TRANSMUTEX

Transmutation of Nuclear Waste with an Accelerator-Driven System

Colloquium presented by Maurice Bourquin

PSI, December 9th, 2021

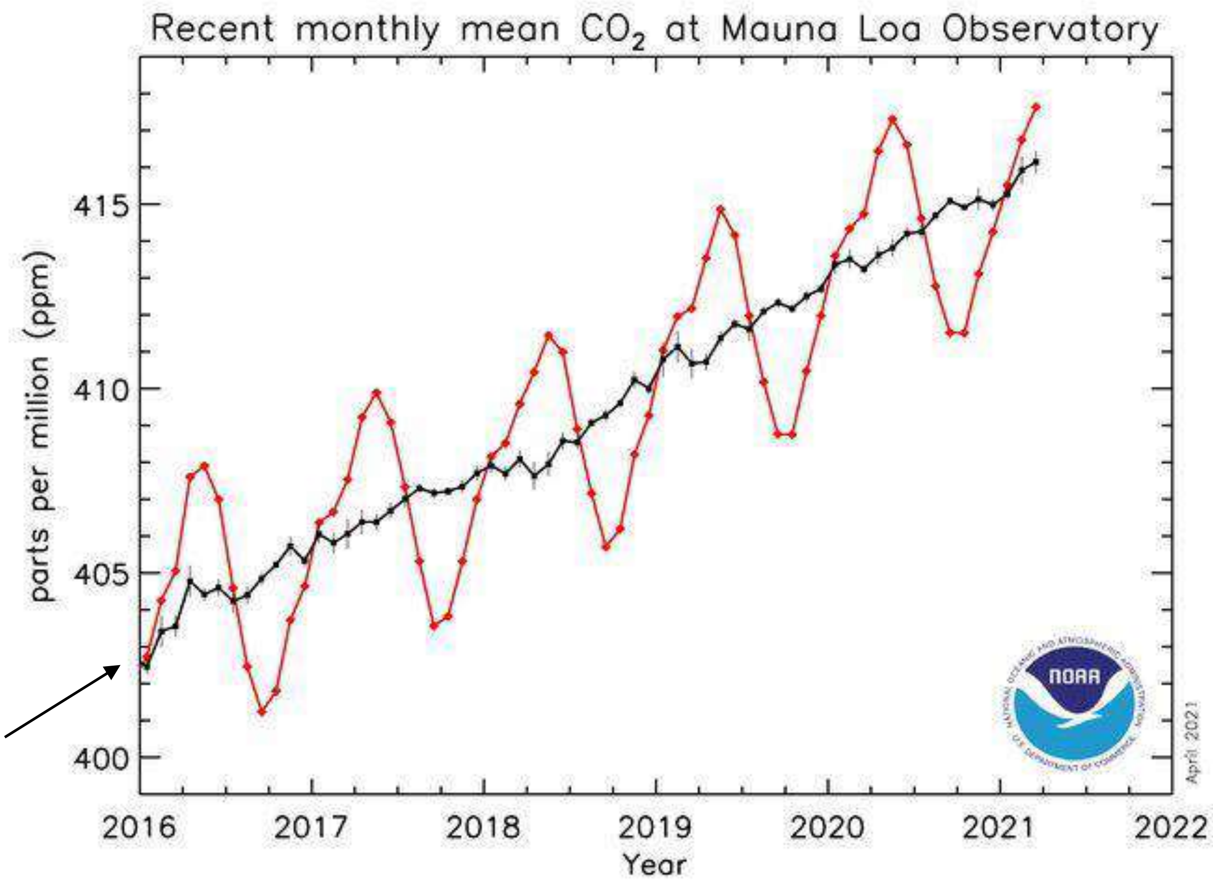
Motivations

- Transmutex SA is a private company, founded in 2019 in Geneva, which aims to develop a new nuclear technology that allows the "burning" of existing nuclear waste, while producing carbon free energy.
- This process was demonstrated at CERN in the 1990’s, confirmed by numerous studies and by PSI.
- And now we have the climate urgency, computing power, new materials, a team, …

Some Members of the Transmutex team in the office in Geneva

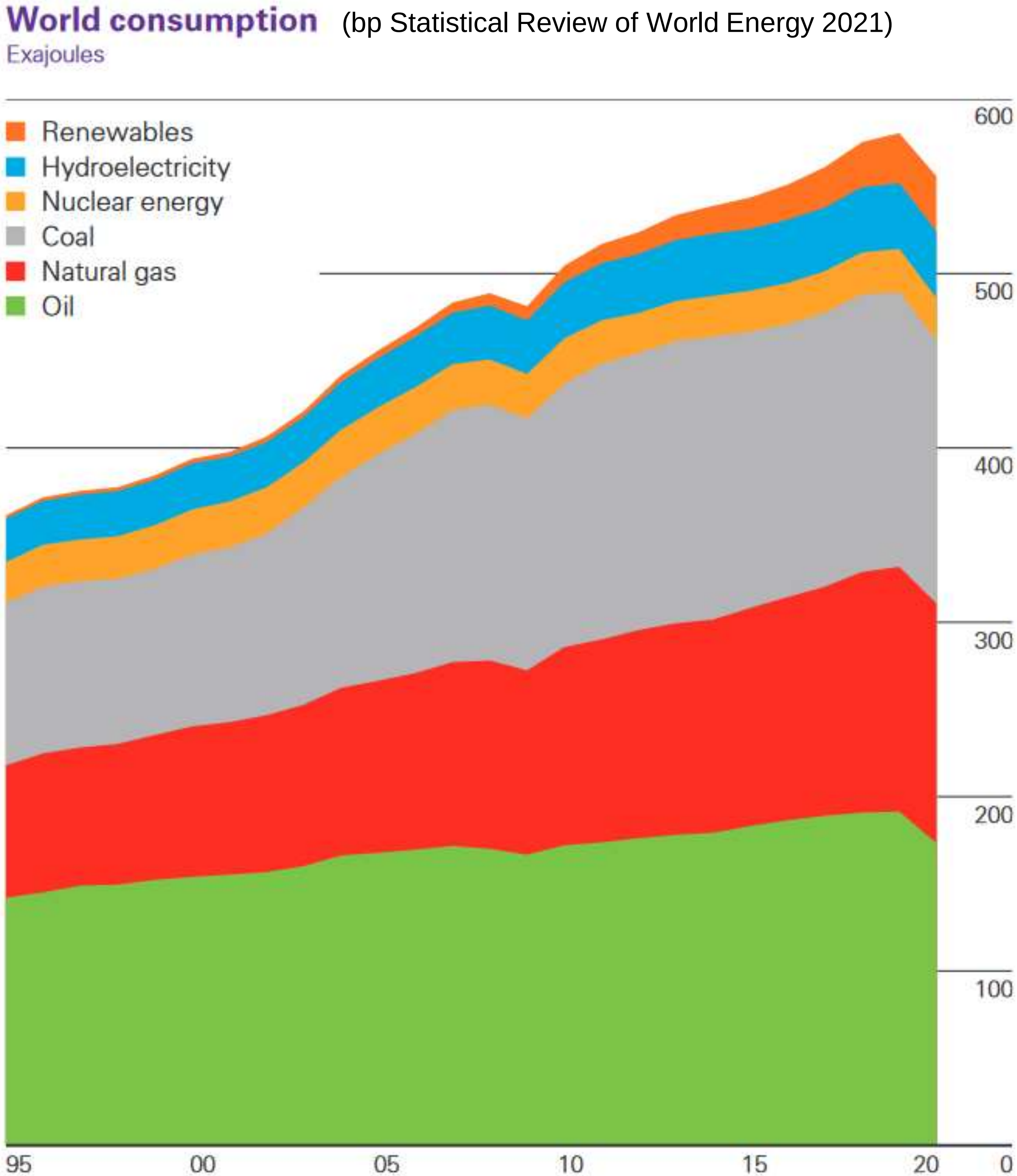
1. Relentless Rise of CO_2

2015
Paris Agreement



2. Huge share of fossil fuel consumption for energy production

(bp Statistical Review of World Energy 2021)



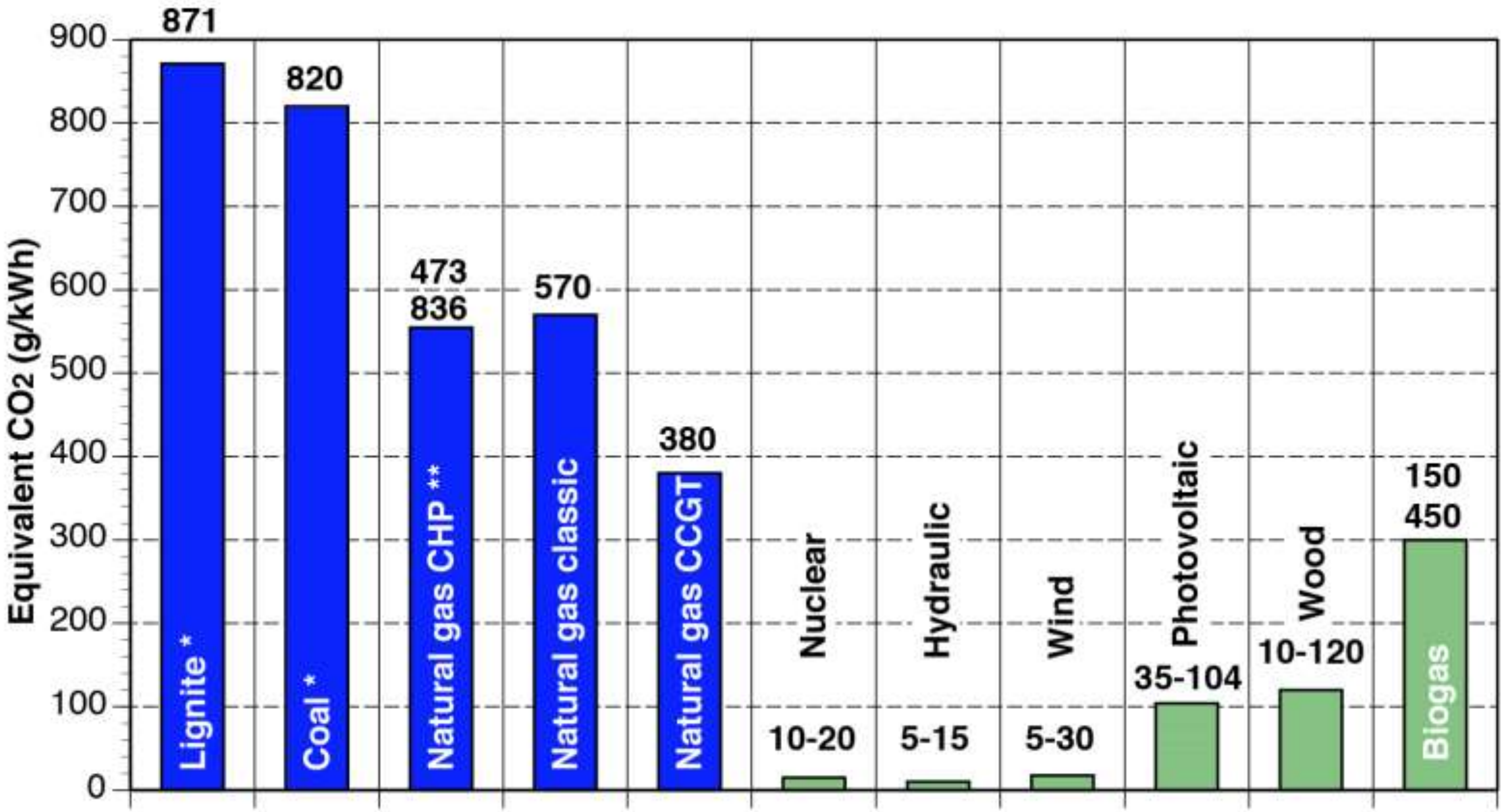
Energy in the form of electricity is about 20% in the world, with growth particularly strong in developing economies,

but also in Switzerland (now 27%, expected 43% in 2050),
12 new TWh needed for electric vehicles and heat pumps

CO_2 Emissions by Electric Energy Source

(See www.electricitymap.org for live data)

