The Abdus Salam
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Transmutation Systems

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R&D IN THE FIELD OF ACCELERATOR DRIVEN SYSTEMS (ADS): INTERNATIONAL STATUS

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Outline

- Why ADS?
  - Background
  - Advanced nuclear fuel cycles
- ADS technology
- Status of ADS research and technology development
  - European Union
  - Belarus
  - India
  - Japan
- Conclusions

Background

- Repository needs and characteristics
  - Present worldwide **spent fuel** and **HLW** arising would need **TWO** and **ONE** Yucca Mountain size repositories, respectively
  - **Spent fuel** repository: high Pu content ➔ non proliferation and criticality concerns
  - **Spent fuel** and **HLW** repository heat load determined by medium-lived fission products (^{137}Cs and ^{90}Sr)
  - **Spent fuel** and **HLW** repository radiotoxicity determined by minor actinides (Np, Am, Cm)

Background, cont'd

- **Spent fuel** and **HLW** repository **Hazard** vs. **Risk**
  - **P**artitioning and **T**ransmutation (P&T) objective ➔ reduction of long-term hazard of **spent fuel** or **HLW** repository by **transforming** long-lived radionuclides into short-lived or inactive elements
  - "Conventional" waste management objective ➔ reduction of long-term radiological risk (combination of potential hazard and confining properties)

Background, cont'd

- Hazard reduction (P&T objective) requires very different and much more fundamental measures as compared to risk reduction:
  - **Long-term hazard** of spent fuel and HLW is associated with the radioactive source, i.e. the transuranics
  - **Short and long-term risks** are due to the **mobility** of fission products in the **geosphere** and the possibility to **enter** the **biosphere**

Background, cont'd

- Nuclear fuel cycle options
  - Conventional
    - ✓**O**nce **t**hrough fuel **c**ycle with direct disposal of spent fuel (OTC)
    - ✓Aqueous reprocessing fuel cycle with vitrification of high-level liquid waste (RFC)
  - **A**dvanced **f**uel **c**ycle with partitioning of actinides (AFC)

Advanced Nuclear Fuel Cycles

- Sustainability (resources, waste management)
- Public acceptance
- AFC
  - Recycle fissile resources
  - Minor actinides and long-lived fission products utilization/transmutation
  - Waste amount and radio-toxicity reduction

Advanced Nuclear Fuel Cycles, cont'd

- Renewed interest in Partitioning and Transmutation (P&T)
  - Worldwide efforts to assess its potential as a radioactive waste management option
- P&T complex technology, requiring
  - Advanced reprocessing ➔ in addition to U, Pu and ^{129}I, "Partitioning" extracts from the liquid high level waste the minor actinides and
    long-lived fission products, e.g. ^{99}Tc, ^{93}Zr, ^{135}Cs, ^{107}Pd, and ^{79}Se
  - Fully new transuranics fuel fabrication plants
  - Innovative transmutation reactors

Advanced Nuclear Fuel Cycles, cont'd

- Present LWRs are not suited for minor actinides and long-lived fission products utilization/transmutation
  - Safety consideration
  - Plant operation
  - Poor utilization/transmutation capability
- Only specially licensed LWRs can cope with MOX-fuel
  - Special reactor designs (e.g. ABB80+, EPR) required for increased Pu loadings (up to 100%)
  - A combination of these reactor types allows Pu inventory stabilization, albeit with increased minor actinides production

Advanced Nuclear Fuel Cycles, cont’d

- Long-term waste radio-toxicity can be effectively reduced only if transuranics are fissioned (utilized) → very hard neutron spectra needed
- New transmuter reactor concepts
  - Dedicated fast reactors
  - Accelerator Driven Systems (ADS)
  - Fusion/fission hybrid reactors

Advanced Nuclear Fuel Cycles, cont'd

- Significant Pu and minor actinides utilization rates can be achieved in symbiotic scenarios
  - LWR-MOX and dedicated fast reactors
  - Fast neutron spectrum ADS for minor actinides utilization
  - Very high thermal flux ADS could also provide significant transuranics transmutation yields

Advanced Nuclear Fuel Cycles, cont'd

- Long-lived fission product transmutation difficult:
  - Occur in elemental mixtures (different isotopes of the same element) ➔ isotopic separation required
  - Transmutation yields small because of very low capture cross sections in thermal neutron fields ➔ dedicated reactors required with very high loadings and/or high thermal flux levels

ADS Technology, cont'd

- ADS couples spallation source with sub-critical core
- The basic idea is to make use of the additional flexibility offered by the excess neutrons produced by the spallation source to
  - Produce energy
  - Transmute radio-toxic isotopes
  - Breed fissile material
- Spallation source
  - High energy proton beam on heavy nuclide target producing hard neutrons
  - Less effective than fission neutron source

ADS Technology, cont'd

Spallation neutrons more "expensive", e.g. for Pb target:

200 MeV ➔ spallation target ➔ $200\times\eta_{th}\times\eta_e\times\varepsilon$ = $200\times0.4\times0.5\times0.5$ = 20 MeV plus $200\times\eta_{th}\times\eta_e\times Z/E_p$ = $200\times0.4\times0.5\times25/10^3$ = 1 hard neutron (φ* ➔ 1.5 hard neutrons) ➔ compared to fission (producing 200 MeV plus 3 hard neutrons), spallation source needs 180 MeV to produce ½ the number of hard neutrons

η_{th} efficiency of thermal to electrical energy transformation

η_e efficiency of electric energy to proton current transformation

ε fraction of incident protons having kinetic energy $\geq$ spallation nucleus dissociation energy

Z neutrons produced in Pb by each proton of energy E_p

ADS Technology, cont'd

- Power control is possible up to a certain extent via the proton beam current
- Should the accelerator have enough reserve, even burnup compensation could be done via the accelerator
- Level of sub-criticality can be chosen, within the technological limits set by the accelerator, larger than β_{eff} ➔ beneficial to power control and safety
- Potential advantages ➔ enhanced safety and flexibility
- Potential advantages need substantiation

ADS Technology, cont'd

- Justification for using "expensive neutron source"
  - Improvement of the dynamics behavior
  - Enhanced flexibility
- R&D efforts aiming at substantiating the potential of ADS and studying their role in innovative reactor and fuel cycle strategies that include systems for large-scale utilization and transmutation of minor actinides and long-lived fission products

