:
  - Mapping of the neutron flux (energy and intensity) inside the lead volume;
  - start-up and shut down procedures;
  - Precision measurement of reactivity and monitoring of the time evolution of the reactivity;
  - operation and monitoring of the system at steady state;
  - practical coupling of an accelerator, a spallation target and the subcritical core, reaction to change in beam power;
  - Temperature coefficient;

- These measurements will employ standard techniques already used for the FEAT and TARC experiments at CERN

Russian Academy of Sciences

INSTITUTE FOR NUCLEAR RESEARCH

60-th October Anniversary prospect, 7a, Moscow, Russia 117312
Tel. +7(499) 135-77-60, +7(495) 851-00-71
FAX: +7(499) 135-22-68, +7(495) 851-07-11
E-mail: inr@inr.ru; Internet: www.inr.ac.ru, www.inr.ru

Prof. Jean-Pierre Revol

President of iThEC

May 27, 2016

Dear Professor Revol,

In order to characterize Accelerator-Driven Systems, define their operation procedures and demonstrate transmutation of nuclear waste, a technical evaluation of the capabilities of the 1-5 MW ADS research facility of the Institute for Nuclear Research (INR), Moscow at Troitsk site was carried out. The results of a design study based on simpler structures and geometries of the core show that an initial experiment with a 250-300 MeV proton beam of 25-90 kW (i.e. 1-2 MW of thermal power in the core) would be feasible in 5 years, at much smaller cost than other currently considered ADS projects.

INR is considering this proposal very seriously and it has a high priority in the Institute research program. At the same time the Institute is in negotiations with our authorization agency namely, the Federal Agency of Scientific Organizations of the Russian Federation, for preparing all needed formalities to move the Project forward. First reaction is positive and we hope on their support for getting a Decree of the Government of the Russian Federation for the Project approval.

For the Project we are considering the iThEC as a strong partner and are counting on the scientific, financial and political support from Your Committee.

Sincerely Yours,

INR Director L.Kravchuk

From the Kremlin website:

"Russia's president Vladimir Putin has asked state nuclear corporation Rosatom and the Kurchatov Institute national research center to prepare a proposal by 1 March 2017 on the prospects for using thorium for nuclear fuel"

Troitsk Road Map and Planning

Phases 0 to 7 over 5 years

0– Preliminary phase (6 months)

- Specifications of technical parameters

1– Conceptual design

2– Obtain government authorization, which requires three steps:

- Declaration of intent
- Estimate of the impact on the environment
- Funding plan

3– Technical design

4– Licensing

5– Permission for construction and installation

6– Construction and installation

7– Permission for commissioning and operation

Characteristics of Troitsk Project

- An experiment to study the coupling of an accelerator to a subcritical core at significant power (≥ 1MW thermal), as ADS is the most practical way of using thorium, for nuclear waste destruction and for energy production
- A unique strategic development toward thorium technologies applied to the energy domain, based on an existing facility at Troitsk
- Provide input for the design of an industrial ADS prototype
- Provide a unique fast neutron test facility available for other developments, such as nuclear material research, with high flexibility in the operation compared to fast critical reactors

The CERN/iThEC superconducting high-power cyclotron project

Accelerator Requirements for ADS

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 $\mathbf{E_{beam} \geq 900}$ **MeV** (See FEAT experiment), but lower energy can be compensated by higher current
- **Beam power**: **a few to ≈ 10 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 ➔ OK ≤ 0.1-0.2 mA/cm^2 , MYRRHA has 0.07mA/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 ≤ 1W/m for LINACS, for cyclotrons losses are localized at injection and extraction)

Accelerator requirements for ADS

- **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 $T_{trip} < 0.1$ s
  - Not more than 100 trips per day $0.1 \text{ s} < T_{trip} < 3$ s
  - Not more than 10 in three months for $T_{trip} > 3$ s
  - Administrative limit if SCRAM event

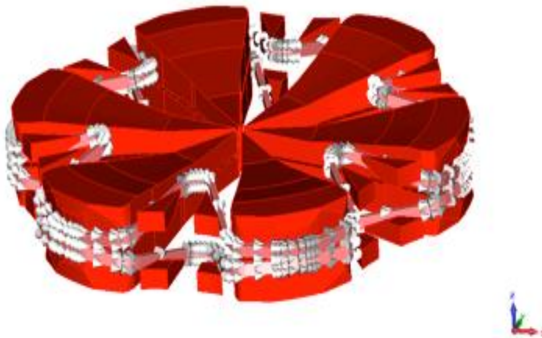
1) Make the accelerator more reliable: Redundancy (several sources, several accelerators, etc.)
2) Improvements in materials, maintenance and operation (the performance of a system generally improves with time, c.f. Beznau in Switzerland)
3) Relax the demands from ADS (Molten Salt-ADS)

A Superconducting Cyclotron for ADS

Principle presented by Pierre Mandrillon at ThEC13:
"**Cyclotron Drivers for Accelerator-Driven Systems**"

- **High reliability:** 3 sources; smaller number of components compared to a linac
- **High efficiency:** cavities see the beam several times; superconductivity reduces the ohmic losses
- **Impact on the environment**: separated turns, beam losses localized
- **Cheaper infrastructure**: the gain comes from the much more compact infrastructure compared to a linac
- **Cost**: we expect the overall cost to be several times less the cost of an equivalent linac (it is one of the goal of the project to determine the cost in a reliable way)