Source : Office Fédéral de l'énergie, Suisse,



* Values for large modern gas power plants with coal gasification

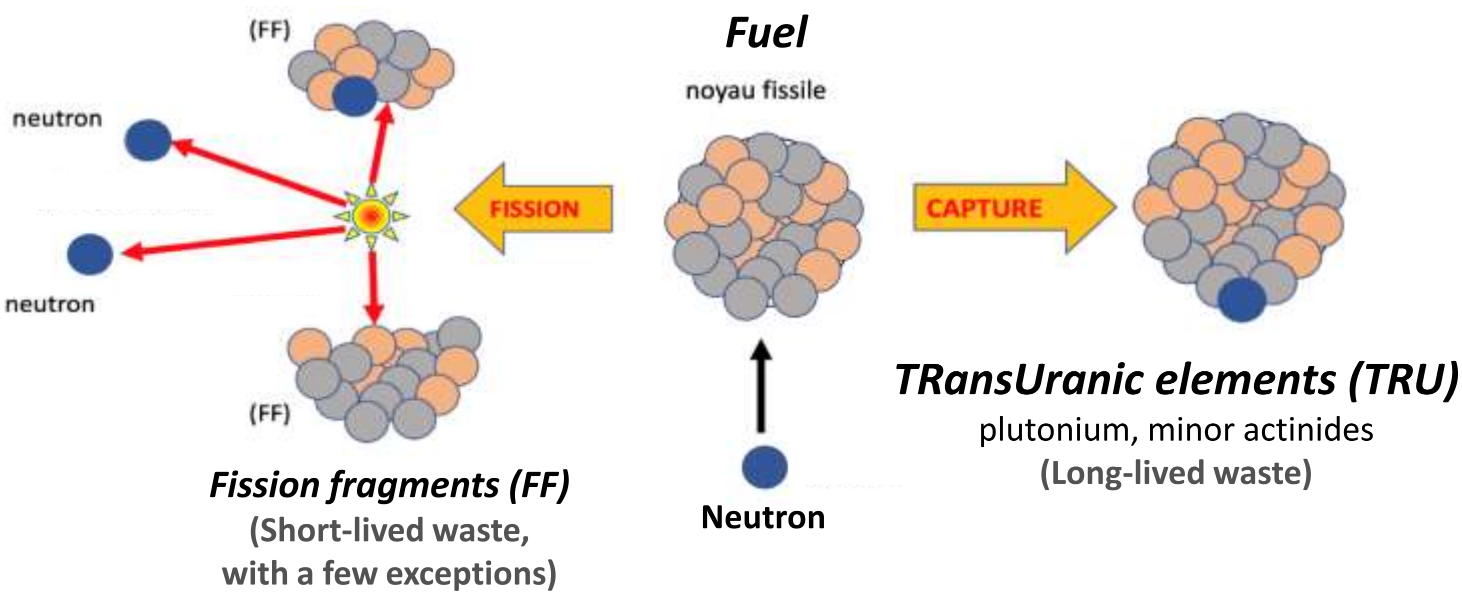
** Cogeneration plants, often called combined heat and power (CHP) facilities

Motivations

- Nuclear energy could play a greater role: an energy source that is carbon free, runs anytime, anywhere, irrespective of the weather
  - EU Commission: “nuclear and natural gas are to be reclassified as part of the renewable energy mix”

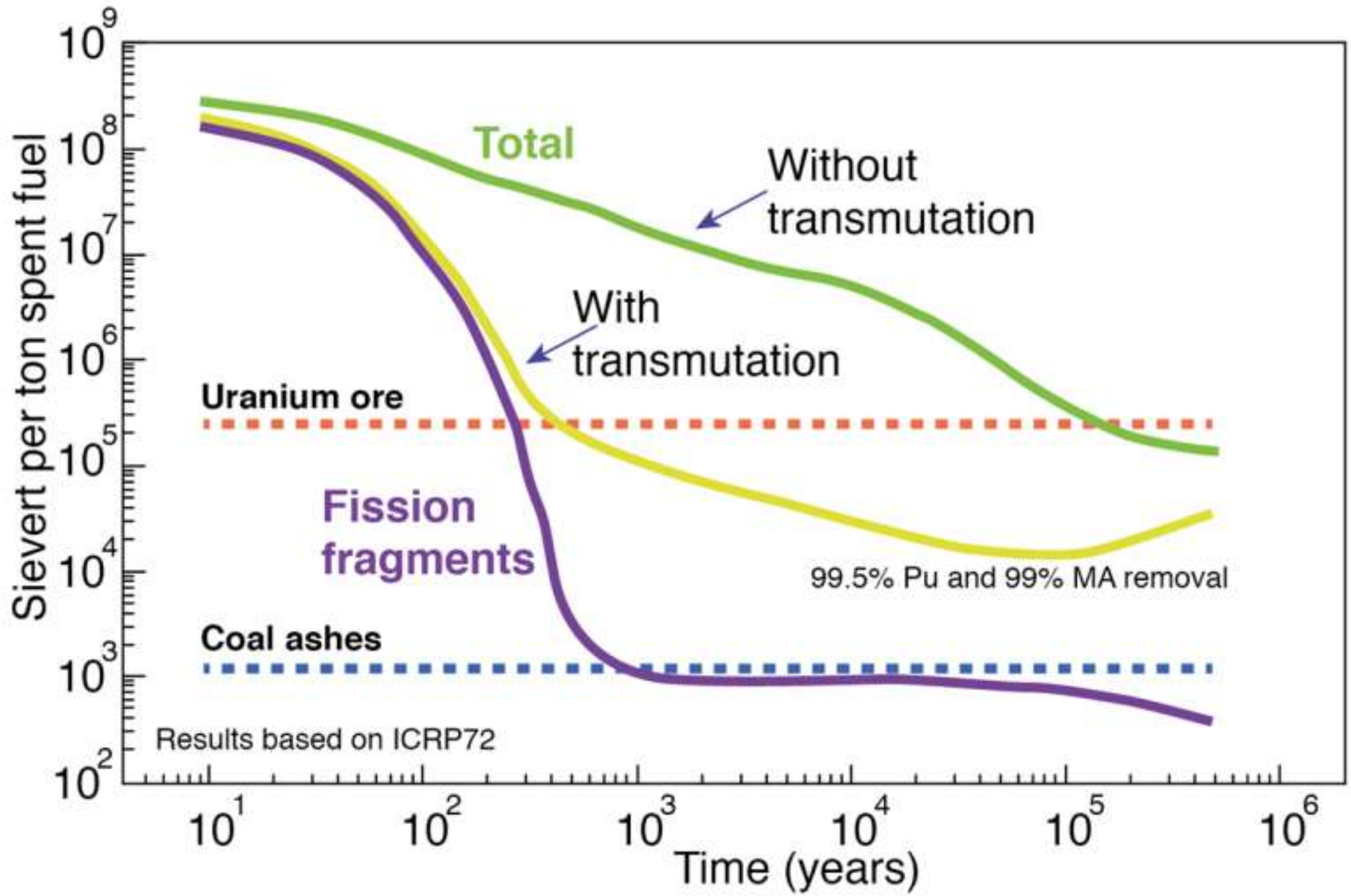
- However **nuclear power plants** fueled by uranium are problematic:
  - risks of accidents (active safety, water cooling…)
  - management of radioactive spent fuel,…

Nuclear Waste

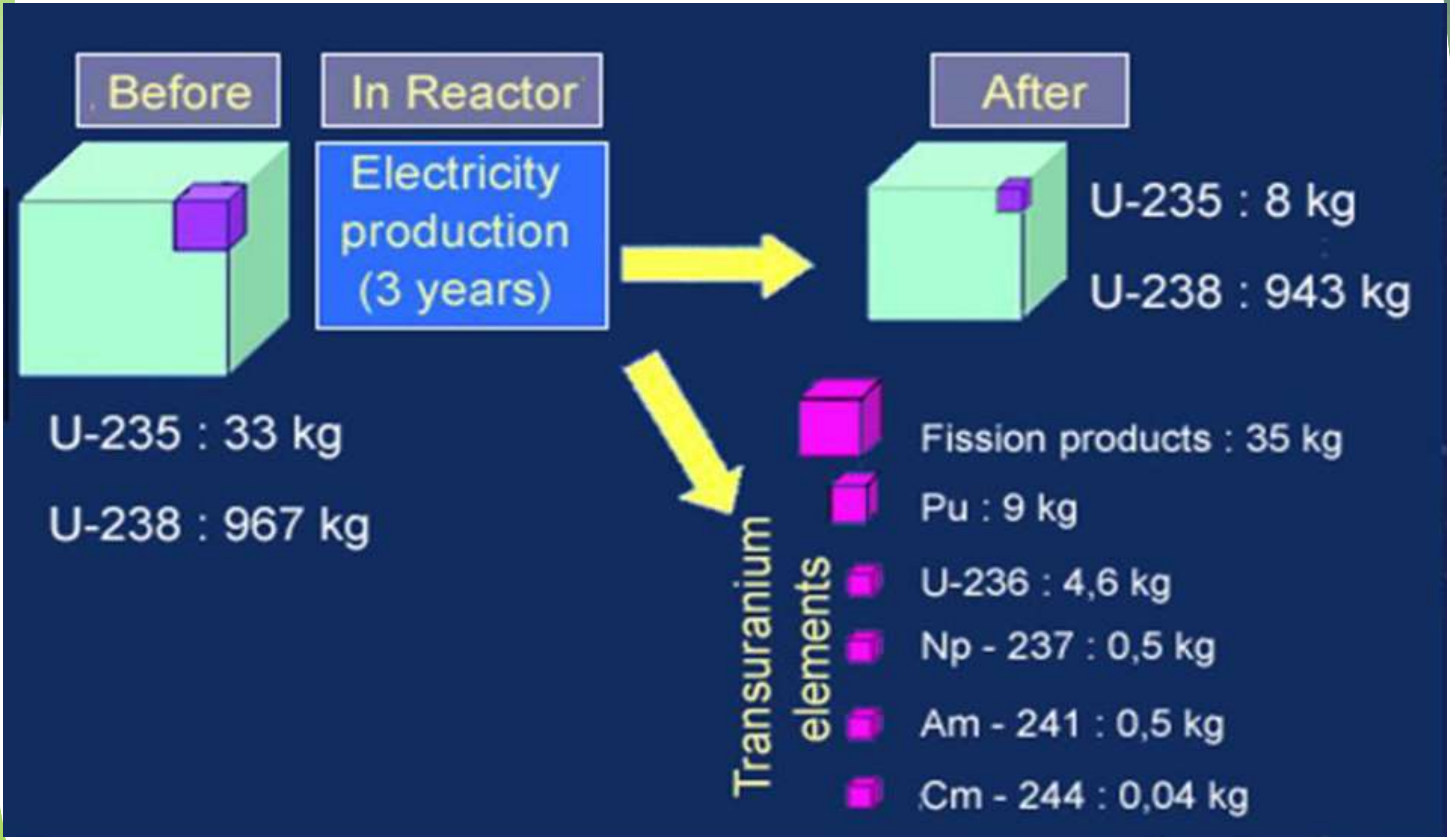


Ingestion radiotoxicity of spent nuclear fuel

in Sv per ton of heavy metal as a function of time after discharge from the reactor



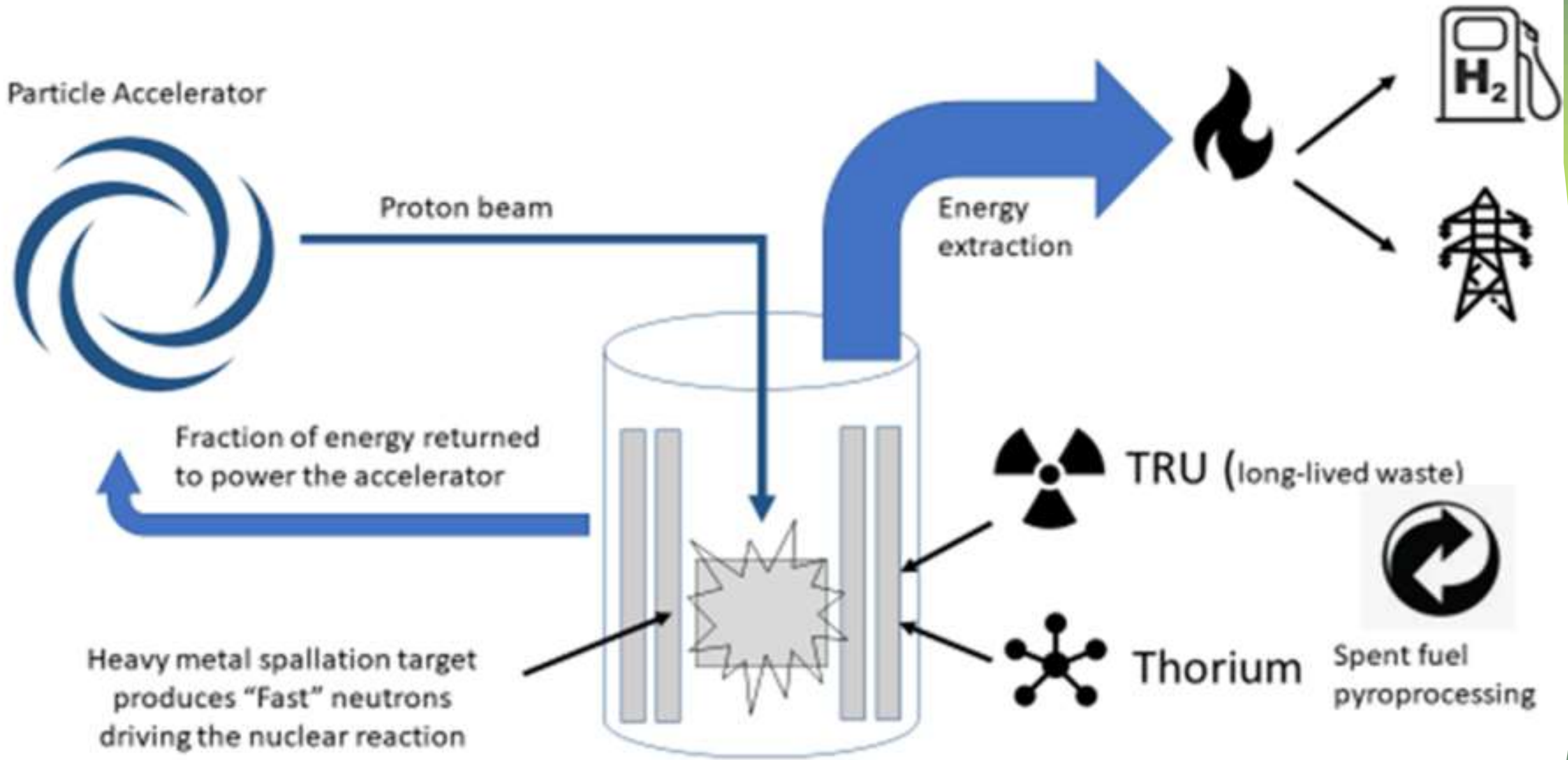
Spent Fuel from Uranium Power Plants



Outline

- **Physics of Accelerator Driven Systems (ADS)**
- Potential of ADS for Transmutation
- Accelerator Technology for ADS
- Sub-Critical Assembly for ADS
- ADS Validation and Development by Transmutex

