FISA 2019
9th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems
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Pitesti, Romania

Partitioning & Transmutation
Contribution of MYRRHA to an EU strategy for HLW management

MYRTE, MARISA, MAXSIMA, SEARCH, MAX, FREYA, ARCAS

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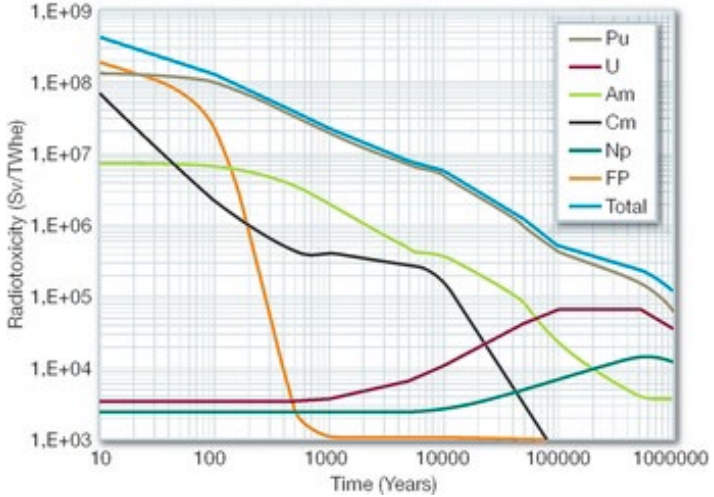
Introduction (1)

Nuc.Energy for Electricity (Foratom, Feb 2019)

- 50% of MS (14 of 28)
- 126 NPP (118 Gwe)
- 26% of EU electricity
- 50% of its low carbon electricity

Spent Nuclear Fuel

- 2500 t discharged annually
  - PU ~22,5 t
  - Minor Actinides (MA)
    - Neptunium (~1,2 t)
    - Americium (~1,2 t)
    - Curium (~0,1 t)
  - long-lived fission products ~87,5 t

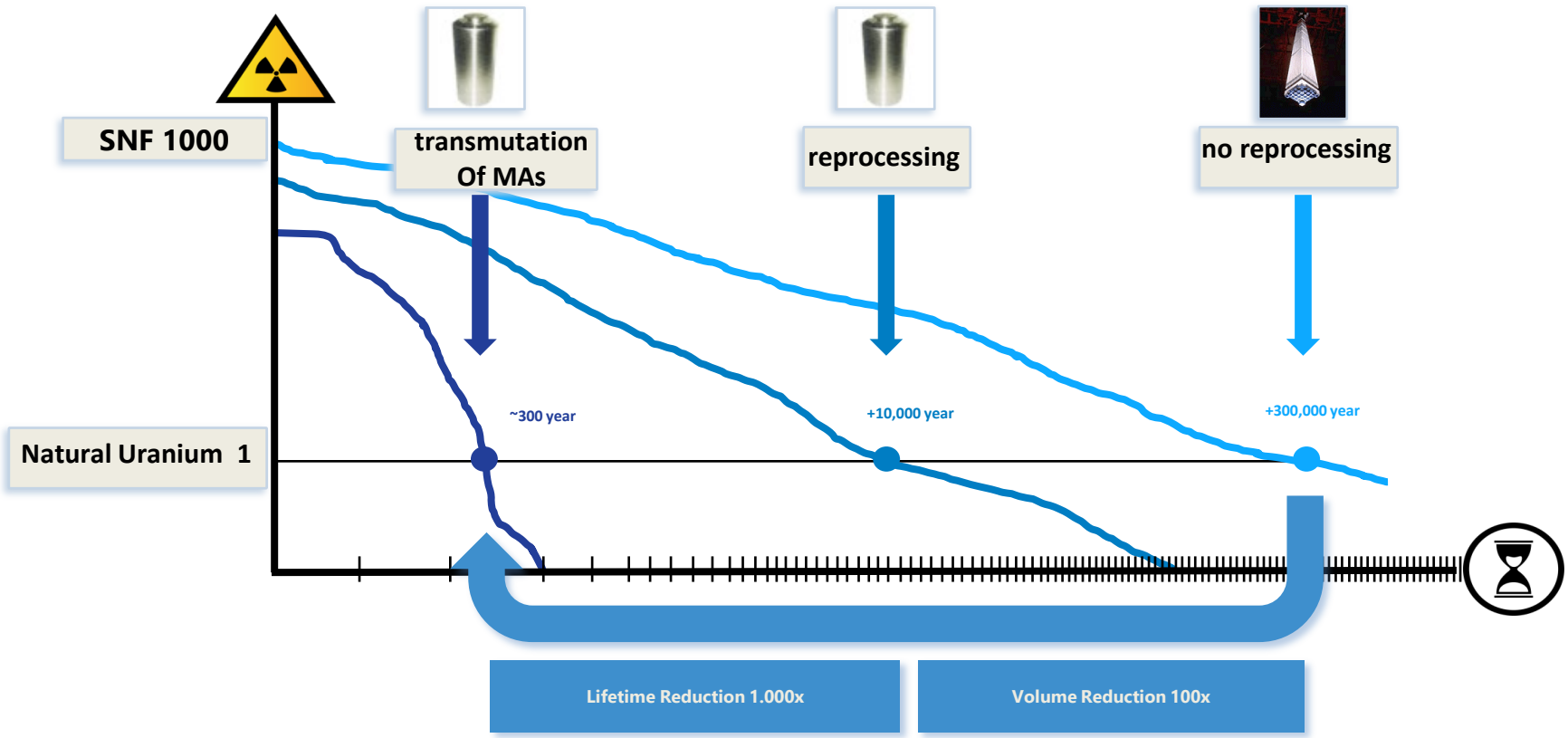


Introduction (2)

- Today, two options for high-level radioactive waste (HLW):
  - No reprocessing and direct geological disposal
  - Reprocessing at industrial scale (PUREX; U and Pu recovered with 0,1% losses to be recycled as MOX fuel), FPs & MAs vitrified to go in geological disposal

- Partitioning and Transmutation (P&T):
  - aim to reduce the inventories of long-lived and high-radiotoxic radionuclides in HLW, thus reducing the burden of waste management problem and gaining the support of the society
  - Partitioning is the advanced chemical separation of MAs & long-lived radionuclides from HLW
  - Transmutation is the conversion of MAs into FPs and some long-lived radionuclides into radionuclides with a shorter lifetime in dedicated burners