Status of ADS R&D: European Union

- EURATOM 6th (2002 – 2006) and 7th (2007 – 2011) Framework Programmes (FPs)
- EUROTRANS project → funded with a total of EUR 45 million, EC contributed 23 million
- Objectives
  - Preliminary design → MYRRHA / XT-ADS (experimental ADS, 50 – 100 MWth)
  - Conceptual design → European Transmutation Demonstrator (ETD, several hundred MWth, modular)
- Major activities
  - MEGAPIE
  - MYRRHA / XT-ADS project
  - GUINEVERE experimental facility
  - FASTEF and CDT (Central Design Team)

Status of ADS R&D: European Union, cont'd

- MEGAPIE **MEGA**watt **PI**lot **E**xperiment
- Joint effort by 6 European Institutes (PSI, FZK, CEA, SCK•CEN, ENEA, CNRS) plus JAEA (Japan), DOE (USA) and KAERI (Rep. of Korea) to demonstrate
  - Design, manufacturing, safe operation, and dismantling of a liquid Pb-Bi eutectic target for high power spallation and ADS applications
  - Assess the target's neutronics performance
  - Collect material data in view of establishing a data base for liquid Pb-Bi eutectic targets
- MEGAPIE was the first liquid Pb-Bi eutectic target operated in the Megawatt regime (0.8 MW provided by the PSI proton accelerator)
  - Successfully irradiated from August until December 2006 at the Swiss Spallation Neutron Source (SINQ) at PSI
  - MEGAPIE received a beam charge of 2.8 Ah of 575 MeV protons
- Dismantling and PIE planned from summer 2009 on

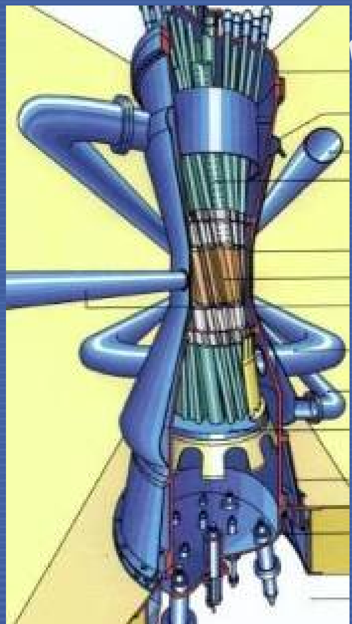
Status of ADS R&D: European Union, cont'd

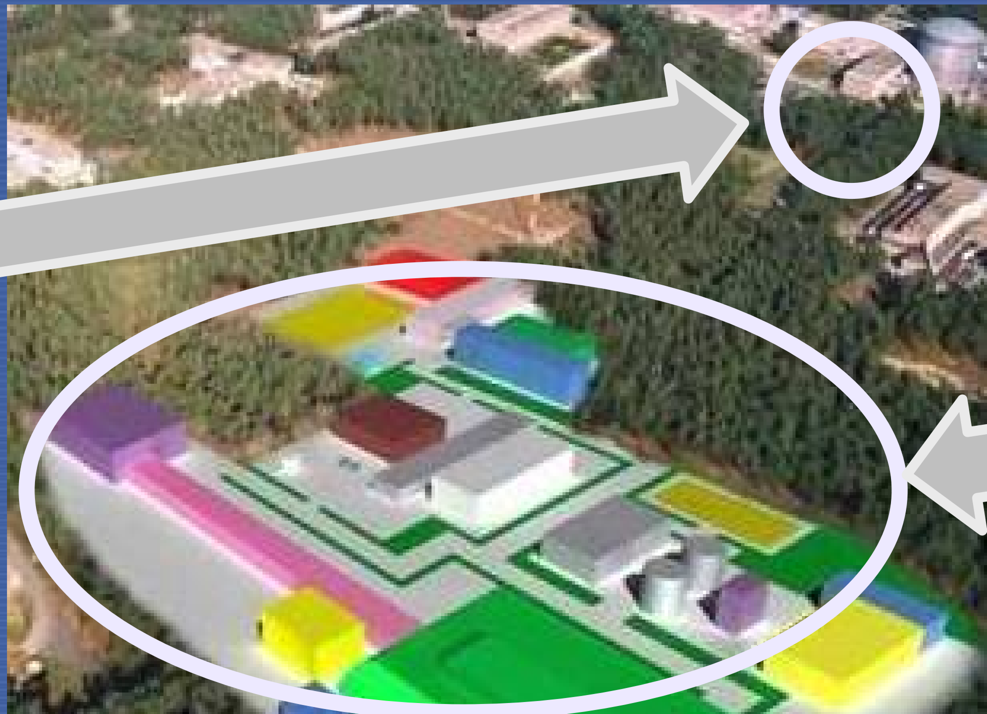
- MYRRHA / XT-ADS demonstrates the feasibility of transmutation with ADS
  - 600 MeV / 2.5 mA or 350 MeV / 5 mA LINAC
  - Pb-Bi eutectic spallation target and coolant
  - Mixed U-Pu oxide fuelled sub-critical core
  - SCK•CEN aligned MYRRHA (full scale ADS demonstrator) R&D activities with XT-ADS efforts:
    - ✓Investigation of design cliff edges
    - ✓Demonstration of accelerator components
    - ✓Thermal hydraulics design of spallation target
    - ✓Experimental coupling of a fast sub-critical core with a neutron source in GUINEVERE

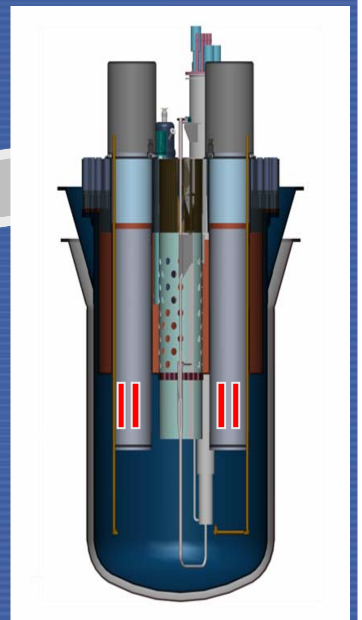
MYRRHA / XT-ADS

1962
BR2
Highest Flux
Material Test
Reactor in Europe

2020
World Premiere
Demonstration
of Nuclear Waste
Transmutation



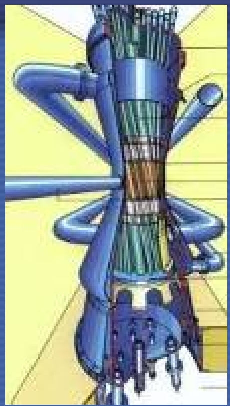




Courtesy Hamid Aït Abderrahim, SCK•CEN, Mol, “MYRRHA Science Towards Sustainability”, AccApp09, Vienna, 4-8 May 2009