Sketch of an Accelerator-Driven System (ADS)

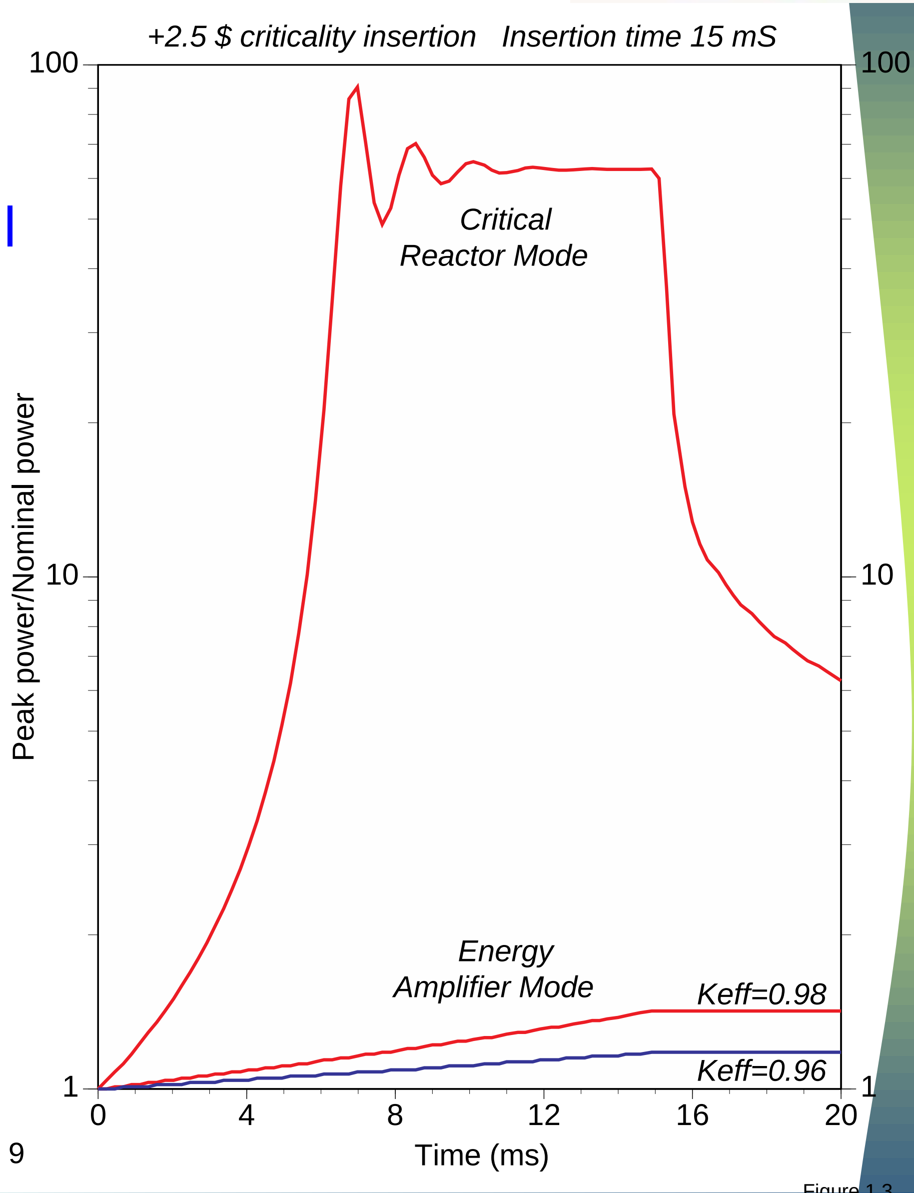


Reactivity Feedbacks

Major difference between a critical reactor and an ADS (reactivity in $\$ = \frac{\rho}{\beta}$ where $\rho = \frac{k-1}{k}$):

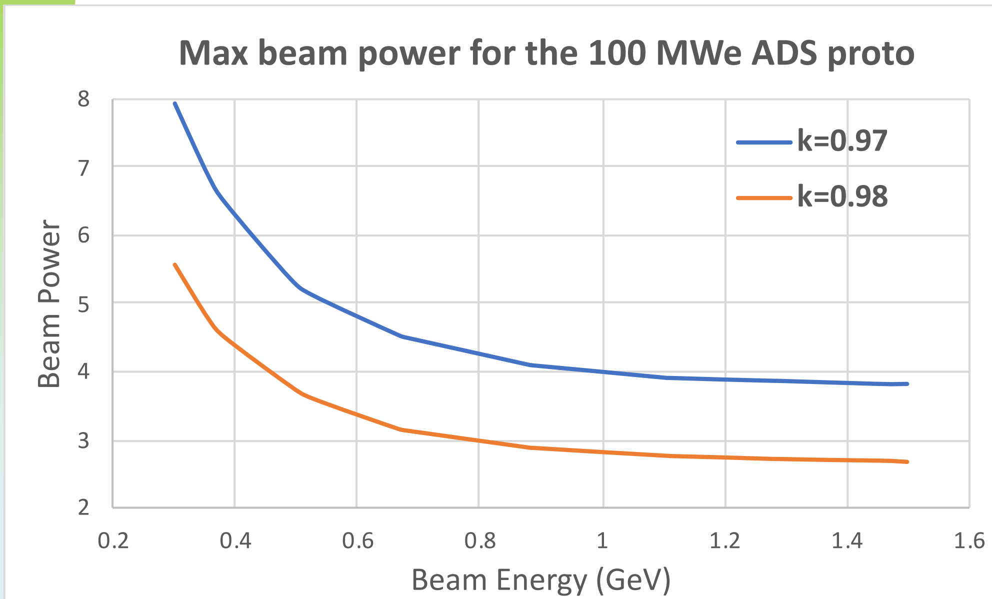
- Effect of a rapid reactivity insertion in the START ADS for two values of subcriticality (0.98 and 0.96), compared with a Fast Critical Reactor
- 2.5\$ ($\Delta k/k \sim 6.5\times10^{-3}$) of reactivity change corresponds to the sudden extraction of all control rods from the reactor

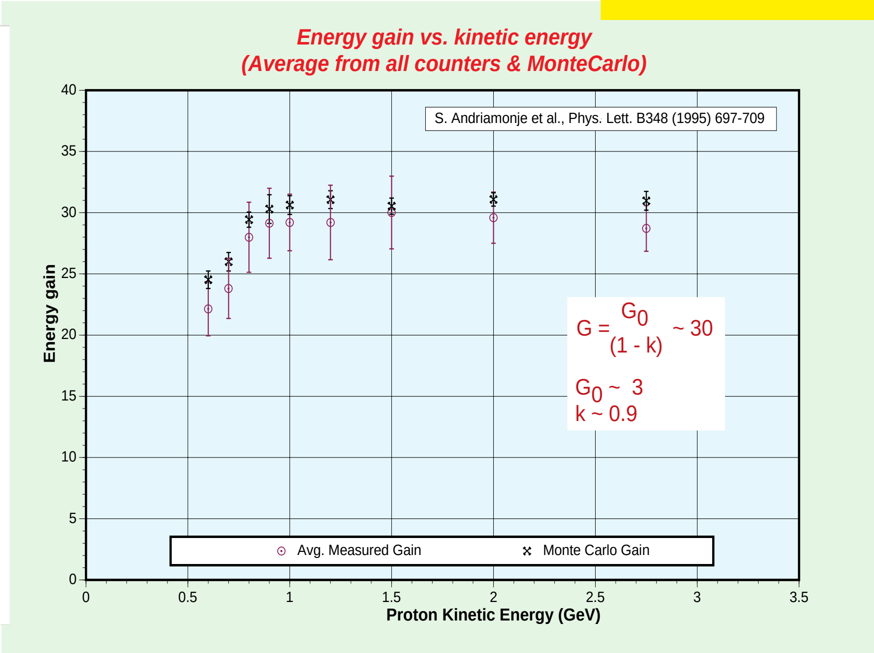
⇨ *Safety:*
The sub-criticality ($k \approx 0.97\div0.98$) is guaranteed at all times



C. Rubbia et al., CERN/AT/95-53 9

The FEAT Experiment – CERN 1994

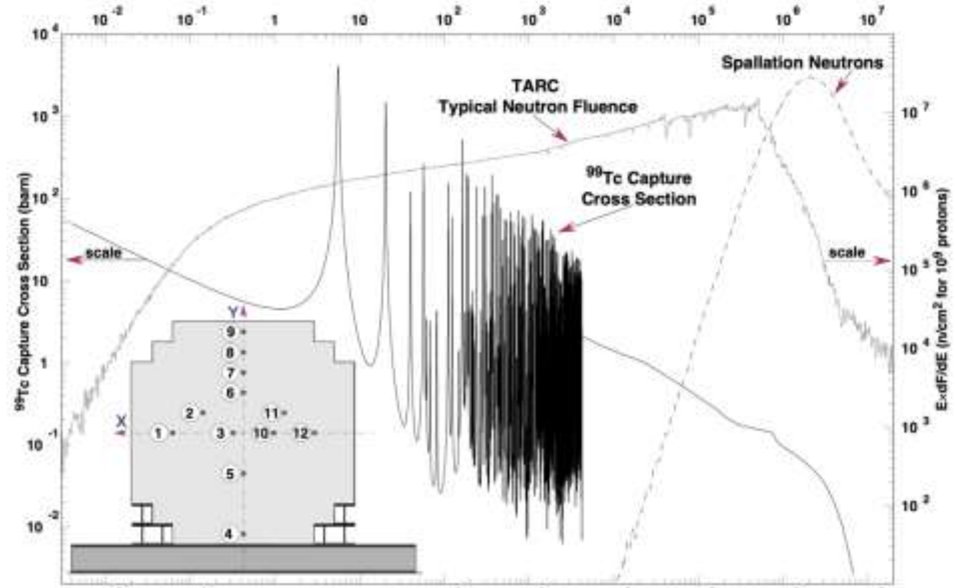


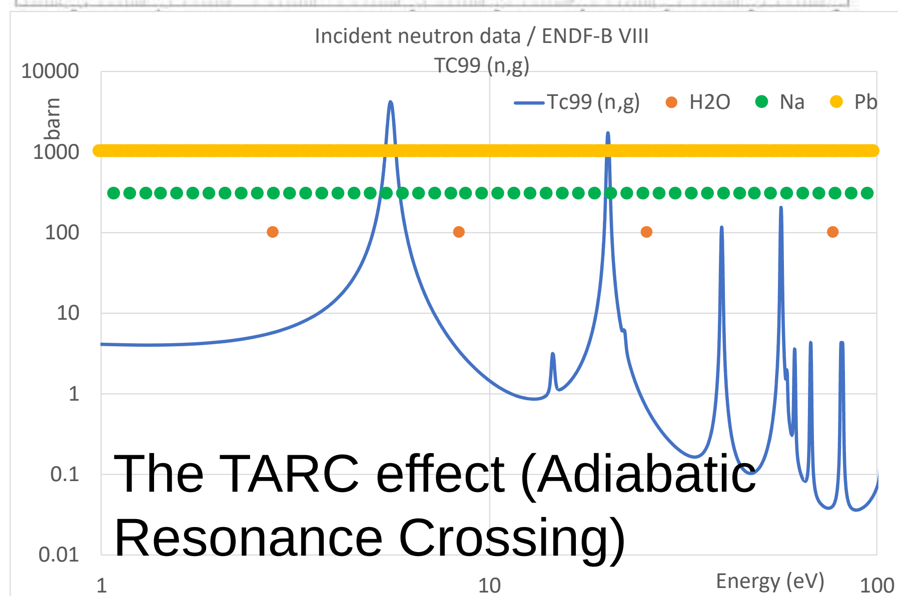


- The first *Energy Amplifier* (power ≈ Watt, k=0.9) was operated at CERN in 1994
- A *real* ADS with a gain of 30 as predicted
- Validation of innovative MC simulation tool.
- **Energy gain increases with particle beam energy** □ constant above 900 MeV