Relative Radiotoxicity of Spent Nuclear Fuel



*SNF = Spent Nuclear Fuel

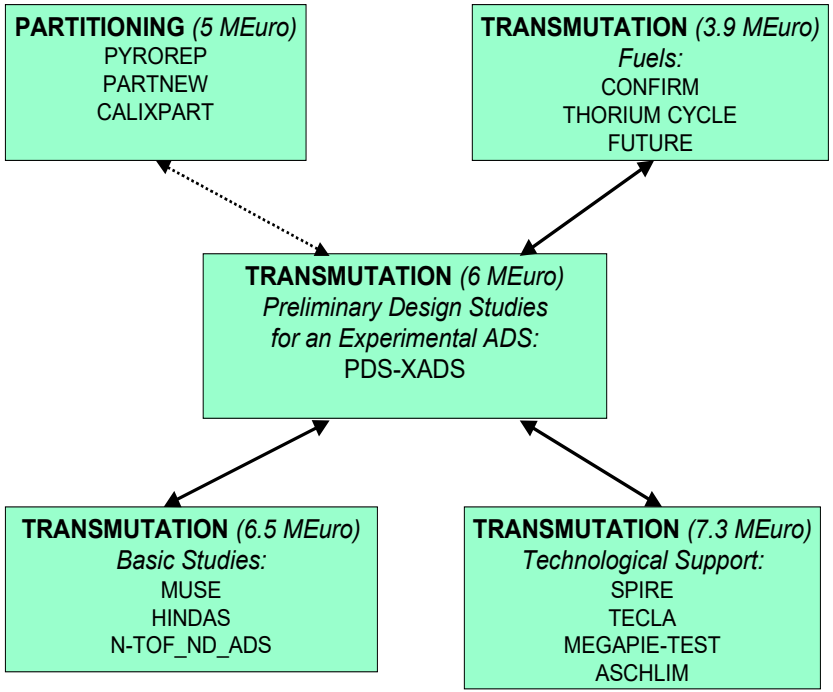
P&T a long history and a sustained support in EURATOM FP

- P&T studies started in the last quarter of the 20th century in France, Germany, UK, Belgium, Japan, USA, Russia …
- EC supported strategy studies on P&T and partitioning experiments in FP3 (1990-1994)
- EC supported experimental work on partitioning, strategy studies on P&T, irradiation of MA fuels in HFR, and computation studies and experimental work on transmutation in FP4 (1994-1998)

Conclusions:

- Fast neutrons more efficient to transmute MA than thermal neutrons (the ratio Fission/Capture is more favorable with fast neutrons)
- Separation factors between MA and lanthanides of ~30-50 necessary for MA safe and efficient transmutation
- Pu to be recycled with top priority (radiotoxicity, proliferation); then Am (radiotoxicity at short term and longer term through ^{237}Np formation)
- Careful with generation of unacceptable amounts of secondary waste and dose increase to persons
- The feasibility of accelerator-driven system (ADS) for transmutation of nuclear waste should be more thoroughly investigated

Continued support in EURATOM FP5 (1998-2002)



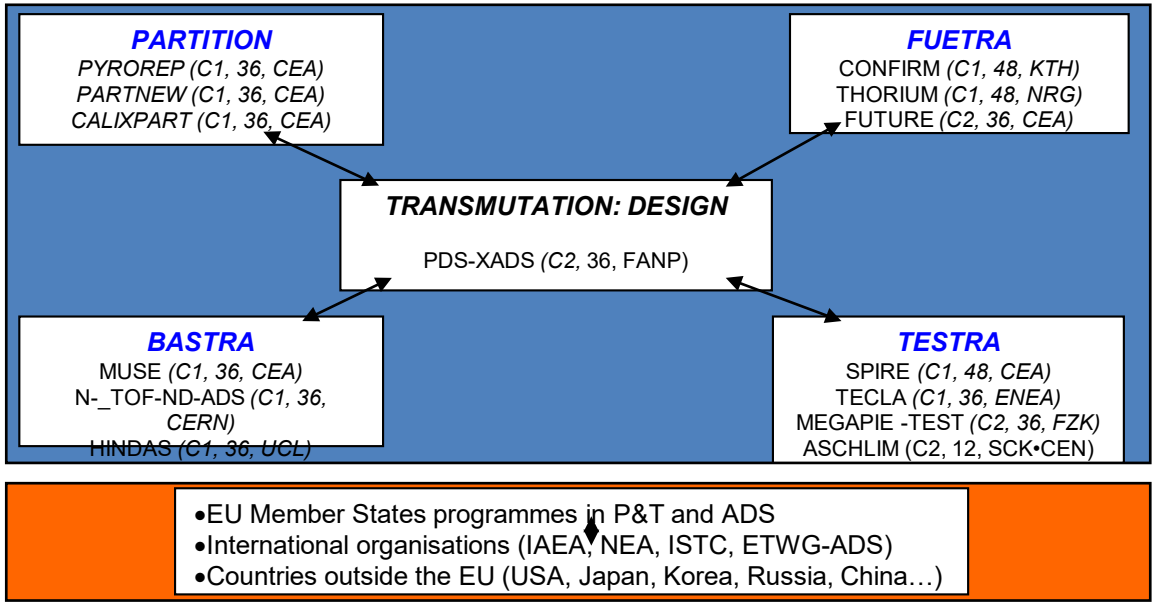
- FP5 Projects on **Advanced Options for Partitioning and Transmutation**
- coordinated by the **ADOPT network**

Objectives of ADOPT

- In Europe there is a strong interest to **explore** the potential **scientific, technical and industrial possibilities of P&T**.
- Integrating the total European efforts (EC & MS) to **speed up the development and put the European R&D at lead in this field**.
- **The specific objectives of ADOPT are:**
  - **to promote consistency between P&T FP5 projects and P&T national programmes**
  - to define rules for info. dissemination and access to national R&D programme data
  - to review results of the P&T FP5 projects and avoid duplications,
  - to identify gaps in the overall programme,
  - to inform the members about the ongoing activities in P&T and ADS outside the EU (Intern. Org., USA, Japan, Korea, former CIS)
  - **to give input to future research proposals and guidelines for further R&D orientation towards industrialisation,**