MYRRHA / XT-ADS: Fast Spectrum Test Facility

Courtesy Hamid Aït Abderrahim, SCK•CEN, Mol, "MYRRHA Science Towards Sustainability", AccApp09, Vienna, 4-8 May 2009



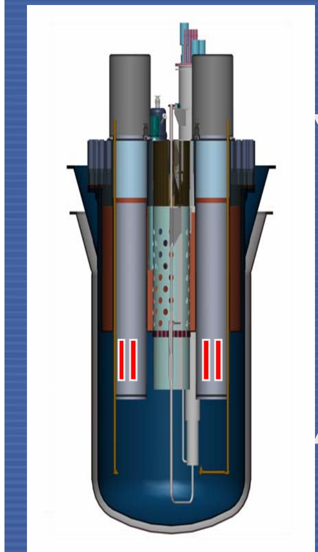
1962

BR2

Fast Neutron Material Test Reactor (fission)

LWR (GEN II/GEN III) Fuel Testing

Irradiation Services:
- **Medical RI**
- **Si doping**
- **Others**



2020

MYRRHA / XT-ADS

Very Fast Neutron Material Test Reactor (fission + fusion)

ADS-Demo + P&T Test

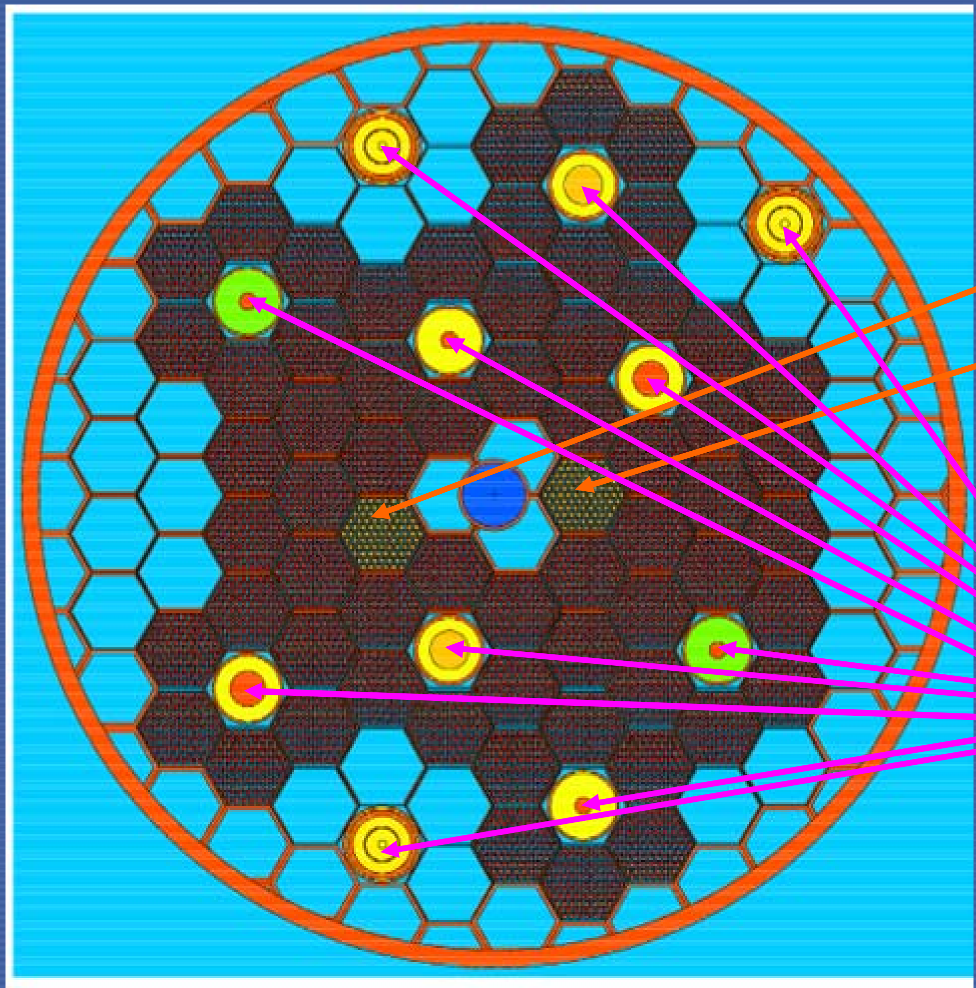
Fuel testing for GEN IV

Irradiation Serv. :
- **Medical RI**
- **Si doping**
- **Others**

GEN IV Lead Fast Reactor Technology Demonstration

MYRRHA / XT-ADS: Flexible Experimental Facility

Courtesy Hamid Aït Abderrahim, SCK•CEN, Mol, "MYRRHA Science Towards Sustainability", AccApp09, Vienna, 4-8 May 2009