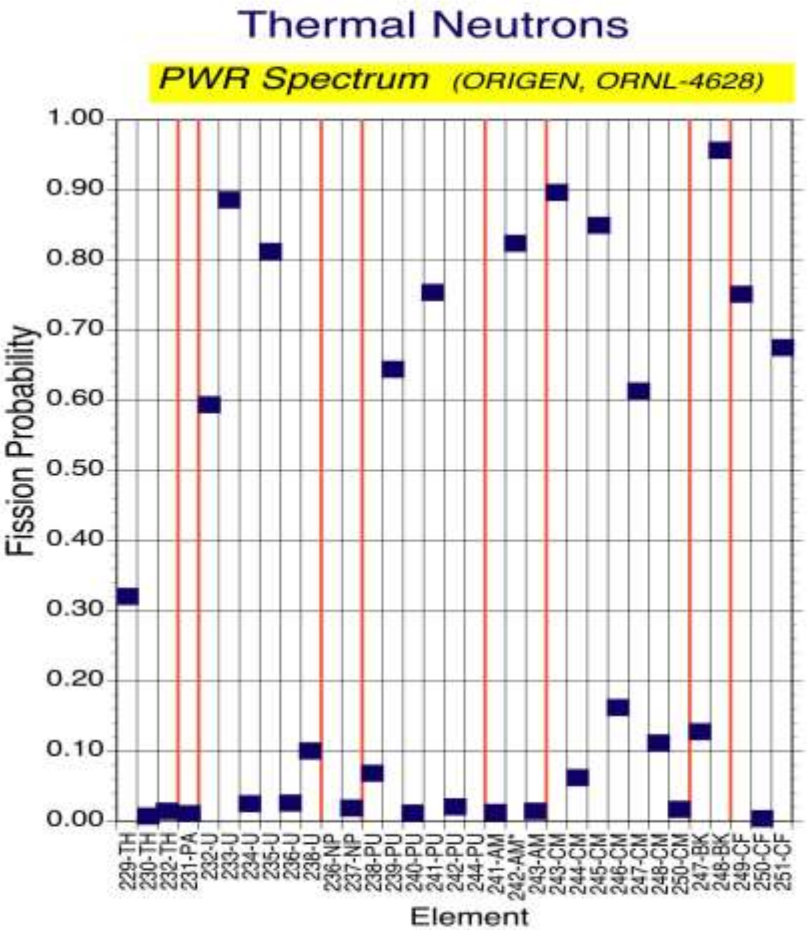
The TARC Experiment CERN 1996

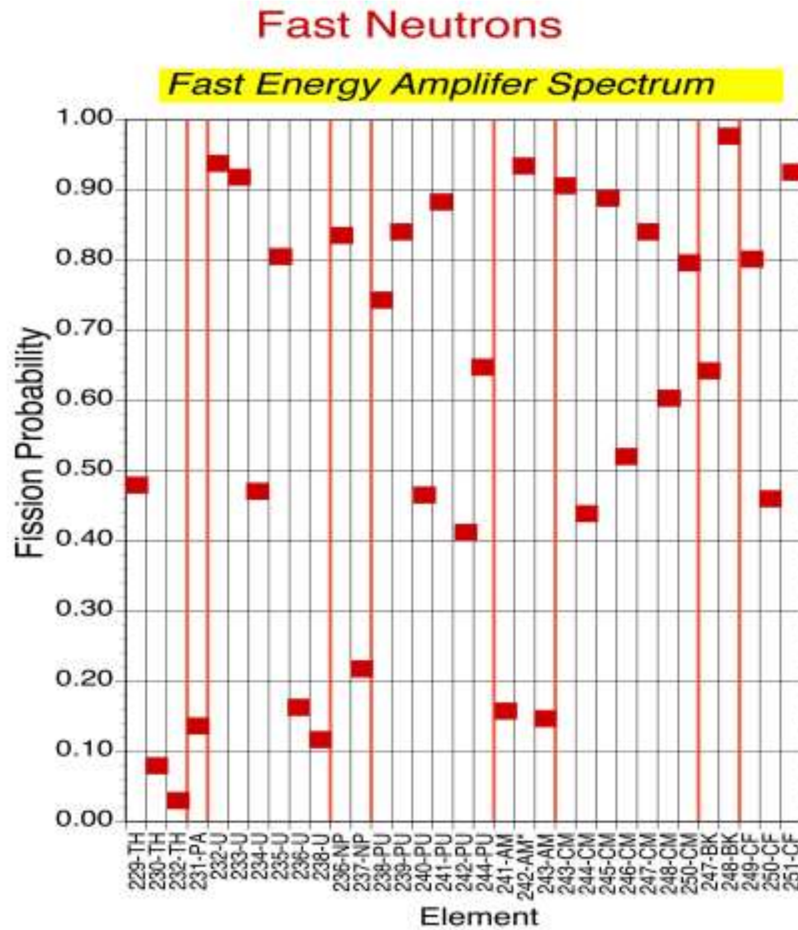
- **LLFP & TRU transmutation in Pb moderator**
- **Higher transmutation efficiency in heavy moderators (TARC effect)**
  - LBE <ΔE/E> ~ 1%
  - Na <ΔE/E> ~ 8%
  - H_2O <ΔE/E> ~15%





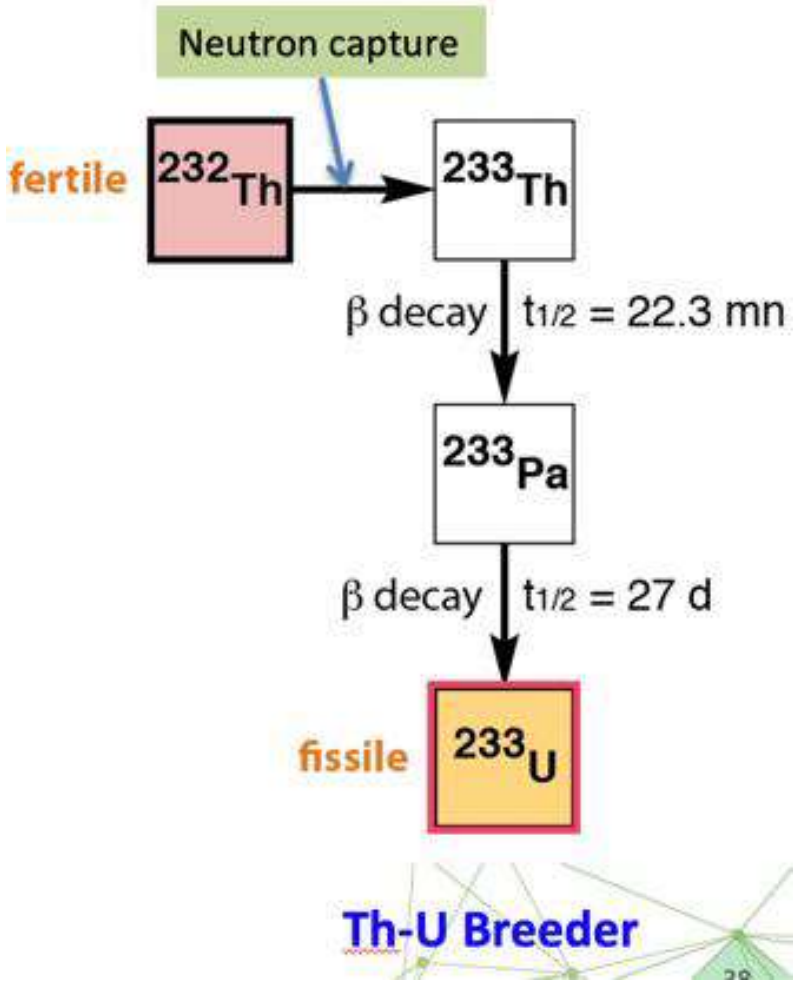
Transcuranic Element Fission Probability



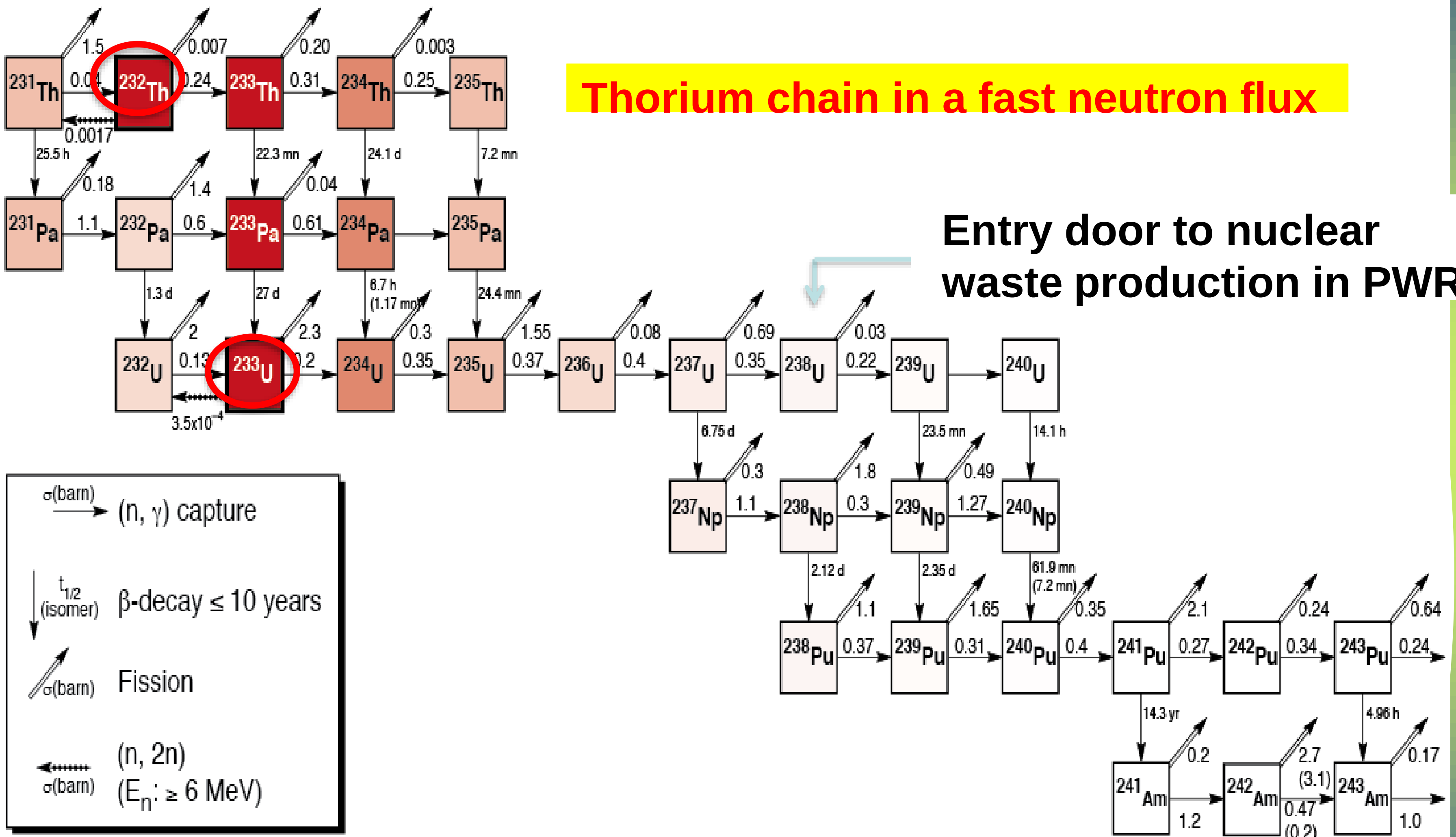


Fast neutrons also reduce captures in FF

^{233}U breeding chain from ^{232}Th.