ADOPT Work Plan & Main achievements

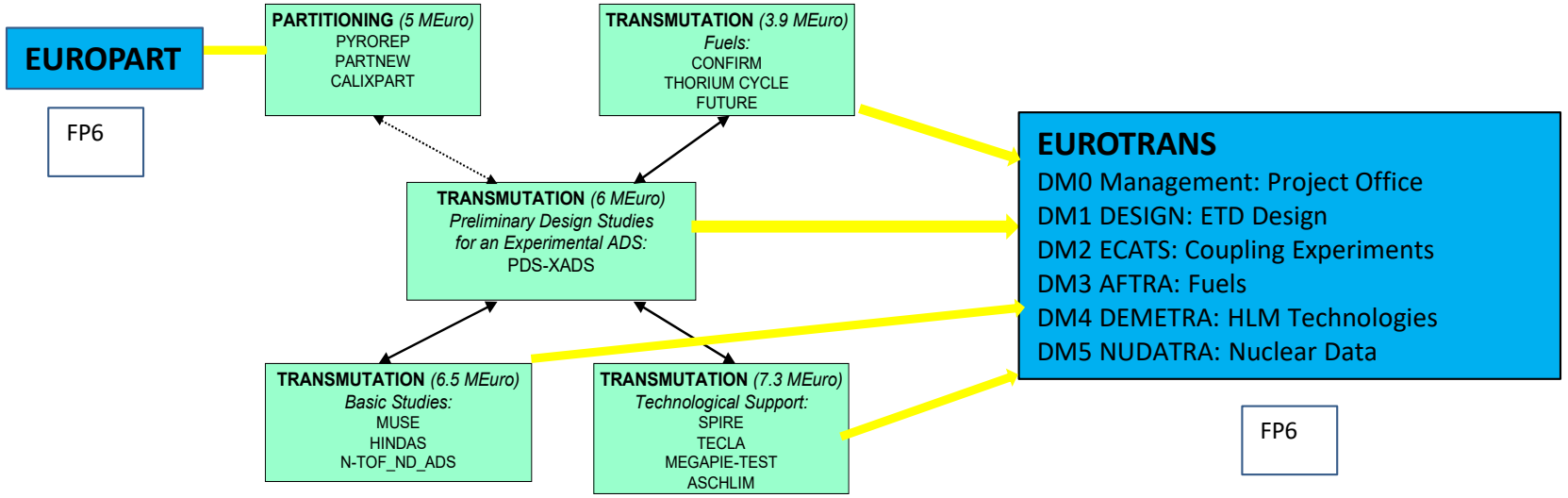
Fostering national programmes and EURATOM P&T project



Unfortunatly in FP6 ➔ we fissioned P (EUROPART) from T (EUROTRANS)

We succeeded to establish the EU 4 building blocks strategy

Continued support in EURATOM FP5 (1998-2002) & FP6 (2002-2006)



- FP5 Projects on **Advanced Options for Partitioning and Transmutation**
- coordinated by the **ADOPT network**

EU Strategy for P&T (2005) industrialisation from 2030-35

EU P&T Strategy 2005: *"The **implementation of P&T** of a large part of the high-level nuclear waste **in Europe needs the demonstration of its feasibility at an "engineering" level**. The respective **R&D** activities could be **arranged in four "building blocks"**:*

P&T building blocks	Description	Name & Location
1 **Advanced Partitioning**	▪ Demonstrate capability to process a sizable amount of **spent fuel** from commercial Light Water Reactors to **separate** plutonium, uranium and minor actinides	
2 **MA Fuel production**	▪ Demonstrate the capability **to fabricate** at a semi-industrial level the **MA dedicated fuel** needed to load in a dedicated transmuter	
3 **Transmutation**	▪ **Design and construct one or more dedicated transmuters**	▪ **MYRRHA (BE)**
4 **MA Fuel reprocessing**	▪ Specific installation to process fuel unloaded from transmuter ▪ Not necessarily the acqueous reprocessing but **pyroreprocessing & electrorefining**	

The European Commission contributes to the 4 building blocks and fosters the national programmes towards this strategy for **demonstration at engineering level**

Objectives of ADOPT

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CONTINUED SUPPORT IN EURATOM FP7 & H2020

MYRTE, MARISA, MAXSIMA, SEARCH, MAX, FREYA, ARCAS

The MYRTE Project – H2020 Framework Programme

Key project information

MYRTE	
Main Objective	Perform research to support the development of MYRRHA
Project type	Research and Innovation Action (RIA)
Duration	54 months
Coordinator	SCK•CEN (Peter Baeten)
Consortium	27 organisations
Granted EC contribution	€8,995,962,-
Total budget	€11,994,610,-

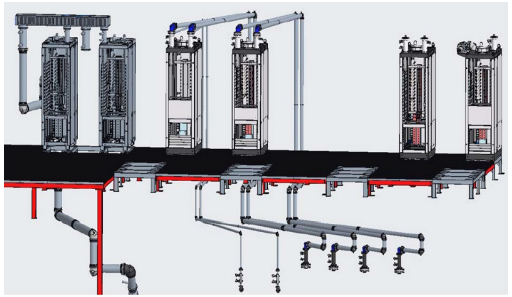
The MYRTE Project – H2020 Framework Programme

Main achievements

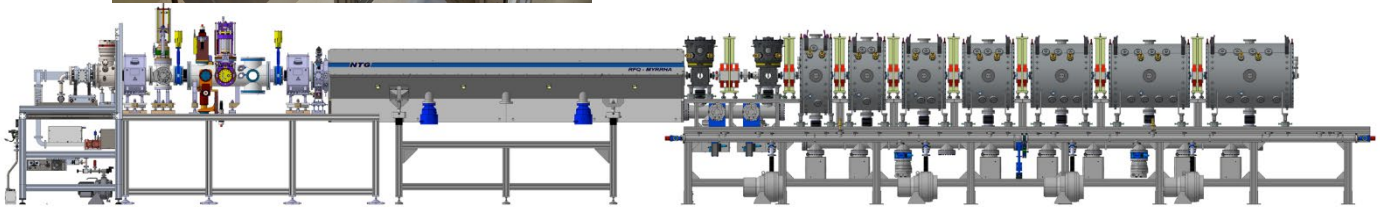
- **Accelerator R&D -** beam dynamics, RFQ, Solid State Amplifier, LLRF, EPICS
- **Heavy liquid metal thermal hydraulics -** Fuel assembly, Pool & Integral system thermal hydraulics, Liquid metal heat transfer
- **Chemistry of Volatile Radionuclides -** Quantification and characterization of the release of radionuclides from LBE and development of capture methods
- **Actinide Fuel -** Interaction test of Np and Am bearing uranium oxide fuel discs in contact with liquid LBE.
- **GUINEVERE sub-critical cores –** Various MYRRHA reactor core configuration with experimental rigs in support of the MYRRHA design
- Course on **Accelerators and ADS systems**, workshop and lecture series

The MYRTE Project – H2020 Framework Programme

Accelerator R&D



- First protons at 30 keV, 15 mA
- Solid State Amplifier – operational
- RFQ conditioning - 145 kW CW reached