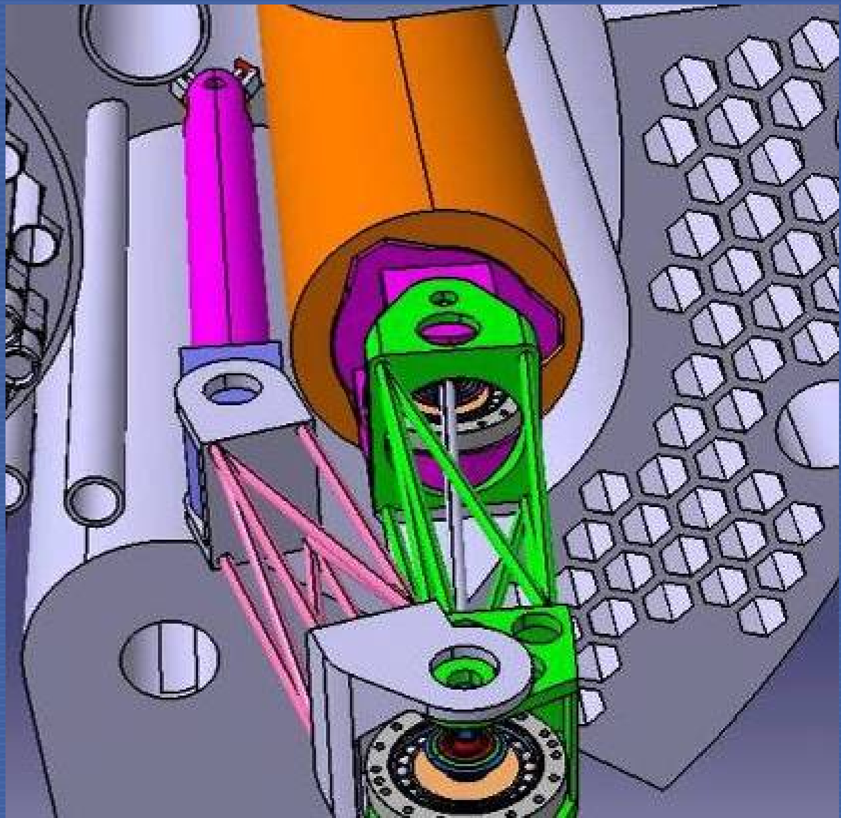
Minor Actinides test assemblies

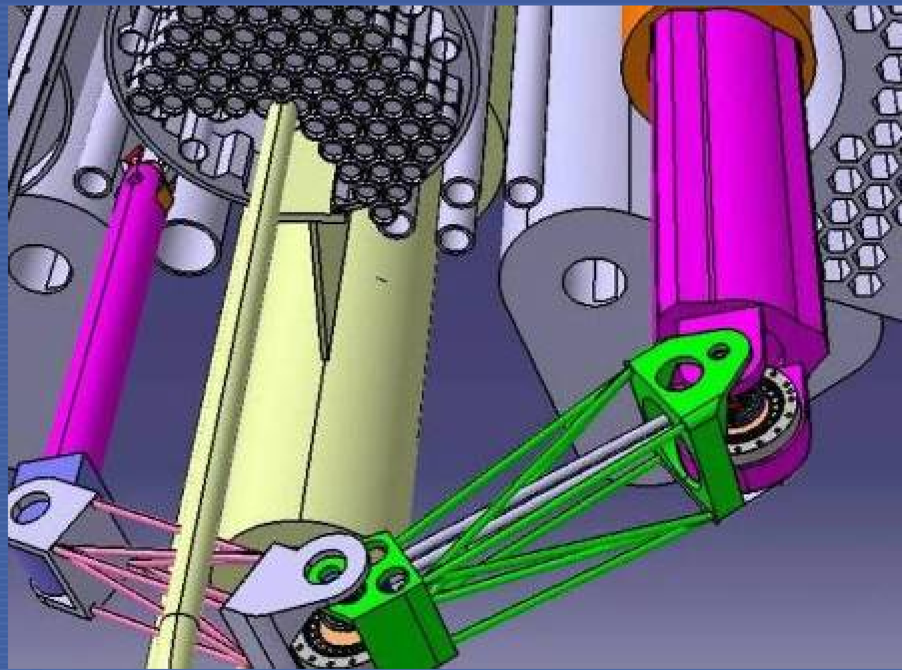
Experimental rigs:

- **dedicated contents**
- **dedicated irradiation**

MYRRHA / XT-ADS: In Vessel Remote Handling

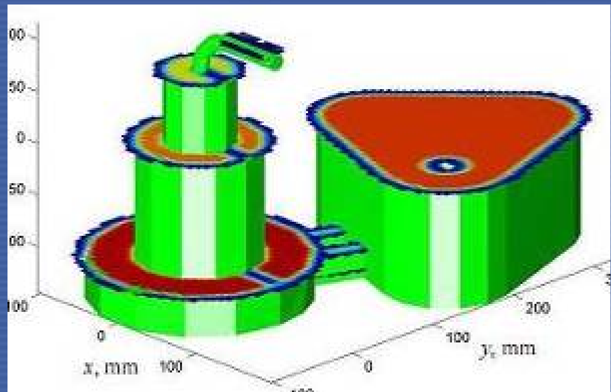
Courtesy Hamid Aït Abderrahim, SCK•CEN, Mol, "MYRRHA Science Towards Sustainability", AccApp09, Vienna, 4-8 May 2009

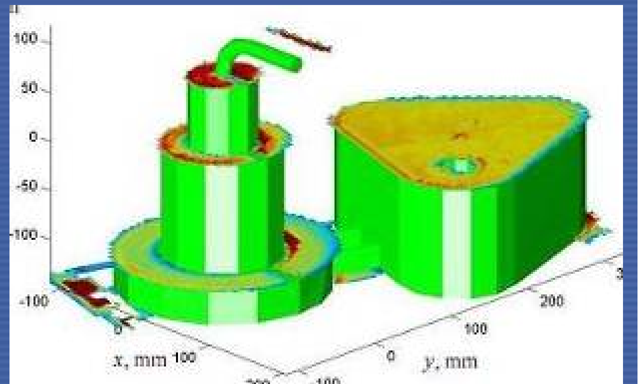




MYRRHA / XT-ADS:
Ultrasonic Imaging in Pb-Bi Eutectic at 300 °C

Courtesy Hamid Aït Abderrahim, SCK•CEN, Mol, “MYRRHA Science Towards Sustainability”, AccApp09, Vienna, 4-8 May 2009