Thorium minimizes high level waste production



Thorium ADS Advantages and Sustainability

- Extremely high level of inherent safety (subcriticality)
- Minimal production of long-lived waste (thorium)
- Ability to burn existing waste (fast n spectrum)
  - Accept fuels that not acceptable in critical reactors (12 to 15 %)
  - Minor Actinides
  - High Pu content
- High resistance to diversion
- Efficient use of naturally available fuel, without the need of isotopic enrichment
- Low cost of the heat produced and higher operating temperature

Outline

- Physics of Accelerator Driven Systems (ADS)
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- ADS Validation and Development

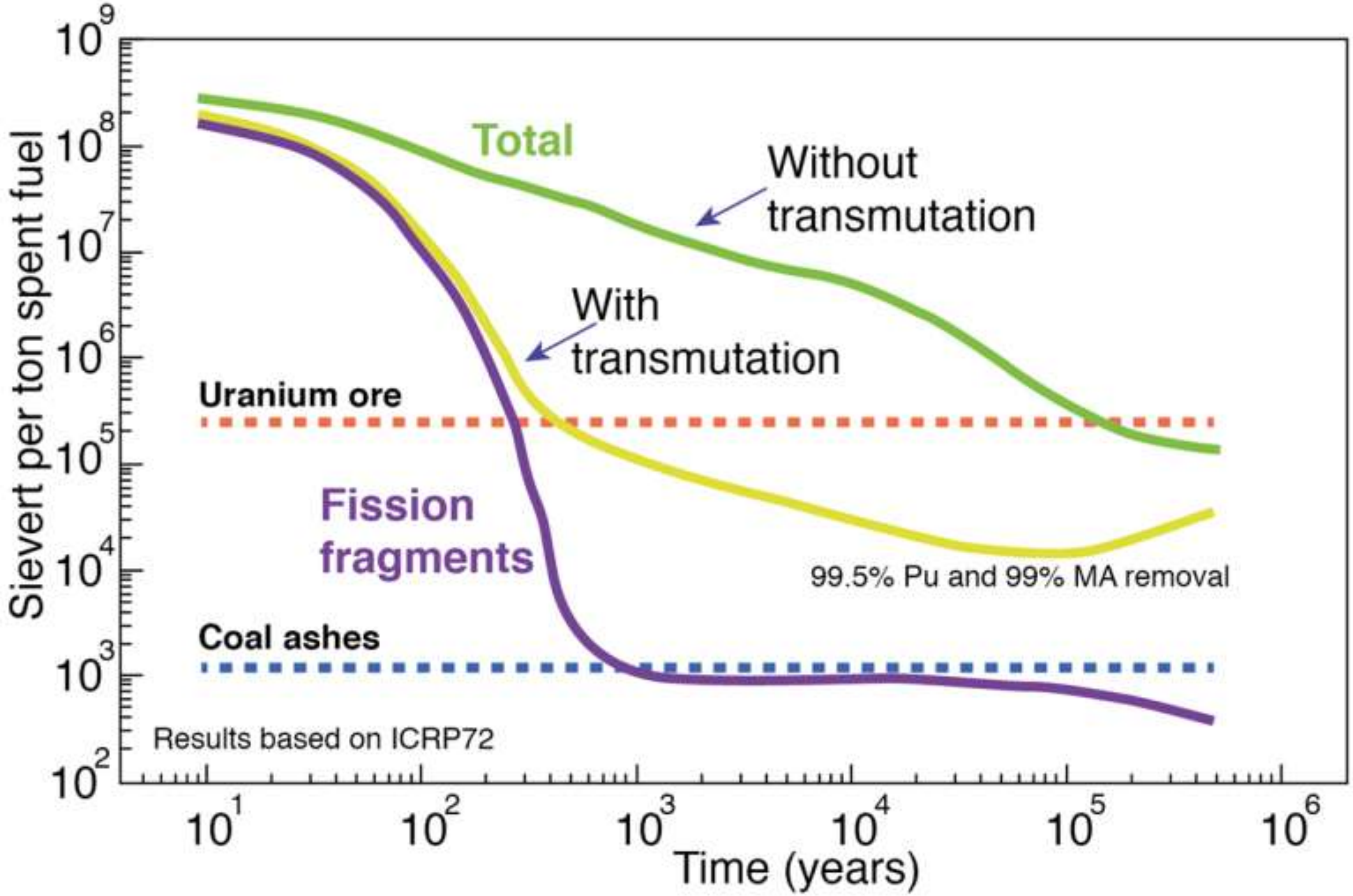
ADS TRU Transmutation

Transmutation rates (kg/TW_{th}h) of Pu, MA and LLFPs

Nuclides	START (ThPuO2) ENDF/B-VI	PWR (UO2)
^{233}U	+ 31.0	
Pu	– 42.8	+ 11.0
Np	+ 0.03	+ 0.57
Am	+ 0.24	+ 0.54
Cm	+ 0.007	+ 0.044
^{99}Tc prod	+ 0.99	+ 0.99
^{99}Tc trans	– 3.77	
^{129}I prod	+ 0.30	+ 0.17
^{129}I trans	– 3.01	

- Plutonium incineration in ThPu based fuel settles to ~43 kg/TWh, 4 times what is produced by a standard PWR (per unit energy)
- MA production is very limited
- LLFP incineration is efficiently implemented by Adiabatic Resonance Crossing
- Such a machine could in principle incinerate up to 3 times what is produced by a standard PWR (per unit energy)

Ingestion radiotoxicity of spent nuclear fuel



Equilibrium concentrations are orders of magnitude lower than in a uranium-plutonium based fuel.

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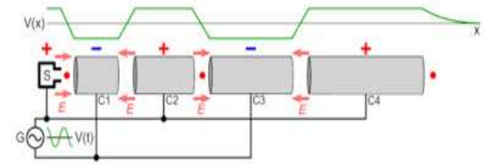
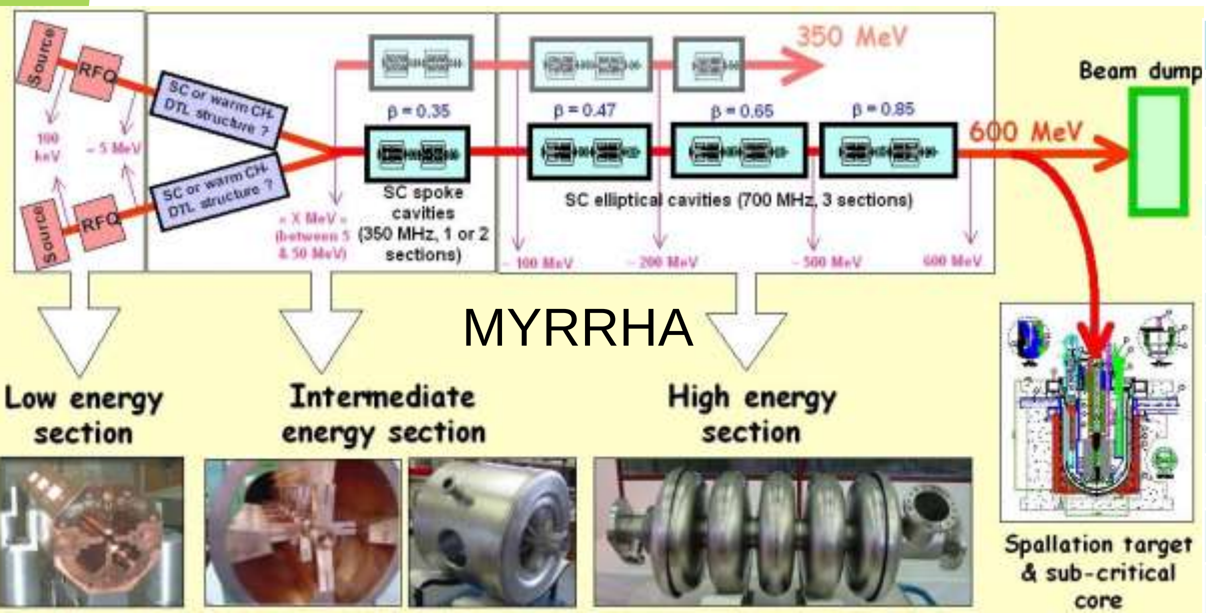
Accelerator Main Considerations

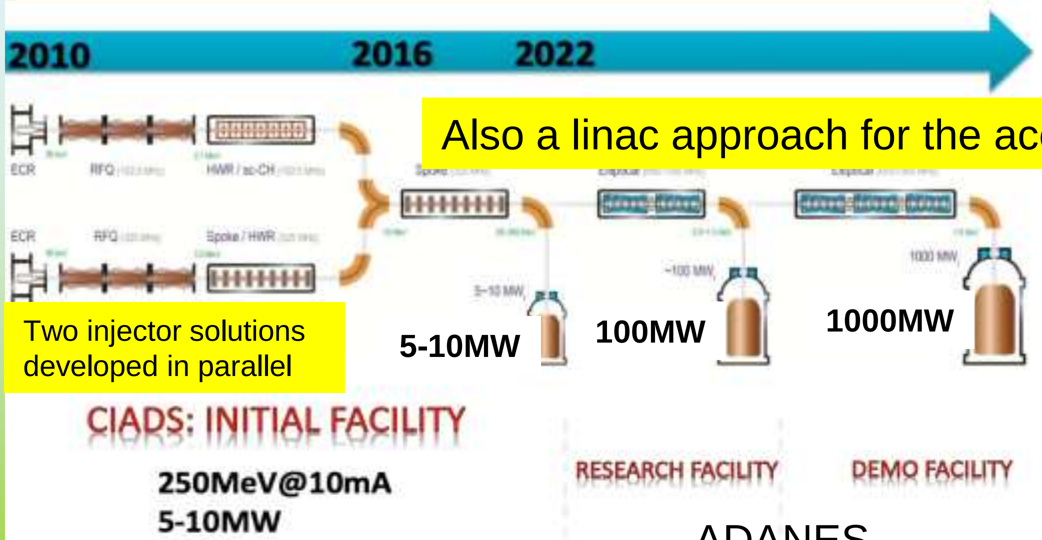
- **Beam Energy:** 900 MeV optimal, but 600MeV better economically
  - At lower energies power deposition density in the spallation target is problematic.
- **Linac vs Cyclotrons**:
  - For a high-power ADS (>10 MW), the logical choice would be a linac
  - At lower beam powers (1-5 MW) cyclotrons are better for compactness, efficiency and cost
- **Accelerator reliability:** to avoid thermal cycling need high reliability
  - Beam trips ~< 1s are OK ⇒ small thermal transients (thermal response time ~< 0.5s)
  - Longer beam trips ~< 100s should be < 100/y (preliminary analysis)
  - Beam trips > 100s should be < 10/y.

Linacs for ADS



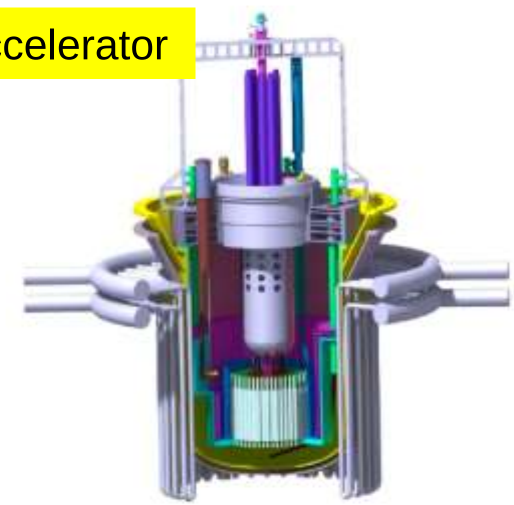


EUROTRANS	
Beam	Protons
Current	5mA
Energy	600MeV
Power	3MW (reactor 60MW$_{th}$)
Duty cycle	100% (CW)
Accelerator	SC linac (250m)
Frequency	352-704 MHz
Beam stability	2% power
Max trips > 1s	3-10/y
Transmission	99.999%
Losses	1W/m