The MARISA Project – 7th Framework Programme

Key project information

MARISA	
Main Objective	Bring the MYRRHA project to a level of maturity required to start construction phase
Project type	Coordination and Support Action (EURATOM Programme)
Duration	3 years From September, 1st 2013 to August, 31st 2016
Coordinator	SCK•CEN (Hamid Aït Abderrahim)
Consortium	16 organisations
Granted EC contribution	€ 3.269.480,-
Total budget	€ 3.413.696,-

The MARISA Project – 7th Framework Programme

Main achievements

- Position of MYRRHA as an International **Open Users Facility** in the European and global research landscape confirmed
- MYRRHA **legal structure**, articles of association, intergovernmental agreements, governing rules, procedures for in-kind contributions and IPR defined
- MYRRHA **management principles** developed, management instruments implemented and access framework for User Groups and Communities detailed
- MYRRHA **financing** mechanisms and instruments defined
- MYRRHA **Environmental Impact Assessment Report** development initiated
- **Technical integration** MYRRHA primary system design, accelerator and Balance of Plant accomplished

The MAXSIMA Project – 7th Framework Programme

Key project information

MAXSIMA	
Main Objective	Contribute to the MYRRHA safety assessment
Project type	Collaborative Project
Duration	72 months
Coordinator	SCK•CEN (Marc Schyns)
Consortium	13 organisations
Granted EC contribution	€ 5.500.000,-
Total budget	€ 10.087.542,-

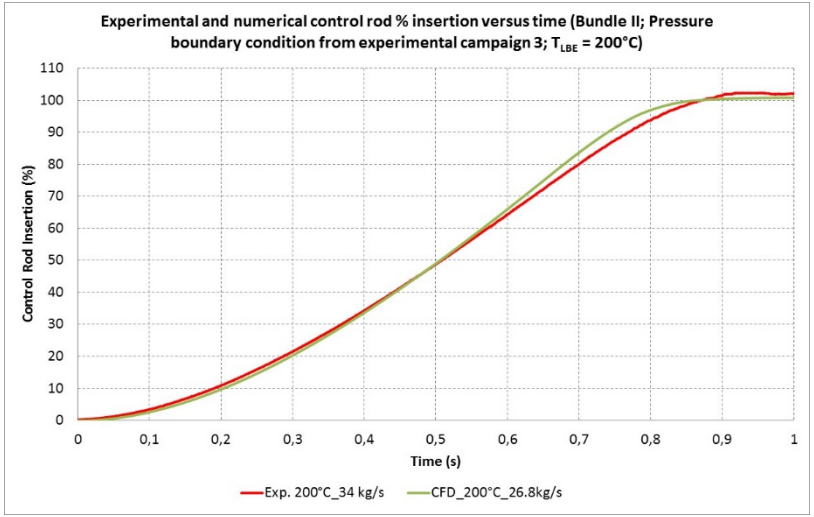
The MAXSIMA Project – 7th Framework Programme

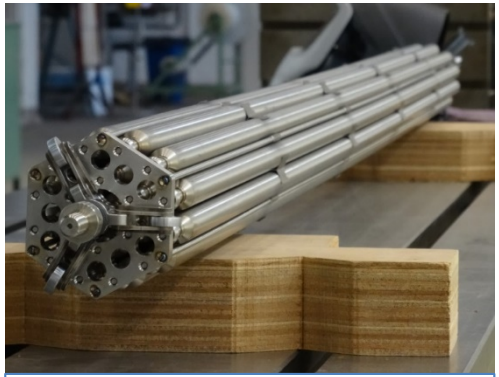
Main achievements

- Neutronic and shielding analysis as well as transient analyses using system codes in support of **safety studies**
- Thermal-hydraulic study of different **blockage scenarios** of the fuel bundle and tests supported by numerical simulations of the hydrodynamic behaviour of a new **buoyancy driven control rods**
- Characterization of the **Steam Generator Tube Rupture** event in a configuration relevant for MYRRHA
- Transient testing of MYRRHA type fuel in the TRIGA ACPR at ICN in Pitesti for the determination of the **pin failure threshold**
- **Fuel / coolant** compatibility tests
- Enhanced **passive safety system** development for decay heat removal
- 2 workshops & 1 lecture series

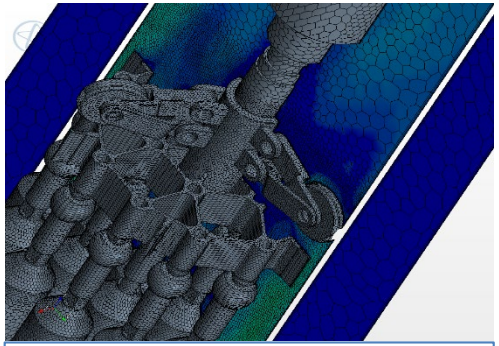
MYRRHA Control Rod Qualification

- Objective: test and qualify the buoyancy driven control rod system
- CFD methodology validated against experiments: excellent agreement





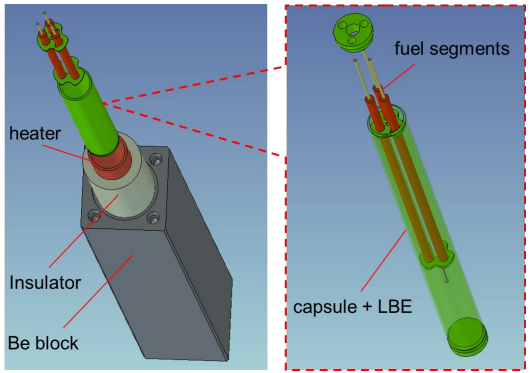
Full-scale hydraulic tests in COMPLOT

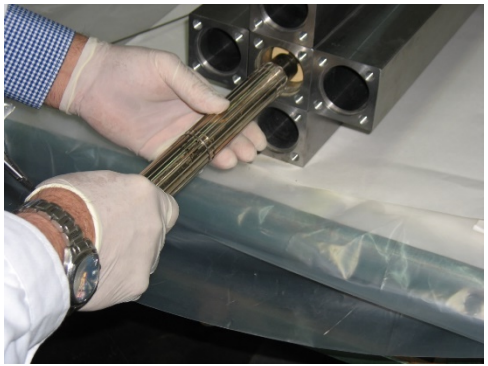


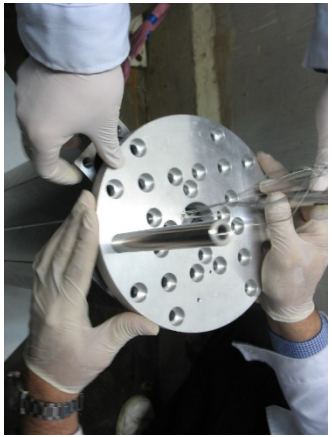
CFD dynamic simulations

Main achievements

- MYRRHA Fuel Transient testing in TRIGA ACPR of ICN in Pitesti







The SEARCH Project – 7th Framework Programme

Key project information

SEARCH	
Main Objective	Contribute to safety related research required for licensing GenIV type heavy liquid metal cooled reactor systems.
Project type	Collaborative Project
Duration	42 months
Coordinator	SCK•CEN (Paul Schuurmans)
Consortium	12 organisations
Granted EC contribution	€ 3.000.000,-
Total budget	€ 5.450.000