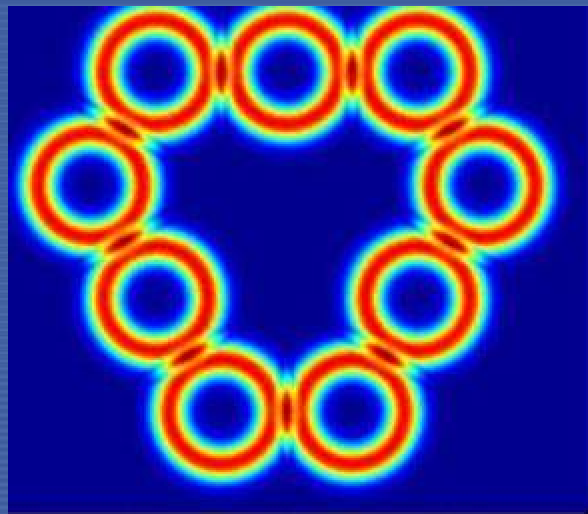


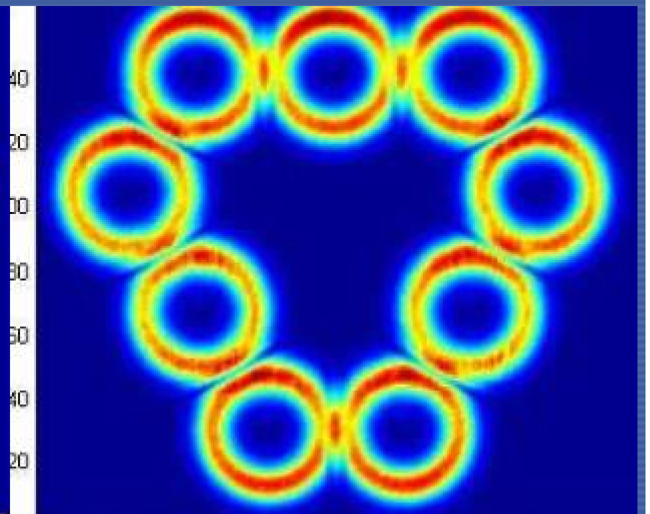


Mockup

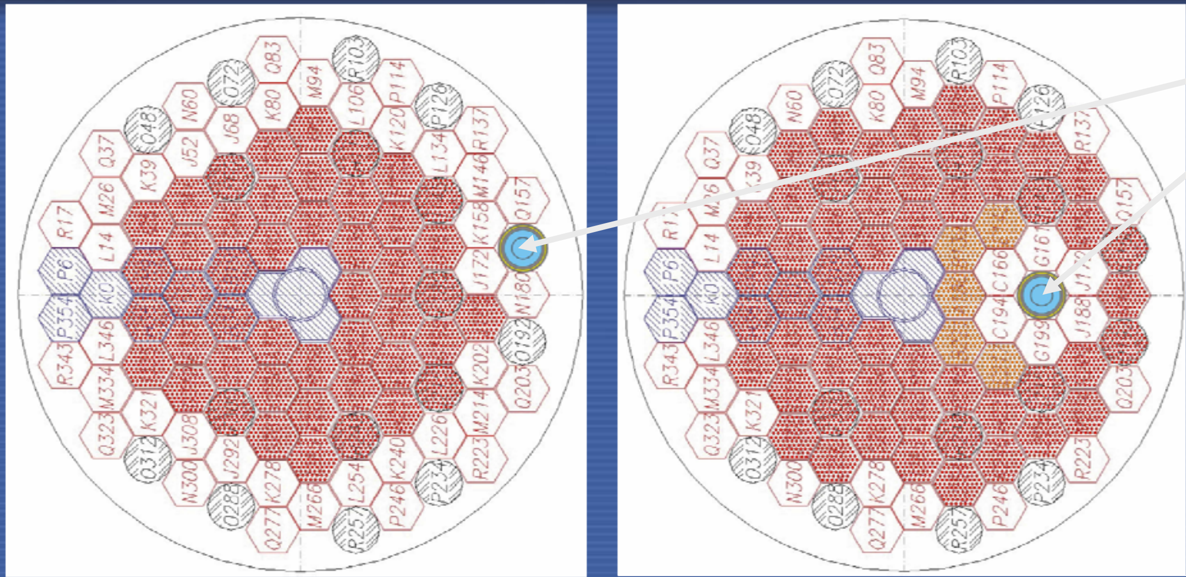
Simulated

Measured





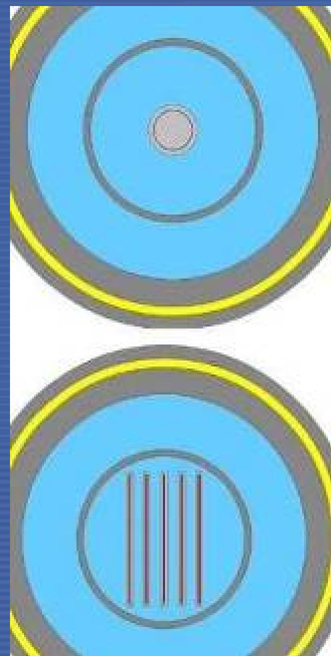
MYRRHA / XT-ADS: Radio-Isotopes Production



Radio-isotopes production

^{nat}Ir capsule → ^{192}Ir

^{235}U plates → ^{99}Mo



Courtesy Hamid Aït Abderrahim, SCK•CEN, Mol, “MYRRHA Science Towards Sustainability”, AccApp09, Vienna, 4-8 May 2009

MYRRHA / XT-ADS: Project Schedule

Courtesy Hamid Aït Abderrahim, SCK•CEN, Mol, “MYRRHA Science Towards Sustainability”, AccApp09, Vienna, 4-8 May 2009