Also a linac approach for the accelerator

ADANES



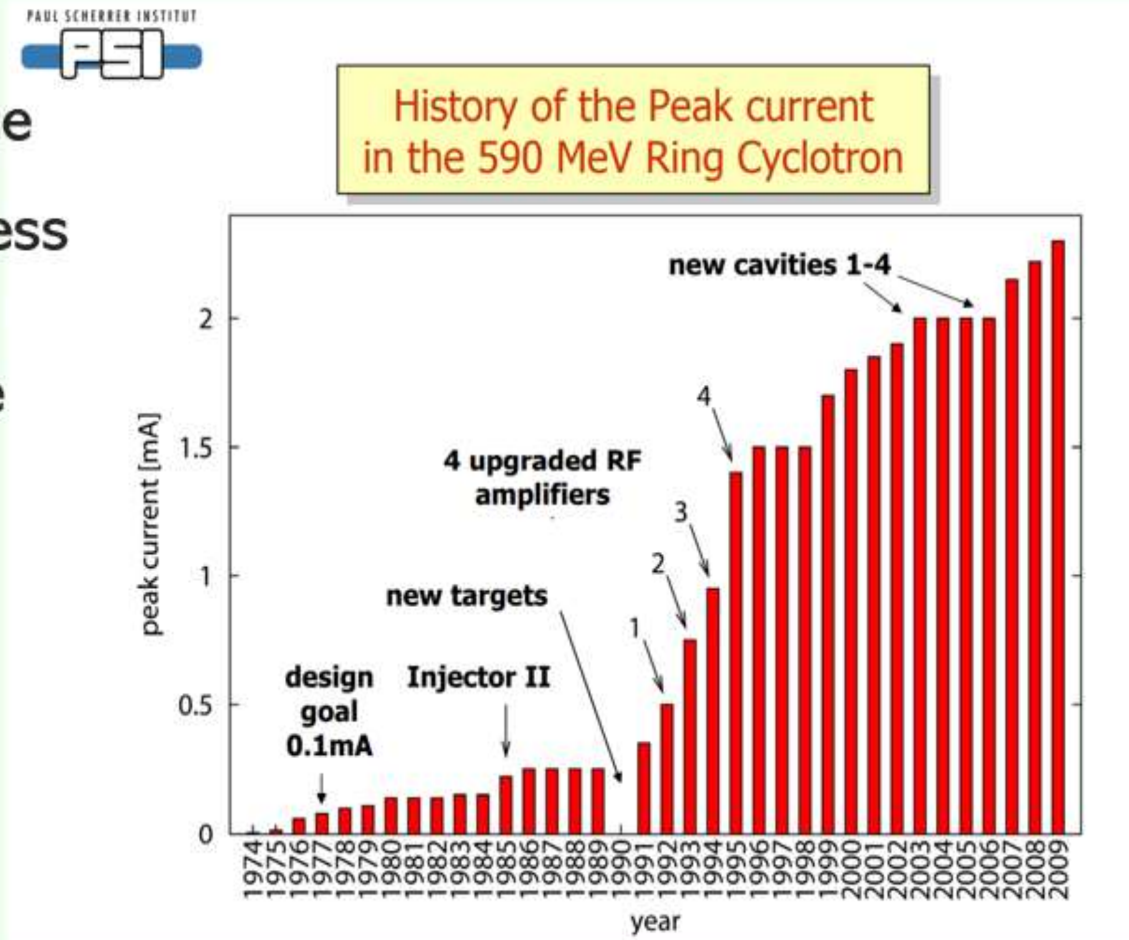
A Cyclotron for Transmutex ADS

Accelerator requirements		
	600 MeV ADS	800 MeV ADS
E_{beam} [MeV]	600	800
I_{beam} [mA]	5.1	3.3
P_{beam} [MW]	3.1	2.7
P_{ADS} (th) [MW]	300	300
G_0	2.00	2.29
Gain (k = 0.98)	98	112

- Evolution of PSI Ring Cyclotron and Injector II (1.4 MW)
  - Larger number of cavities
  - Two injections
  - …
- **Transmutex is evaluating options, together with PSI**

PRELIMINARY IDEAS

- Speed is of the essence
- Even a machine with less than 6mA but "on the floor" quickly will have ample changes to be upgraded
- See PSI example
- Focus on reliability!



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Lead-bismuth Eutectic (or Lead) Fast Neutron Reactors

The fast reactors used on Alpha class submarines of the Soviet Union are the only one that have many years of real proven experience and are the only one already realized that are providing the flux needed for the ADS

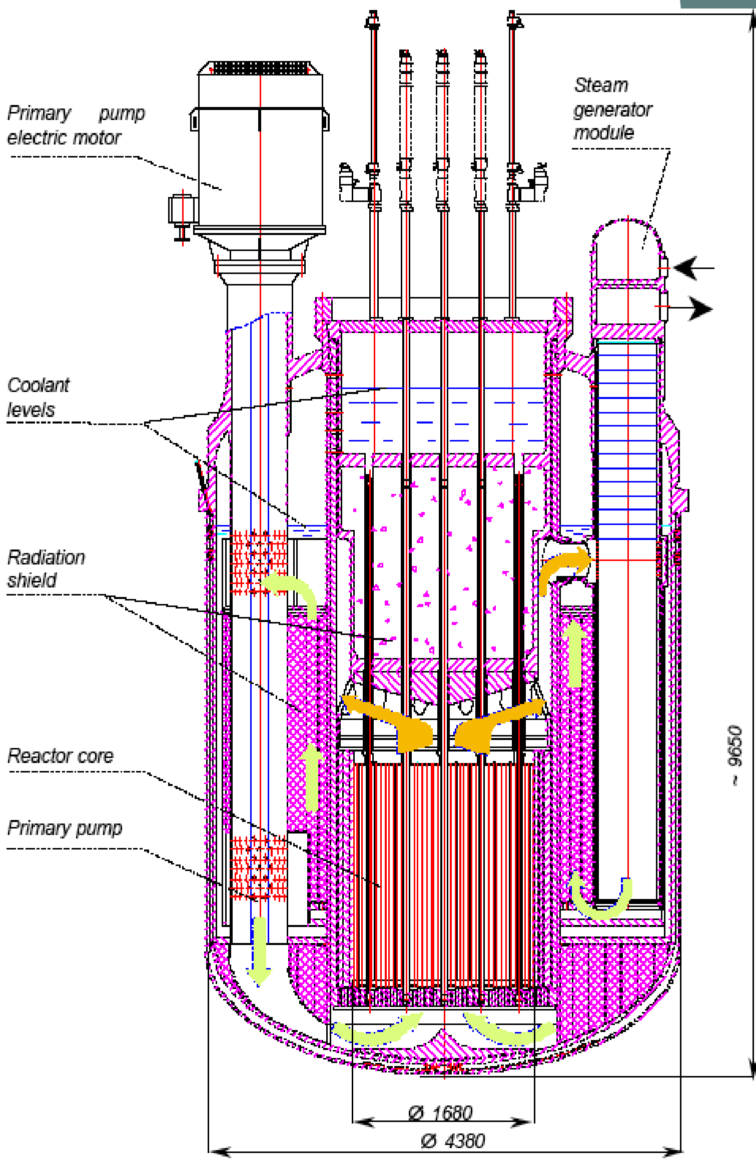
Prof. G.I. Toshinsky

AKME ENGINEERING
SMALL MODULAR REACTOR NUCLEAR SYSTEMS

Lead-bismuth Eutectic Fast Neutron Reactor: Russian SVBR-100

- Commercial version of the LBE fast reactor used on Alpha class subs (thermal output 280 MW (th))

- Studying the modifications of the SVBR to accommodate a spallation target and use ThO_2 fuel
  - Detailed calculations in progress



MEGAPIE LBE spallation target @ PSI

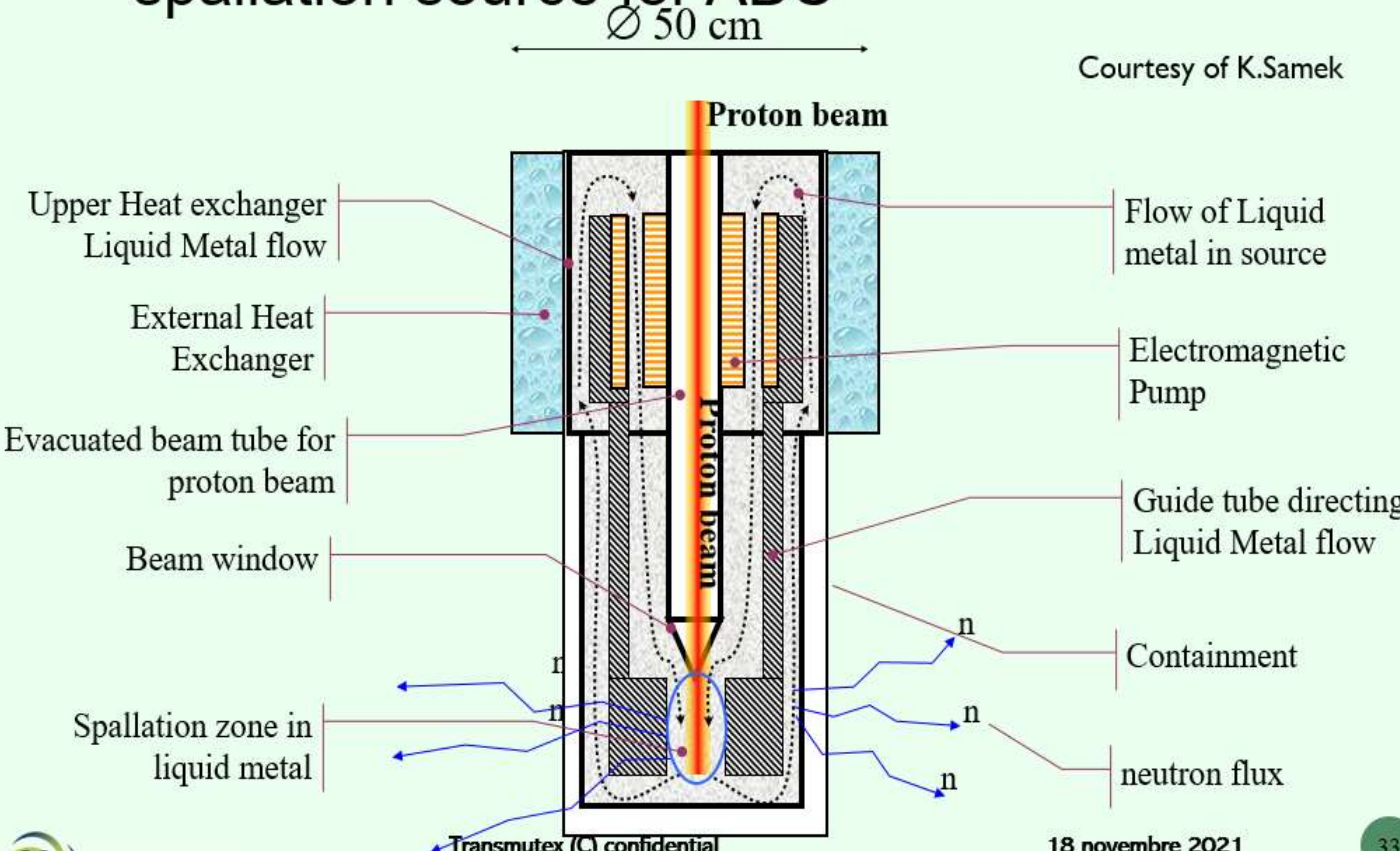
- MEGAPIE Project at PSI
- 0.59 GeV proton beam
- 1 MW beam power
- Feasibility successfully demonstrated in 2005
- 4 months service life

F. Groeschel et al. (PSI)

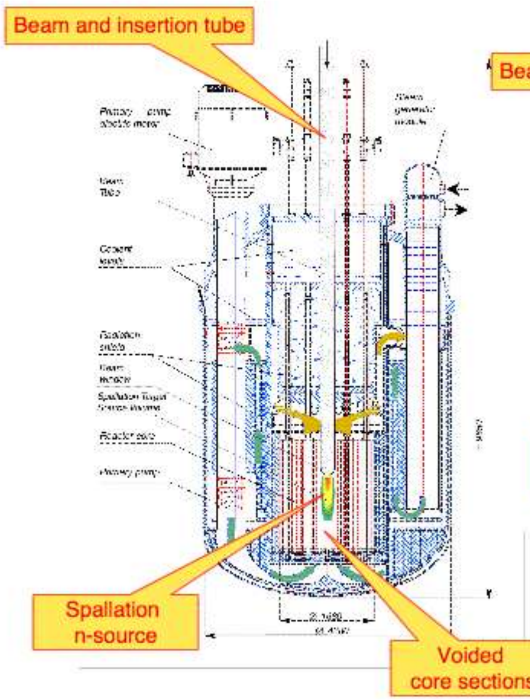
With the collaboration of CEA and Subatech

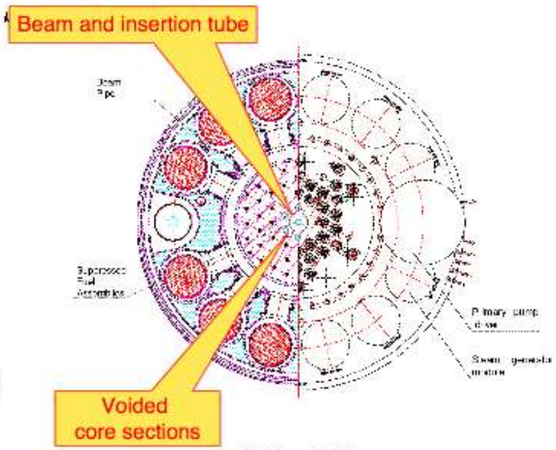
Proposed design of a high-power spallation source for ADS

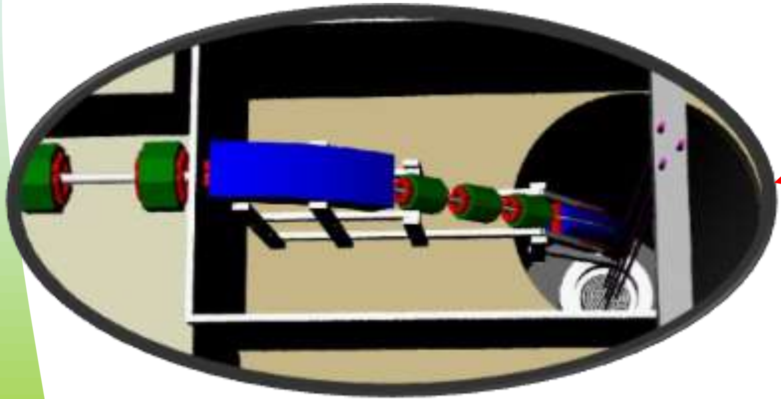
Courtesy of K.Samek

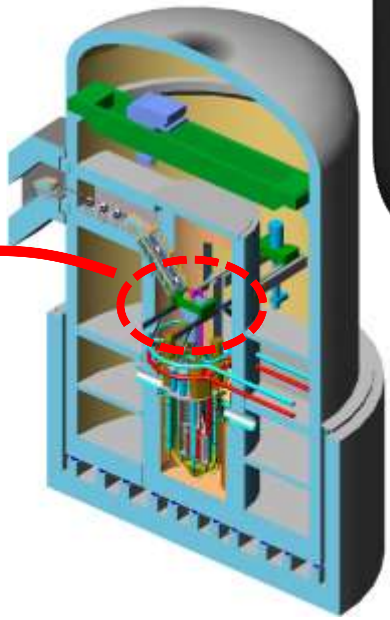


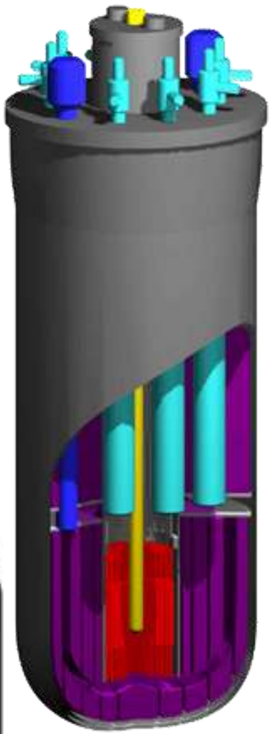
Conceptual modifications to SVBR Reactor











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- **ADS Validation and Development**

The Three Levels of ADS Validation and Development

- **First**, validation of the different component concepts, taken separately (accelerator, target, subcritical core, dedicated fuels and fuel processing methods).