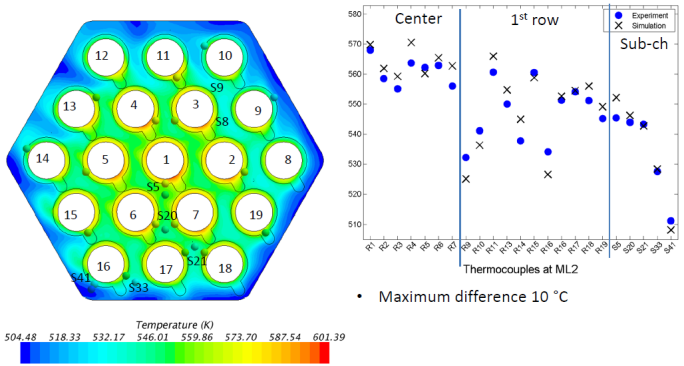
The SEARCH Project – 7th Framework Programme

Main achievements

- Heat transfer test of wire-spaced fuel bundle in forced and natural convection
  - Heat transfer correlation established
- Development of impurity and oxygen control
  - Impurity source terms from corrosion and spallation
  - Mechanical and cold trap filtering tests
- Showed compatibility of homogenous and sintered MOX fuel with LBE at 500°C and 800°C
- Build CFD and Simmer models for fuel dispersion studies.
  - Particle transport studies, accumulation zones determined
- Measured release of Hg and Po from LBE
  - Hg : ideal behaviour; Po: dependent on covergas and LBE oxygen content, volatile molecule formed with water vapour, stable deposition on steel below 300°C
- Held 2 workshops & 1 lecture series

The SEARCH project – 7th Framework Programme

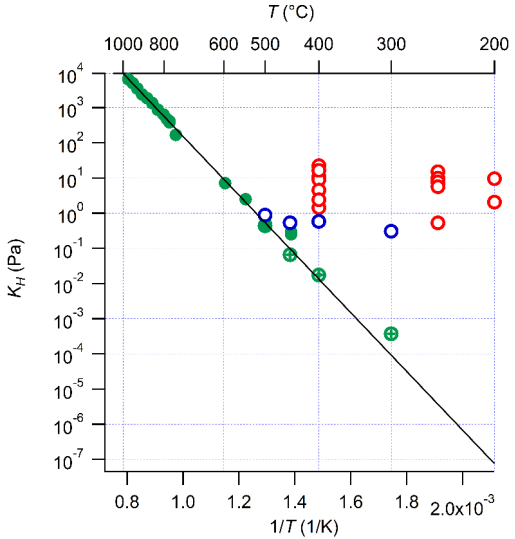
- Heat transfer in fuel bundle
  - CFD methodology validated against experiments: excellent agreement



- Maximum difference 10 °C

Comparison CFD-experiment in central plane

- Po release from LBE
  - High T (>500°C) : evaporation in agreement with Henry constant
  - Low T(<500°C) inert cover gas : initial faster evaporation, slower later on
  - Volatile Po formed with H_20 vapour



The MAX project (FP7, 2011-2014)

Key Project information

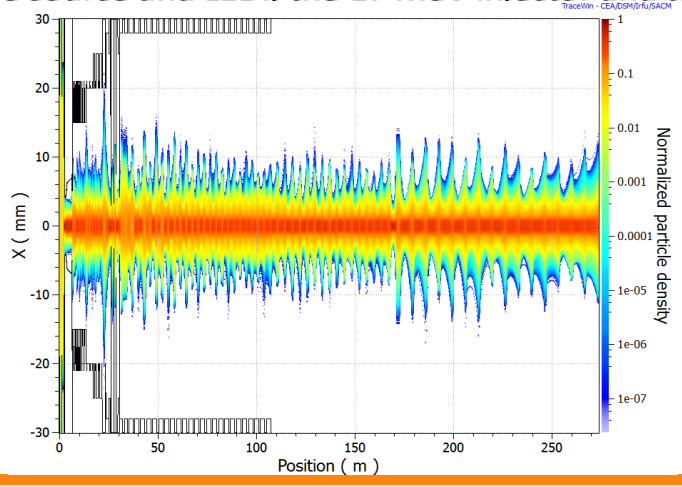
MAX	
Main Objective	Deliver a consolidated reference layout of the MYRRHA linac with sufficient detail and adequate level of confidence in order to initiate in 2015 its engineering design and subsequent construction phase
Project type	Collaborative Project
Duration	42 months
Coordinator	CNRS (Jean-Luc Biarrotte)
Consortium	11 organisations
Granted EC contribution	2.9 M€
Total final budget	6.1 M€

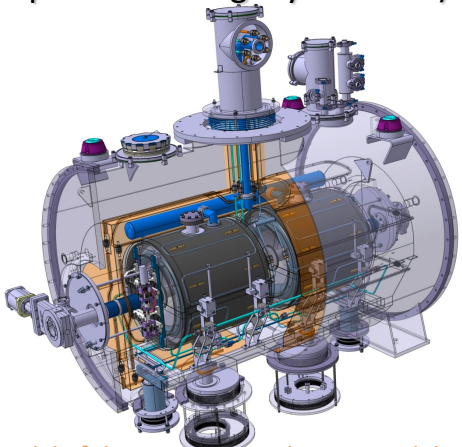
The MAX Project – 7th Framework Programme

Main achievements

➢ Production of a reference design for the whole MYRRHA accelerator

- A fully reliability-oriented overall consolidated design of the 600 MeV accelerator (incl. cryogenic plant)
- A set of benchmarked modeling tools allowing for start-to-end beam simulations.
- An operational reliability model based on the SNS experience.
- A detailed engineering design of a few critical elements (eg: the source and LEBT. the 17 MeV iniector and the Spoke superconducting cryomodule).