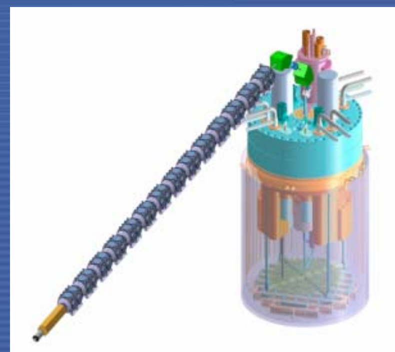
2009-2011
Detailed Engineering Design

2012-2013
Techn.specs
Call for Tenders and Awards

2014-2016
Construction of components and Civil Works

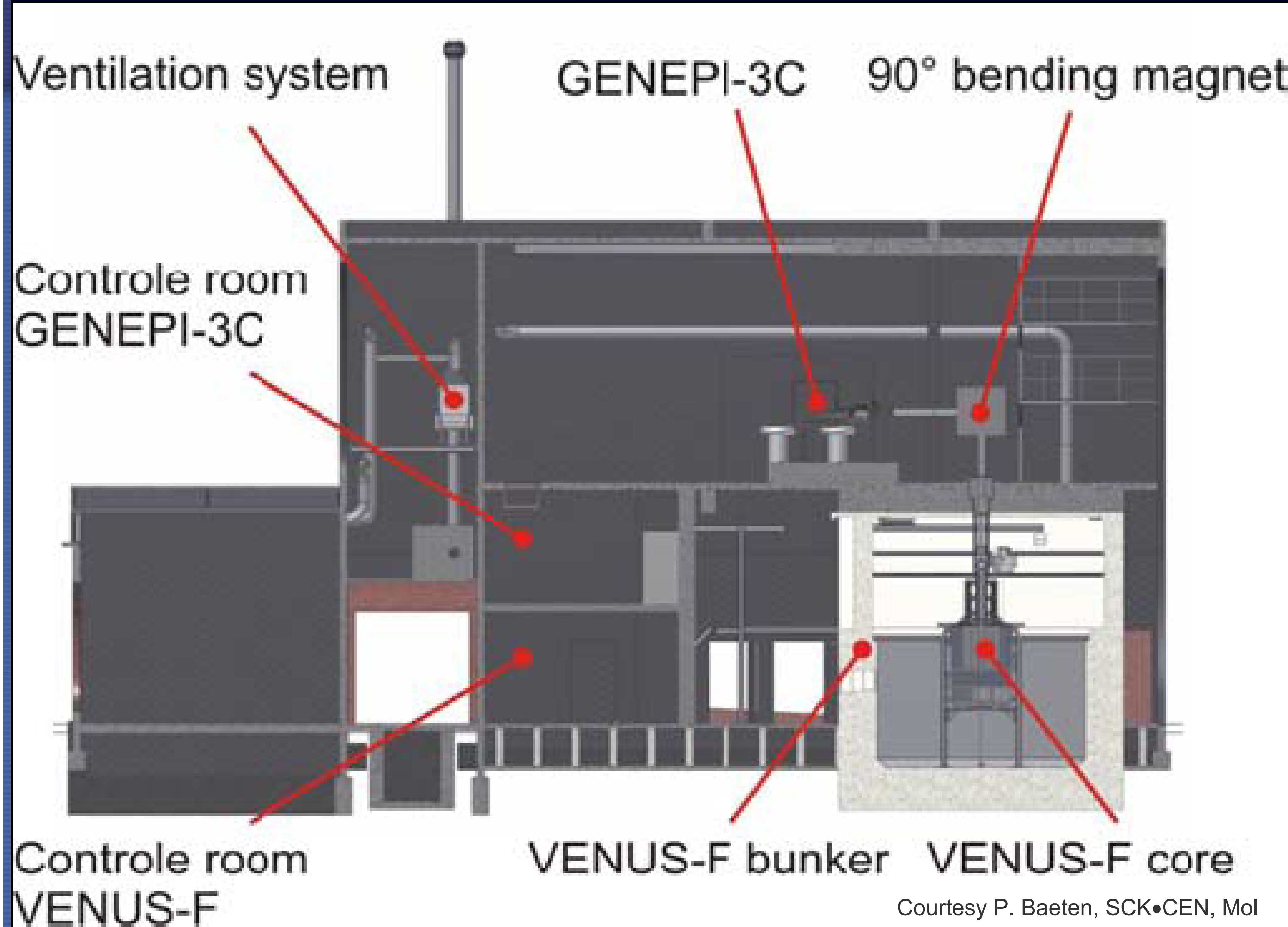
2017
Components assembly on site

2018-2019
Commissioning



Status of ADS R&D: European Union, cont'd

- GUINEVERE (**G**enerator of **U**ninterrupted **I**ntense **NE**utrons at the lead **VE**nus **RE**actor)
  - Experimental facility allowing physics experiments and technological research under conditions representative for XT-ADS
  - Deuteron GENEPI-3C accelerator operating in pulsed and continuous mode
  - Ti^3H target producing 14.1 MeV neutrons
  - Zero-power fast sub-critical 30% ^{235}U enriched metallic U fuelled core in Pb matrix



Courtesy P. Baeten, SCK•CEN, Mol

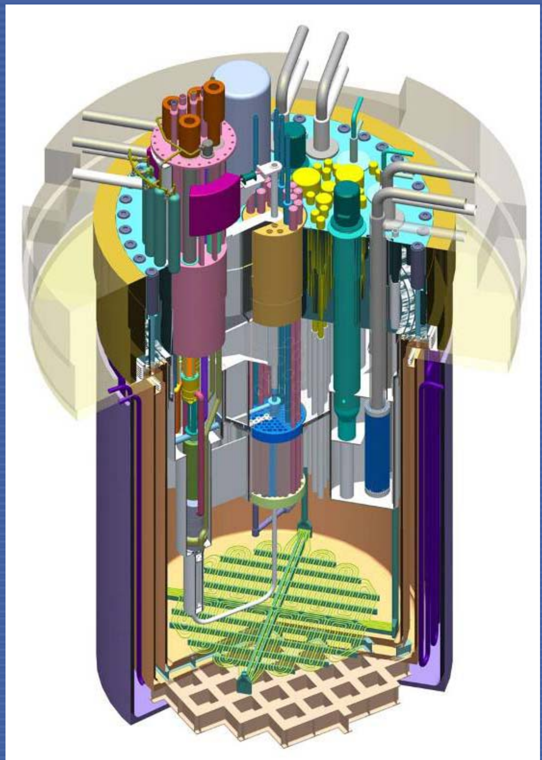
Status of ADS R&D: European Union, cont'd

- GUINEVERE studies of on-line reactivity monitoring techniques at various sub-criticality levels
  - Current-to-flux reactivity monitoring (GENEPI-3C in continuous mode, representative for power ADS)
  - Time dependent neutron spectra measurements (after beam interruptions) ➔ prompt decay method, source jerk, etc

Status of ADS R&D: European Union, cont'd

- FASTEF
  - Builds on MYRRHA / XT-ADS
  - Flexible fast spectrum irradiation facility
  - A full step ADS demo facility and P&T testing facility
  - Contributes to the demonstration of heavy liquid metal technology
- CDT (Central Design Team) Project
  - Set up of a centralised multi-disciplinary team at SCK•CEN in Mol
  - Produce advanced design of a flexible fast spectrum irradiation facility operating in both sub-critical (ADS) and critical mode
  - Create the nucleus of the "Owner Engineering Team" for the realization of MYRRHA / FASTEF