- **Second, validation of the coupling of the different components in a significant environment (KIPT, Ukraine) + (CVR, Czech Republic) including full simulations**

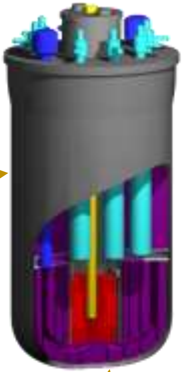
- **Third**, validation in an installation explicitly designed for demonstration. This third step should evolve to a demonstration of transmutation fuels

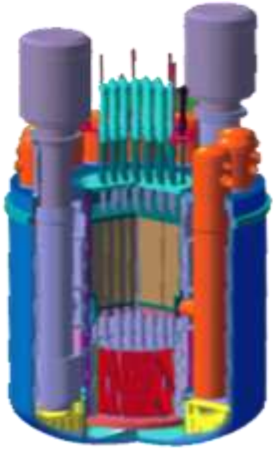
TRANSMUTEX's Strategy

Based on existing technologies for a demonstration of a 300 MW Pilot Plant by 2032

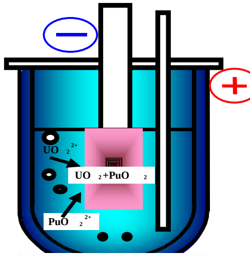
High-power cyclotron

Liquid metal spallation target

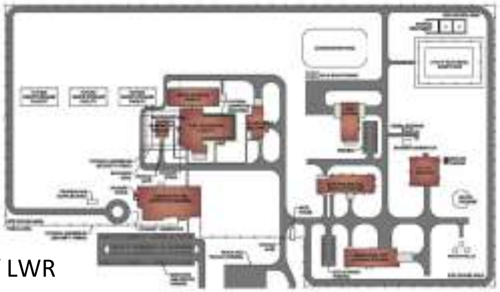




Lead-Bismuth fast neutron reactor SVBR-100



Simulation technology based on FLUKA and GEANT4



Pyroprocessing of LWR spent fuel,

production of Th fuel, reprocessing of Th fuel

Argonne National Lab, USA

ALCEN and Egis, France

A most Advanced Simulation Project

Based on existing well validated codes

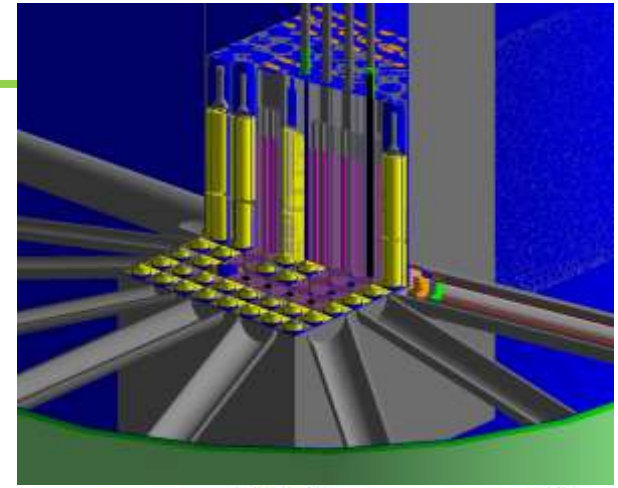
FLUKA

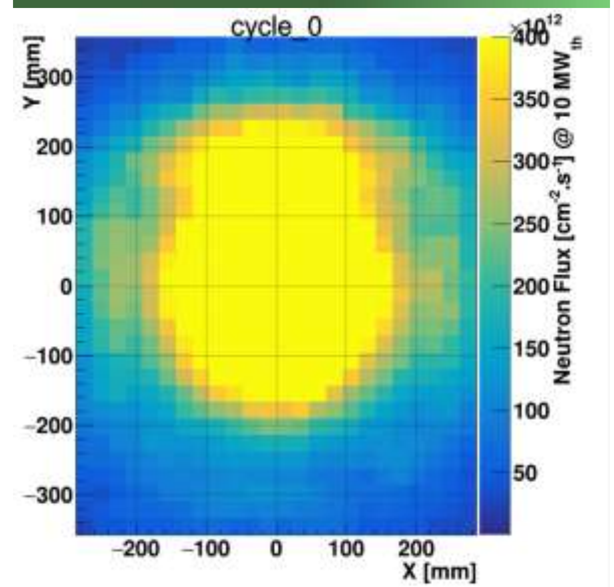
GEANT4 A SIMULATION TOOLKIT

FLUKA	GEANT4
General-purpose Multi-particle Design of accelerator Radiation protection High-energy Physics Experiments ... N-Multigroup transport Soon: pointwise No criticality evaluators Source available	General-purpose Multi-particle High-energy Physics Experiments ... N-pointwise transport Criticality evaluators added by TRANSMUTEX Open source

Validated for many aspects of neutronics but not adapted to nuclear fuel evolution

Extending current codes





Additional features

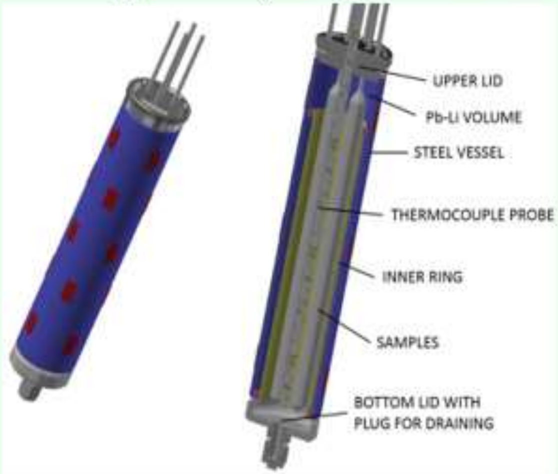
- Time evolution of materials composition by neutron flux and coupled Bateman equations (burnup evolution)
- State-of-the-art k_{eff} estimators
- Time evolution of the beam current to keep the thermal power constant
- DPA calculation
- Radiotoxicity calculation

Under development

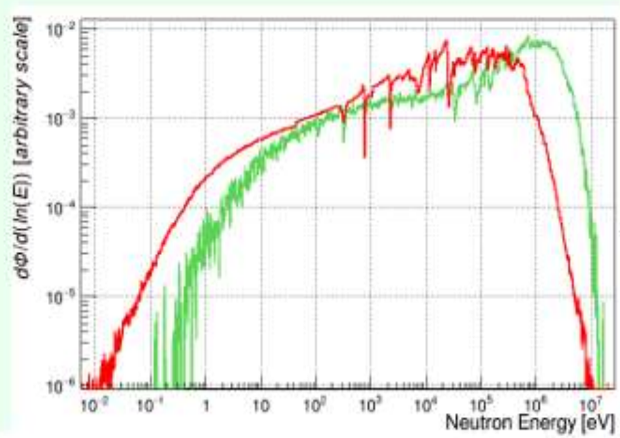
- Temperature evolution
- Coupling with deterministic fluid-dynamic codes
- Extended validation with international benchmarks
- Cloud computing

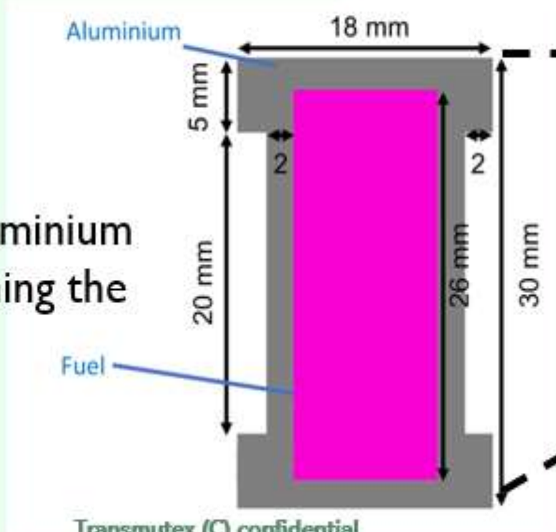
FUEL PELLETS IRRADIATION IN A FAST LEAD RIG