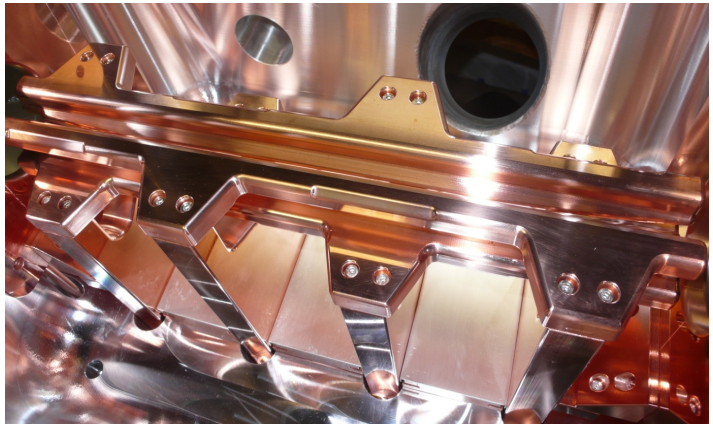


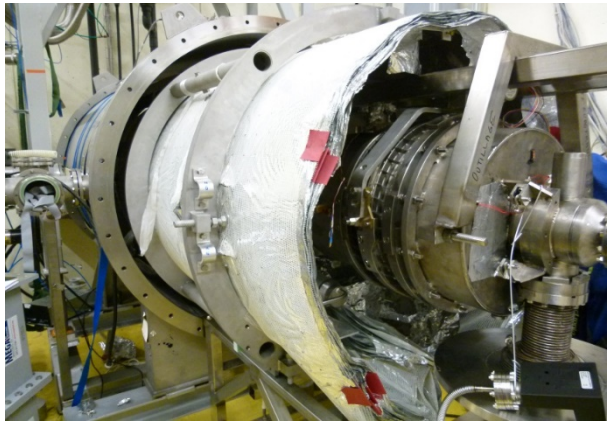
3D model of the MYRRHA Spoke cryomodule

The MAX Project – 7th Framework Programme

Main achievements

- **Specific experimental results, matched to particular aspects of an ADS-accelerator**
  - Cooling performance tests of the 4-rod RFQ model cavity in real CW RF operation.
  - Investigation of the behavior of a low-beta elliptical superconducting (SC) cavity in accelerator-like conditions (2K, high RF power).
  - Assessment of a SC cavity fault-recovery scenario using a digital low level RF feedback system and featuring an adaptative tuner controller.
  - RF test of a superconducting CH cavity at 4K and 2K in vertical cryostat.
  - Performance of a 704 MHz solid state RF amplifier module & associated power combiner.





Elliptical prototype cavity in its cryomodule at Orsay

The FREYA Project – 7th Framework Programme

Key project information

FREYA	
Main Objective	To validate the methodology of on-line reactivity monitoring To support the development and operation of new reactor concepts such as MYRRHA and Lead Fast Reactor
Project type	Collaborative Project
Duration	60 months
Coordinator	SCK•CEN (Anatoly Kochetkov)
Consortium	16 organisations
Granted EC contribution	€ 2.800.000,-
Total budget	€ 5.060.000

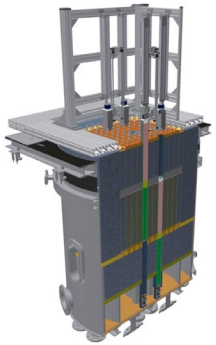
The FREYA Project – 7th Framework Programme

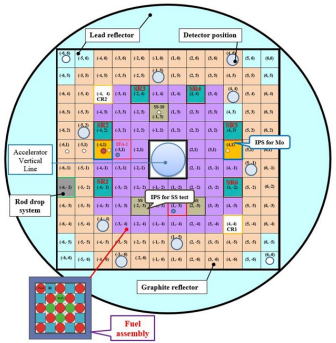
Main achievements

- Several VENUS-F fast reactor cores were coupled to an GENEPI-3C accelerator that delivers a deuteron beam. GENEPI-3C provides an external neutron source to the VENUS-F reactor through T(d,n)^{4}He fusion reactions
- Different sub-criticality levels of the VENUS-F fast core for the nominal operation mode of ADS (k-eff varied 0.95-0.99) as well as a deeper subcritical level of 0.90 (core loading) were studied
- The applicability of the different sub-criticality measurement techniques was investigated
- FREYA experimental programme with regard to the LFR as well as for the critical mode operation of MYRRHA for the licensing of these designs so as for the validation of reactor codes has been accomplished
- Held 6 workshops & dissimilation lab-session (one week)

The FREYA project – 7th Framework Programme

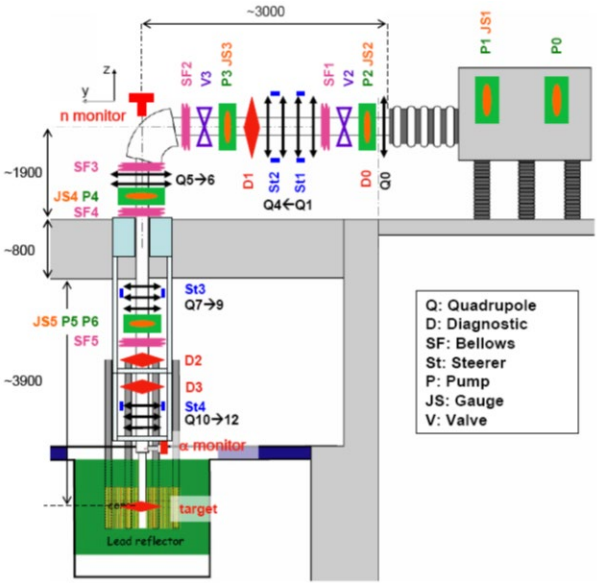
- 03/2011: **start FREYA project VENUS-F critical core**





Fuel	U 30%, metal
Assembly	U + Pb\Bi+ Al2O3, 8 x 8 cm
Core layout	Maximum 12 x 12 FAs
Core height	60 cm
Reflectors	~ 40 cm Pb everywhere
Regulation	2 CRs, B_4C natural
Safety	6 SR, B_4C with fuel followers

- 10/2011: **Sub-critical VENUS-F core coupling with GENEPI-3C, ADS mode simulation**



T(d,n)^{4}He reactions
➔ 14Mev neutrons

The ARCAS Project – 7th Framework Programme

Key project information

ARCAS	
Main Objective	Comparison of Fast Reactor and ADS transmutation in a European regional approach
Project type	CSA-SA Support Action
Duration	24 months
Coordinator	SCK•CEN (Gert Van den Eynde)
Consortium	13 organisations
Granted EC contribution	€ 488.180,-
Total budget	€ 509.528,-