High-power Superconducting Cyclotron



- ***EU Call**: "**Future and Emerging Technologies** 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."*

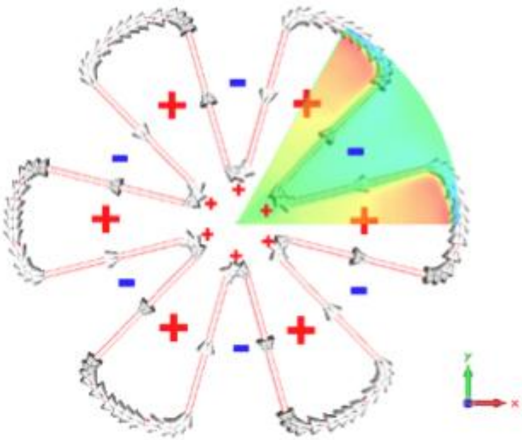
- **Project**: Conceptual design of a superconducting one stage H_2^+, cyclotron with 3 injections, 600 MeV, 6 mA, high electrical efficiency (> 40%)
- **Applications**: ADS, high flux particle beams, various other industrial applications
- **Collaboration**: iThEC, PSI*, AIMA**, ASG, Hydromine Nuclear Energy, Nuclear-21, project coordinated by CERN

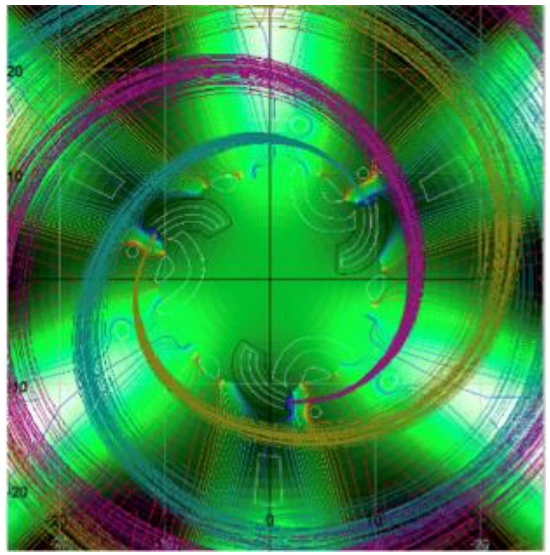
  ** Paul Scherrer Institute, Switzerland, operating the highest power cylcotron*

  ***P. Mandrillon, cyclotron expert, Centre Antoine Lacassagne, Nice*

The AIMA Reverse Valley B-Field Cyclotron®

Pierre Mandrillon @ ThEC13





Achieving isochronism while keeping vertical focusing at high energies is challenging: isochronism implies a large Positive radial gradient of the average B-field resulting in a strong vertical defocusing:

$$\Delta\nu_z^2 = -(\gamma^2-1) = -(d\langle B\rangle/dr)r/\langle B\rangle$$

which could be overcome by edge and spiral focusing (cf. PSI Ring Cyclotron)

$$\nu_z^2 = -(\gamma^2-1)+F^2(1+2\tan^2\zeta)$$

F^2 = Field Flutter = $(\langle B^2\rangle-\langle B\rangle^2)/\langle B\rangle$

Where ζ = spiral angle of the sector

A simpler Separate Sector Cyclotron:

=> No spiral => Stronger Flutter

= Reverse valley B-field

Proton extraction through stripping of H_2^+ is simple !

A major advantage: The B-field configuration in the central Region allows acceleration at low energies

➔ An injector cyclotron is not needed anymore !

High-power Superconducting Cyclotron

- The objective is to deliver a conceptual design that is in principle adoptable by the market.
- We plan to demonstrate the main conceptual aspect of our design with prototypes and PoC demonstrators that are aimed to bridge the gap to industrialization.
- We plan to get a full understanding of the cost drivers that have made unacceptable this technology so far.

Conclusions

iThEC has initiated two projects, to contribute to the energy problems of tomorrow:

An EU-H2020 project, implemented through a Future Emerging Technology call (FET) : designing a **single stage High Power Superconducting Cyclotron** to drive spallation neutron sources.

The formation of a **multi-national collaboration to use the Troitsk facility for ADS**; a workshop will be organized next year; we are looking for political and financial support in several countries.

Additional Slides

Thorium ($^{232}Th_{90}$)

- **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: > 4.4x10^{6} tons (> 1700 years of world electric energy consumption*); poor indicator because not searched systematically. "***Thorium is a source of energy essentially sustainable on the human time scale***"

C. Rubbia @ ThEC13

- **Relatively cheap**: 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, 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). Better thermal conductivity of Th is better than U: **Higher margins for design and operation**
- **Smaller production of TRU:** Less Pu and MA production than uranium
- **Proliferation resistant**

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

*World electrical power consumption: ~2.5 TW

Thorium Supplies ?

- Constitute a yet unused energy resource.
- *Is chiefly refined from [monazite] sands as a by-product of extracting [rare earth metals].*
- Norway could have the world's third largest deposit of thorium, most of it at the Fen field.
- The Fen volcano had a sister which was last active much more recently – in 2007.

The Doinyo Lengai Volcano, Tanzania. (Photo: Pedro Gonnet, Creative Commons)