PbLi rig already tested at CVR

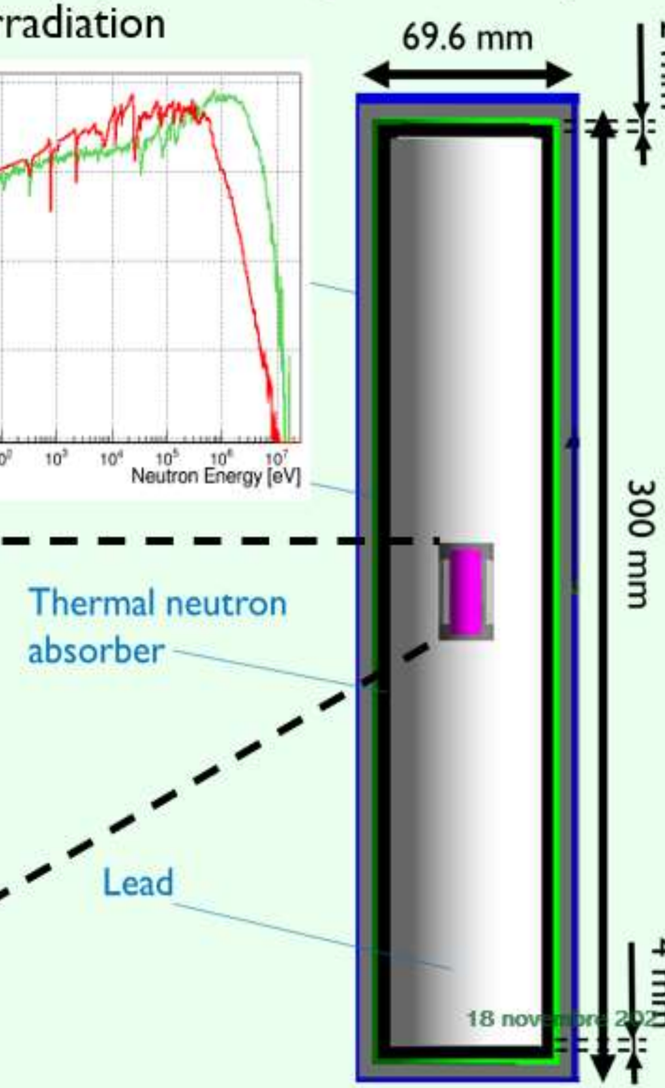


Conceptual lead rig for fuel sample irradiation



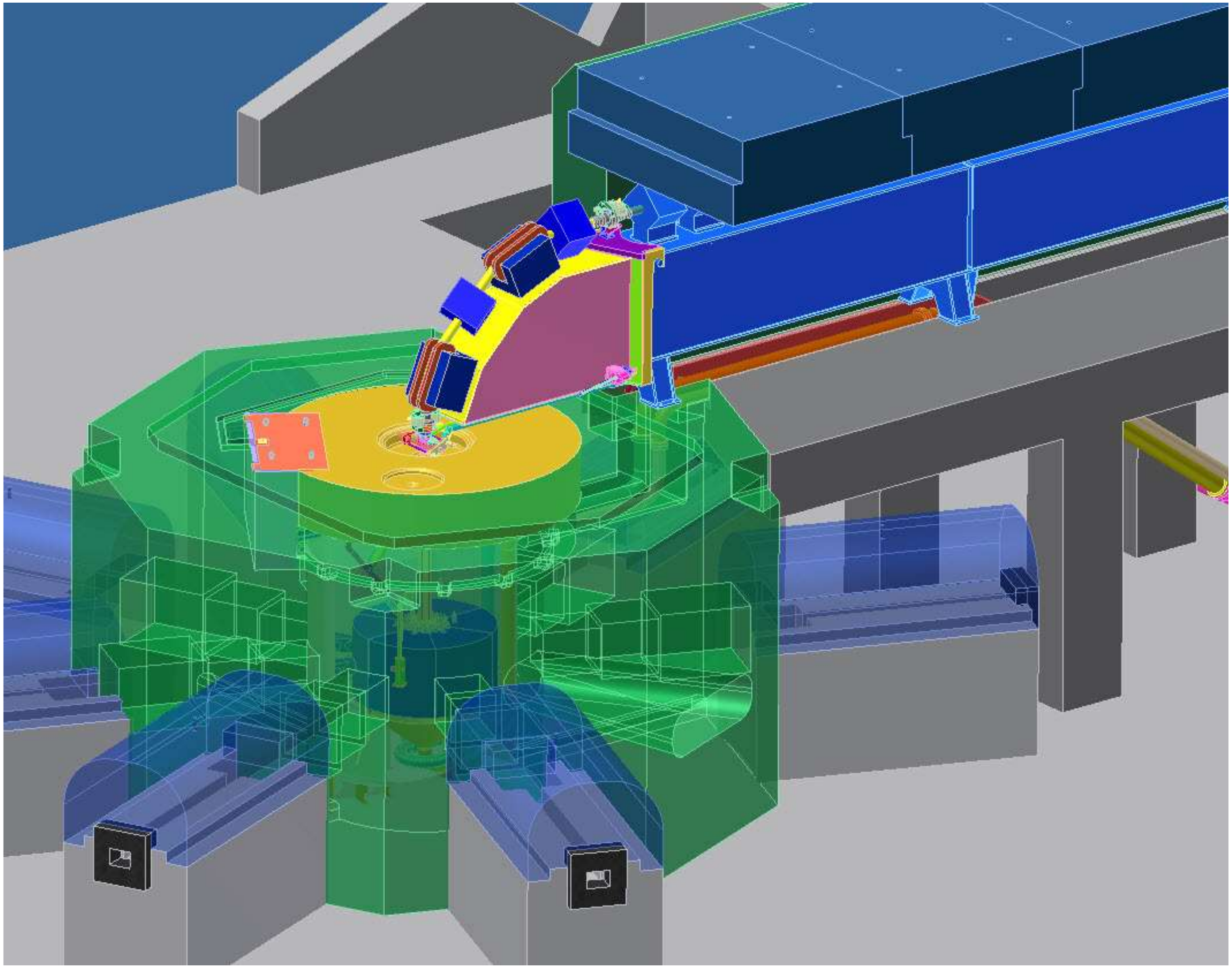


Conceptual aluminium capsule containing the fuel sample

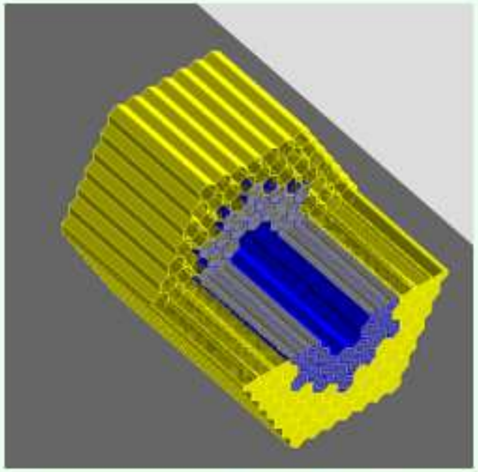


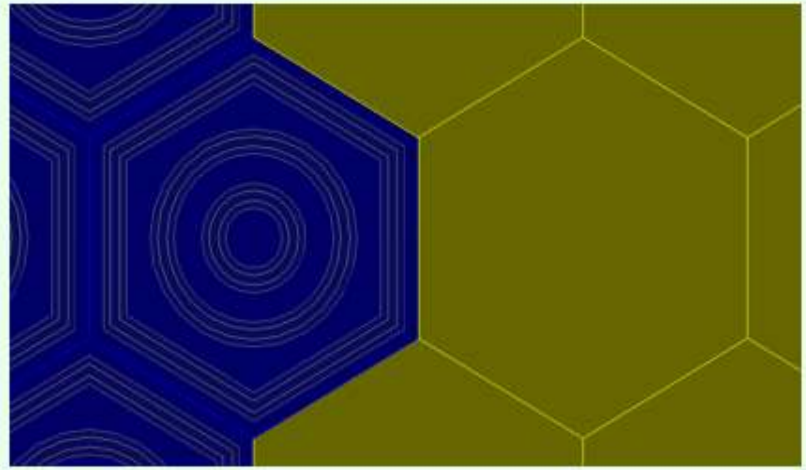
At Kharkov Institute of Physics & Technology, Ukraine:

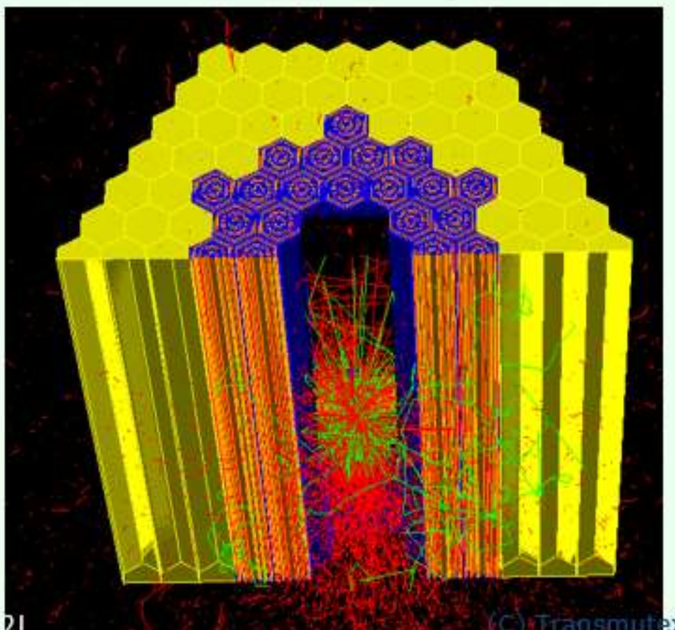
Validate the Transmutex simulation code with the data coming from the KIPT accelerator driven subcritical facility

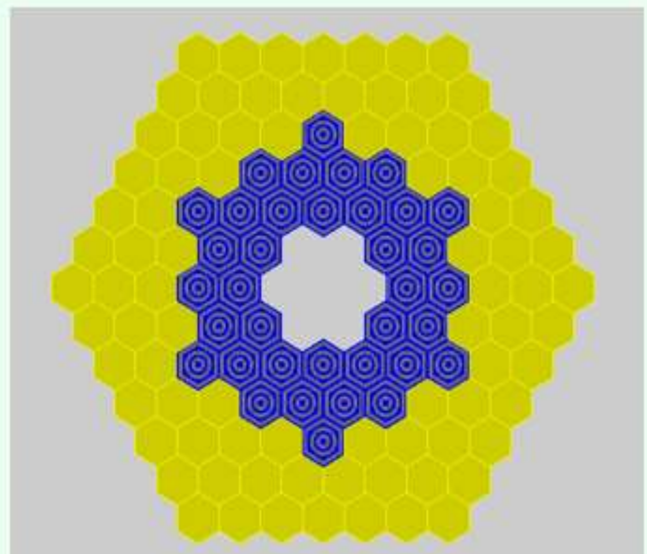


REPRODUCTION OF THE KIPT REACTOR

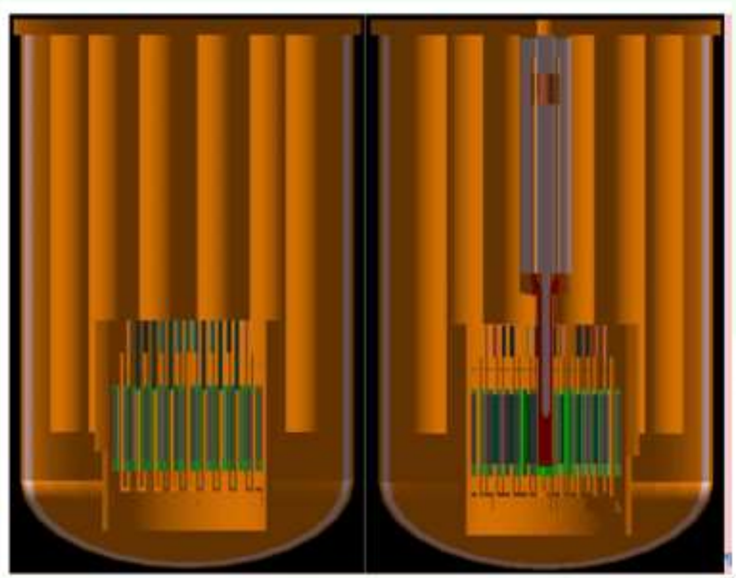




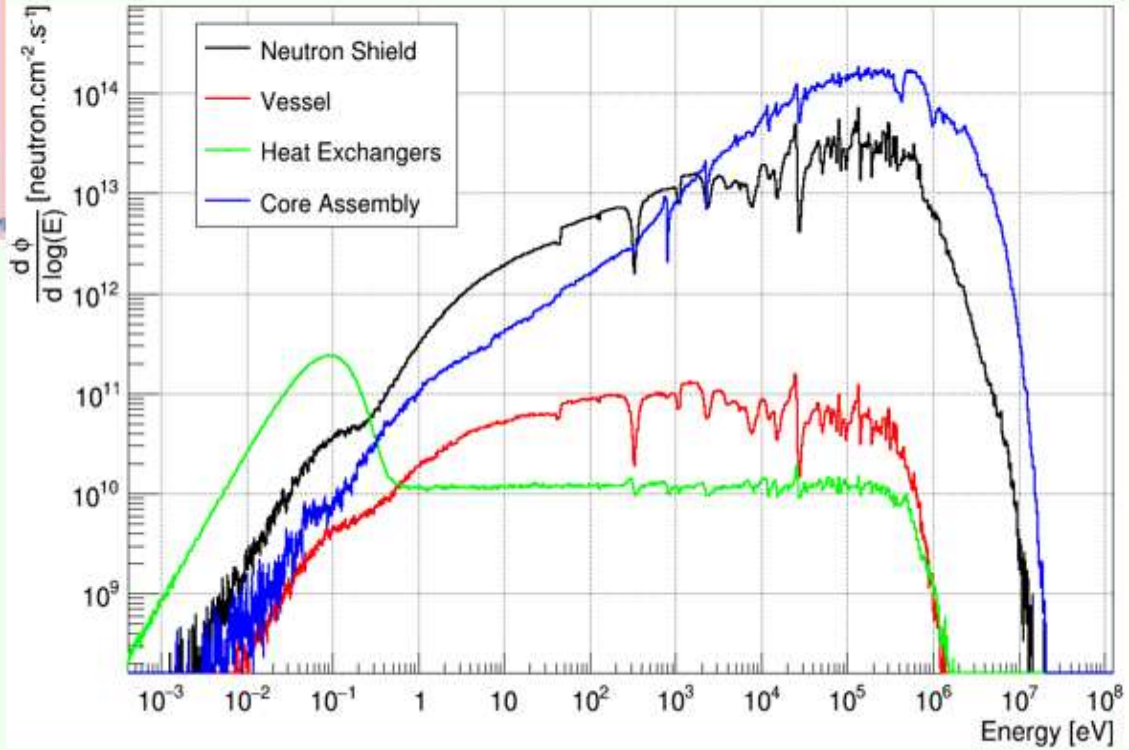




DETAILED SIMULATION



SVBR-100 with GEANT4



An Ambitious Coordinated Development Plan in Three Phases

PHASE I

Collaborations
2020 - 2021
CHF 8 million

Established Key Collaboration and Developed proprietary nuclear simulation software.

PHASE II

Design and Engineering
2022 - 2027
~ CHF 700 million

System design and key demonstrations: Long-lived waste transmutation, Hi-power cyclotron, Fuel fabrication, Site selection, Licensing, etc.

PHASE III

Pilot Plant 300MWth
2028 - 2032
~ CHF 1,5 Billion

Build a 300MWth Pilot Plant, seek license based on USA-NRC guidelines for Subcritical Systems

Worldwide Deployment

Develop Scalable Manufacturing capabilities

Conclusion

- The technology is ready
  - Cyclotron
  - LBE/Lead reactor cores
  - Spallation targets
  - Pyroprocessing plant
- A safe and efficient way to
  - Produce carbon-free energy
  - Transmute TRU and LLFP
- A clear path forward for validation by 2025
- Demonstrator by 2032

Thank you