The ARCAS Project – 7th Framework Programme

Main achievements

- Establishing a reference **minor actinide stream** for a European region eligible for transmutation
- Study of homogeneous and heterogeneous **transmutation** in sodium-cooled **Fast Reactor** from FP7-CP-ESFR
- Study of homogeneous **transmutation** in lead-cooled **Accelerator Driven System** EFIT from FP6-IP-EUROTRANS
- **State-of-the-art** report on transmutation **fuel fabrication** and **reprocessing**, including Technological Readiness Levels
- **Scenario** studies, including economic assessment, of transmutation in a regional European frame work

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Partitioning & Transmutation

Contribution of MYRRHA to an EU strategy for HLW management

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In Belgium, for Europe and beyond:
sustainable & innovative applications from nuclear research

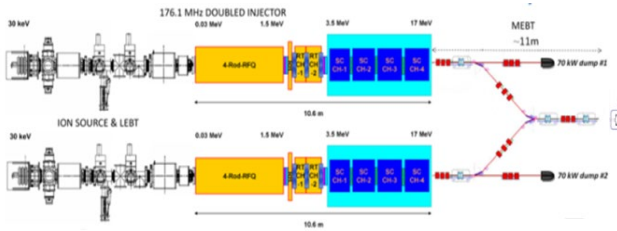
Belgian Government decision on September 7, 2018

- **Decision to build** in Mol a new large research infrastructure MYRRHA
- Belgium **allocated budget** of 558 M€ for the period 2019 - 2038:
  - 287 MEUR investment (CapEx) for building MINERVA (Accelerator up 100 MeV + PTF) for 2019 - 2026
  - 115 MEUR for further design, R&D and Licensing for phases 2 (accelerator up to 600 MeV) & 3 (reactor) for 2019-2026.
  - 156 MEUR for OpEx of MINERVA for the period 2027-2038
- Establishment of an **International Non-Profit Organization**
  - in charge of the MYRRHA facility for welcoming international partners
- **Political support** for establishing MYRRHA international partnerships
  - Belgium mandates Vice Prime Minister Kris Peeters for promoting and negotiating international partnerships

MYRRHA = Accelerator Driven System

Key Objectives

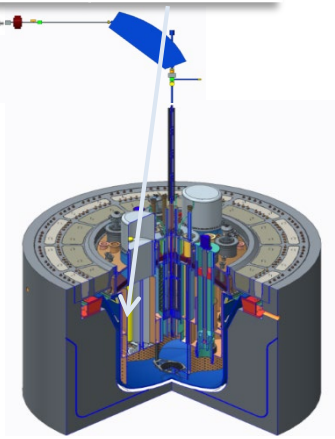
1. **Demonstrate the ADS concept at pre-industrial scale**
2. **Demonstrate transmutation**
3. **Multipurpose and flexible irradiation facility** (with fast neutron source)



Target	
main reaction	spallation
output	$2 \cdot 10^{17}$ n/s
material	LBE (coolant)

Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA

Reactor	
power	65 to 100 MW_{th}
k_{eff}	**0,95**
spectrum	fast
coolant	LBE



MYRRHA application portfolio

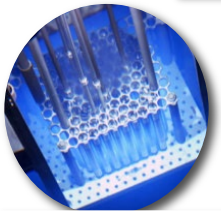
SNF*/ Waste

Fusion

Medical Radioisotopes

Fundamental research

Multipurpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications



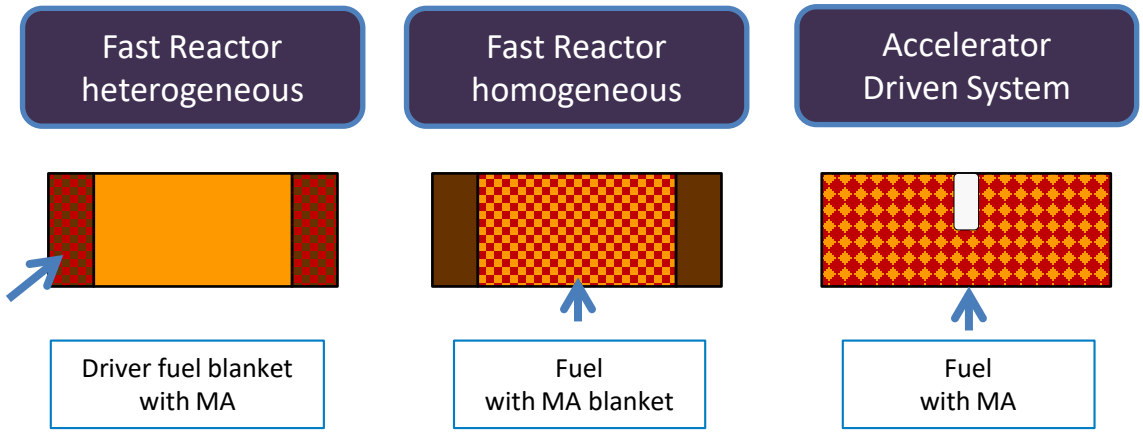
Support Fission GEN IV

Support to SMR LFR

*SNF = Spent Nuclear Fuel

Three options for Minor Actinides (MA) transmutation

EU is presently considering two approaches for transmutation:
via Fast Reactor or Accelerator Driven System (ARCAS FP7 Project)



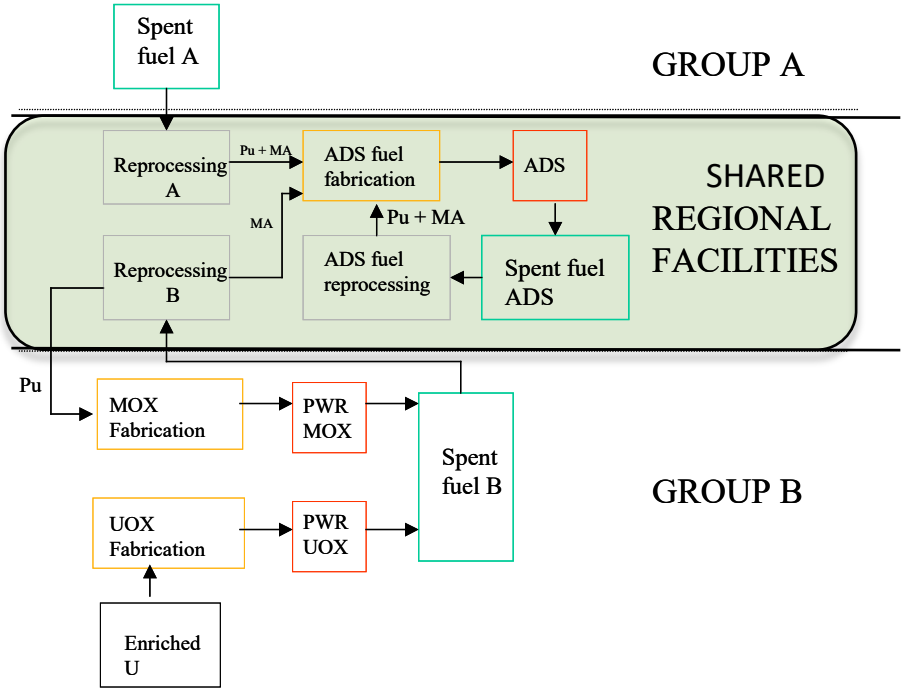
Core safety parameters limit the amount of MA that can be loaded in the critical core for transmutation, leading to transmutation rates of:

- **Fast Reactor ➔ 2 to 4 kg/TWh**
- **Accel.Driven System ➔ 35 kg/TWh** (based on a 400 MW_{th} EFIT design)

Different national nuclear energy policies: EU solution for High Level Waste works with ADS

Scenario 1 objective: elimination of SNF for countries Group A spent by 2100

(A = Countries Phasing Out; B = Countries Continuing / FP6 PATEROS project)



❑ Advantages for A

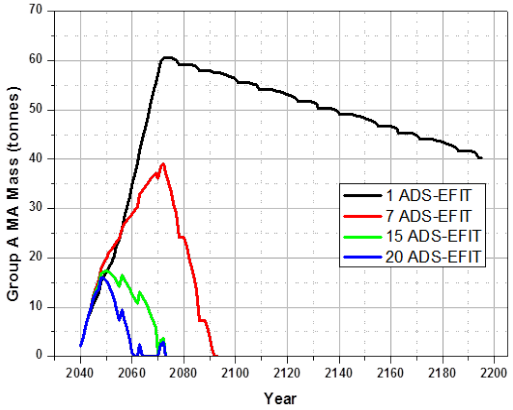
- ADS shared with B
- ADS burn A's Pu& MA
- Smaller Fu-Cycle units & shared

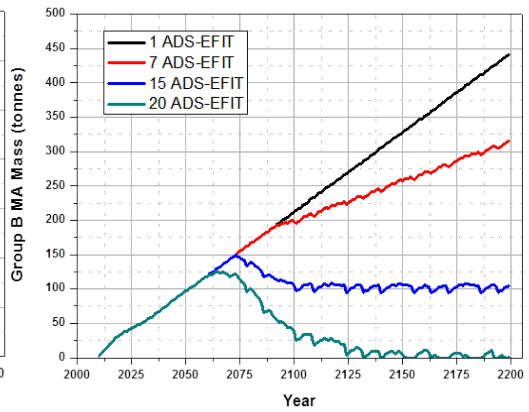
❑ Advantages for B

- ADS shared with B
- ADS burn B's MA
- A's uses B's Pu (part) as resource in FR
- FR fleet not contam with MA's
- Smaller Fu-Cycle units & shared

Shared & efficient solution for Minor Actinides management

- **Europe believes in a regional approach** (see PATEROS, ARCAS)
- **Countries with different nuclear energy policies to collaborate together**
  - Countries willing to continue Nuclear Energy
  - Countries willing to develop fast reactor systems
  - Countries in nuclear phase out, interested in Partitioning &Transmutation (P&T)





15 EFIT * 400 MWth = 6000 MWth
For all EU HLW treatment

Doel (BE) = 9000 MWth
Tihange (BE) = 9000 MWth

Gravelines (FR) = 17118 MWth

Zaporizhzhya (UA) = 18000 MWth

Bruce (CND) = 18702 MWth

Kashiwazaki-Kariwa = 23895 MWth

MYRRHA is recognized in Europe to contribute to strategic objectives of both Energy and Knowledge economy

ESFRI
European Strategic Forum for Research Infrastructure

SET Plan
European Strategic Energy Technologies Plan

EIB InnovFin	MYRRHA is selected by the **European Investment Bank (EIB)** as a potential project for financing and benefits from advisory services from EIB InnovFin
Juncker Plan	MYRRHA is on the list of projects candidate to be financed by the **European Fund for Strategic Investments** (**EFSI**, also called **"Juncker plan"**)

MYRRHA is embedded in an international R&D network

EURATOM FP a very good trigger for this network

All this is possible thanks to fantastic people we have at SCK•CEN and in our international MYRRHA team

Source:

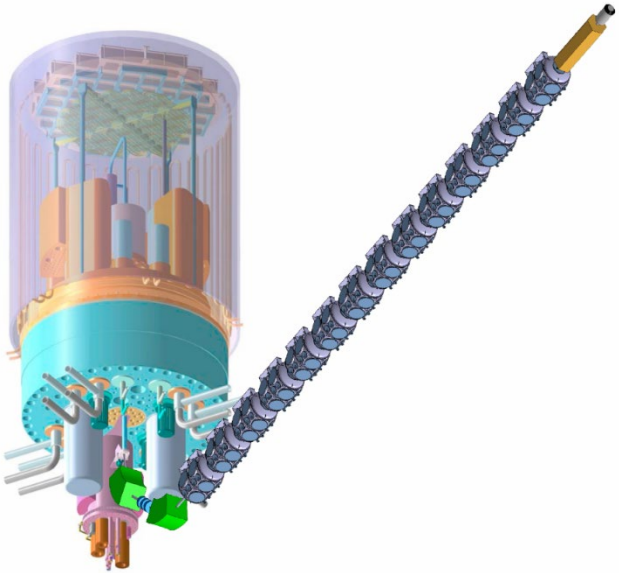
Conclusions

- Are we dreaming to industrialize P&T ?
- Life without dreams is not worth
- MYRRHA is decided we can now join effort to make it happening in Europe and offer this opportunity for our talented young people
- We should now do the same for the other blocks in particular the **A**dvanced Partitioning
- We need to join forces again between P and T (go back to P&T)
- **I call for a CA on P&T European strategy in the next work programme of EURATOM** where we can consolidate a European vision that we can feed in the OECD/NEA NI2050 Template, I'm coordinating on:

Advanced Fuel Cycle and P&T

steps towards possible industrialisation

Ceci n'est pas un réacteur



« MYRRHA, une œuvre scientifique et technique pas artistique mais qui s'en inspire »
Hamid Aït Abderrahim