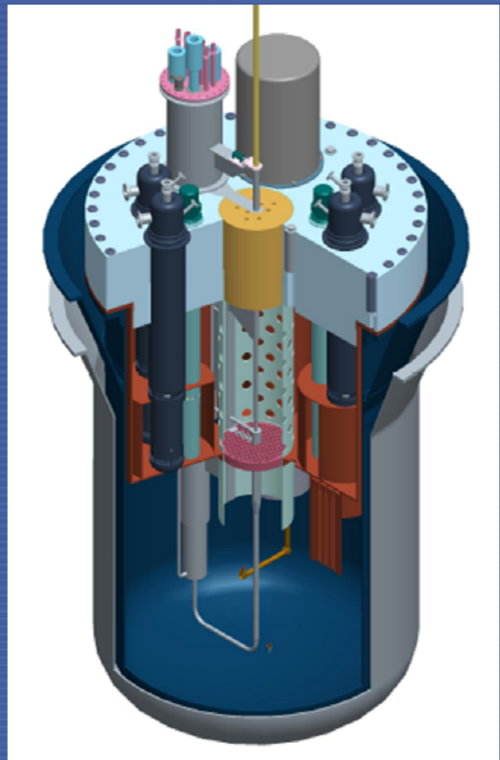
CDT, MYRRHA/FASTEF, cont'd



MYRRHA

2005

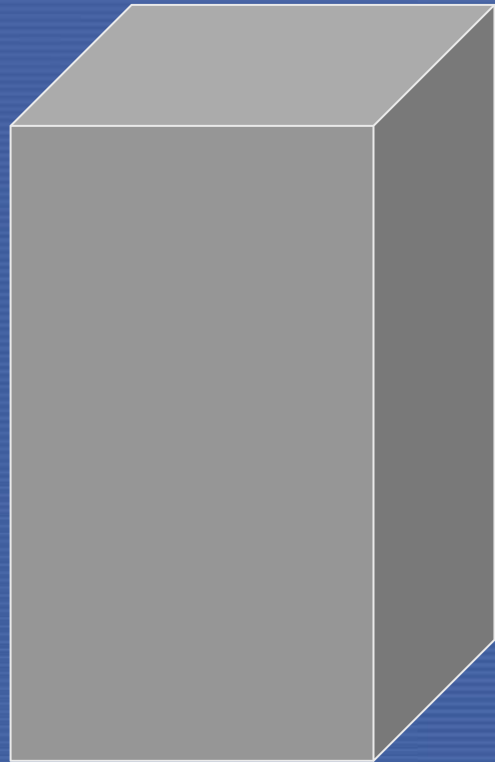
⇨



XT-ADS

2009

⇨



FASTEF

2012

Courtesy D. De Bruyn, SCK•CEN

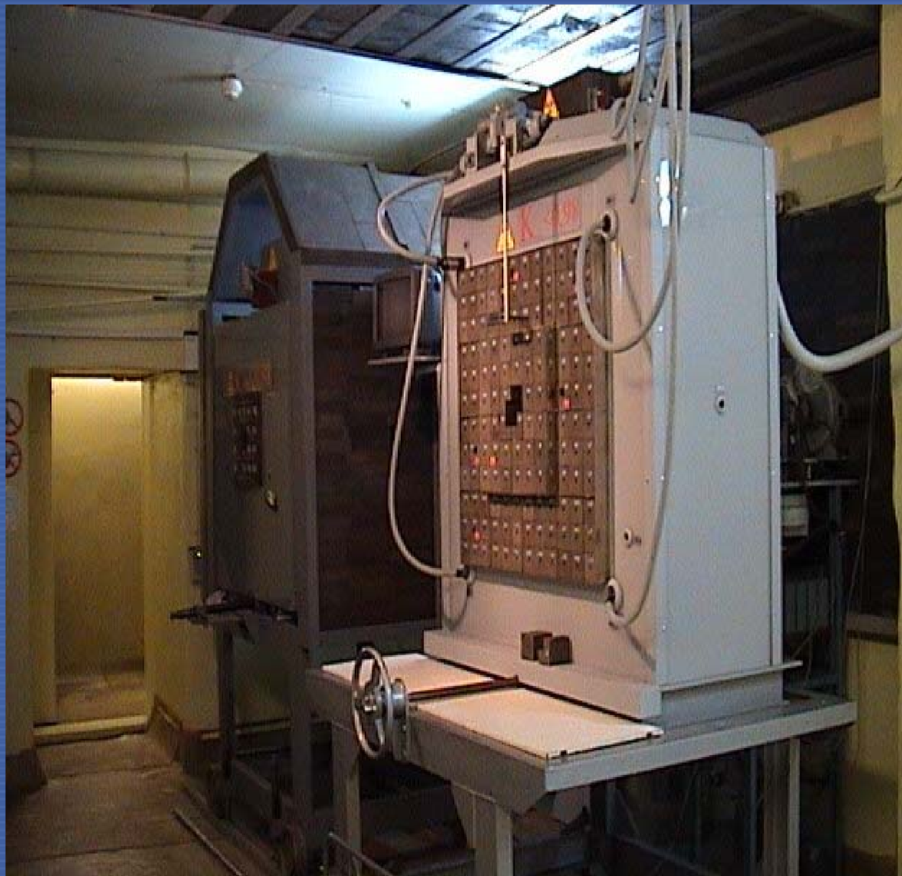
Status of ADS R&D: Belarus

- Joint Institute for Power and Nuclear Research – SOSNY (JIPNR-SOSNY) → YALINA experimental program
- Contributes to EUROTRANS and to an ISTC project (HEU to LEU conversion)
- Objectives
  - Minor actinides and long-lived fission product transmutation in fast spectrum sub-critical facilities
  - ADS physics

Status of ADS R&D: Belarus (2/2)

- Research activities (YALINA-BOOSTER configuration)
  - Development and testing reactivity monitoring techniques used in power ADS
  - Investigation of spatial kinetics of sub-critical systems driven by external neutron sources
  - Measurement of transmutation reaction rates
  - Maintenance and operation characteristics of sub-critical systems driven by external neutron sources

YALINA Facility, JIPNR-SOSNY, Belarus

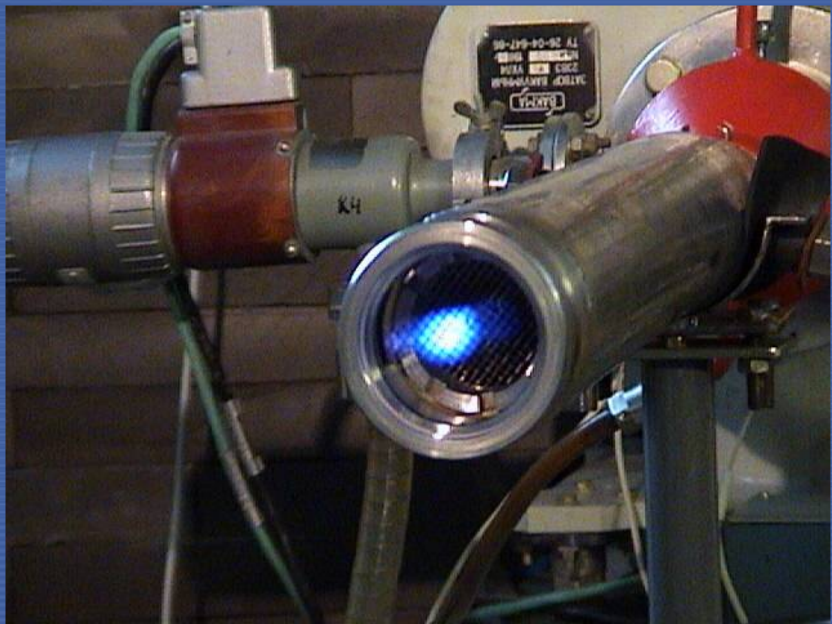


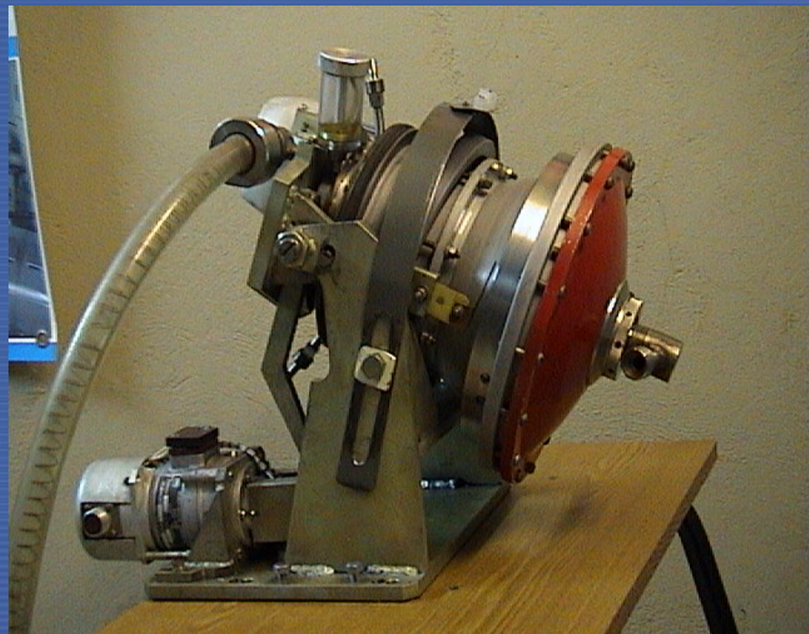
Courtesy of A. Kiyavitskaya, JIPNR-SOSNY

YALINA Targets

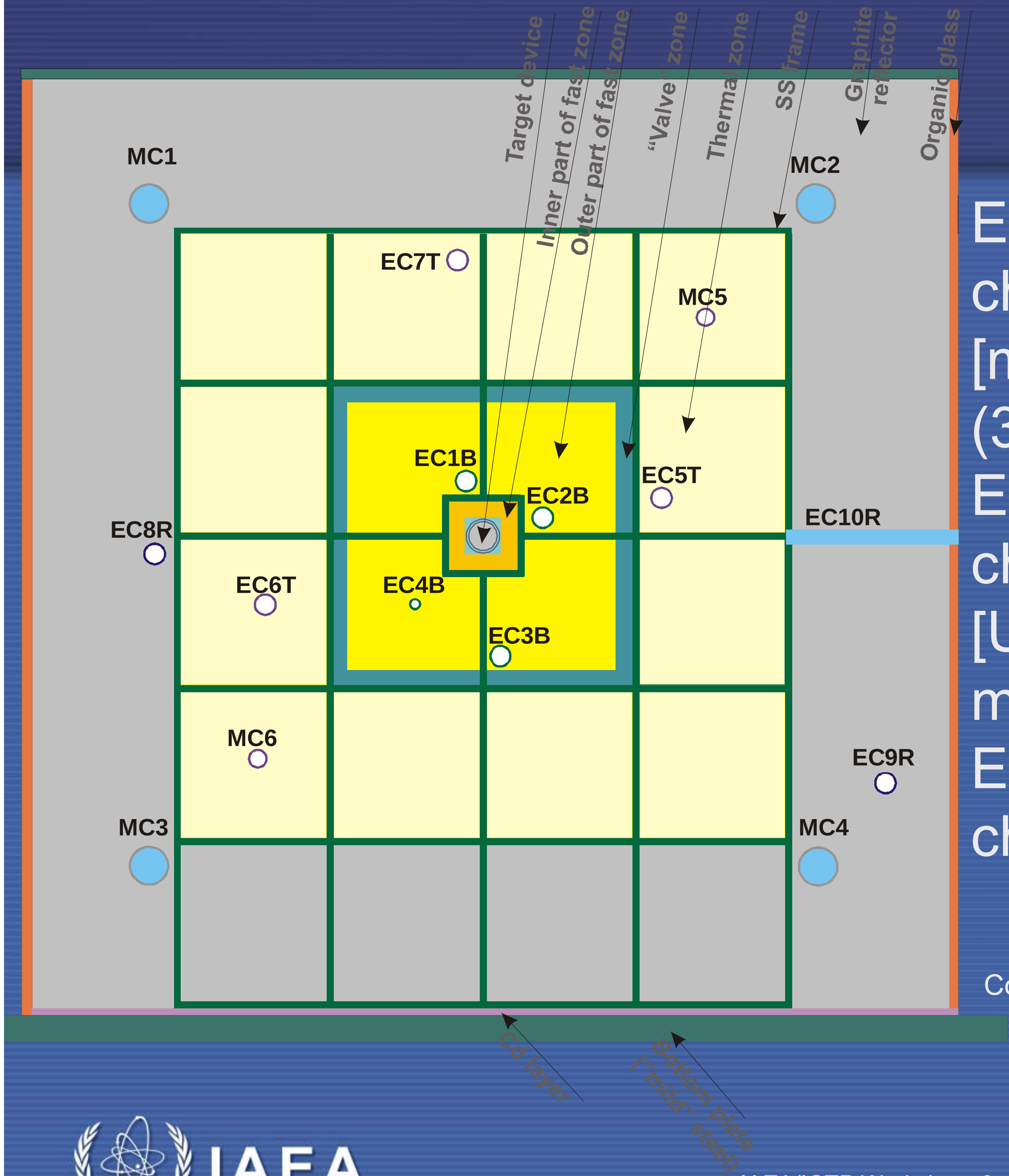
Target diameter [mm]	45	230
Rotation speed [rpm]	560	560
Beam current [mA]	1 – 2	1 - 12
Neutron energy [MeV] (D-D / D-T target)	2.5 / 14	2.5 / 14

Courtesy of A. Kiyavitskaya, JIPNR-SOSNY





YALINA Booster



EC1B-EC4B: experimental channels in fast zone [metallic U (90%) and UO_2 (36%) in Pb matrix)

EC5T-EC7T: experimental channels in thermal zone [UO2 (10%) in polyethylene matrix

EC8R-EC10R: experimental channels in reflector

Courtesy of A. Kiyavitskaya, JIPNR-SOSNY

Status of ADS R&D: India

- Objectives of ADS R&D programme
  - P&T as part of advanced fuel cycles
  - Fissile material breeding → thorium utilization
- Nuclear data
- Code development for high energy particle transport
- High power proton accelerator technology
- 14-MeV D-T neutron source coupling with sub-critical reactor (water cooled, natural uranium fuelled)

Status of ADS R&D: India, cont'd

- Spallation target systems and heavy liquid metal thermal hydraulics
  - Pb-Bi eutectic loop with simulated proton beam window heating (plasma torch and electron beam)
  - Corrosion testing
  - Validation and qualification of Computational Fluid Dynamics codes
- Sub-critical core design
  - Thorium fuel utilization in sub-critical systems
  - Experimental reactor offering the flexibility of being transformed into a sub-critical system driven by a spallation source

Status of ADS R&D: Japan

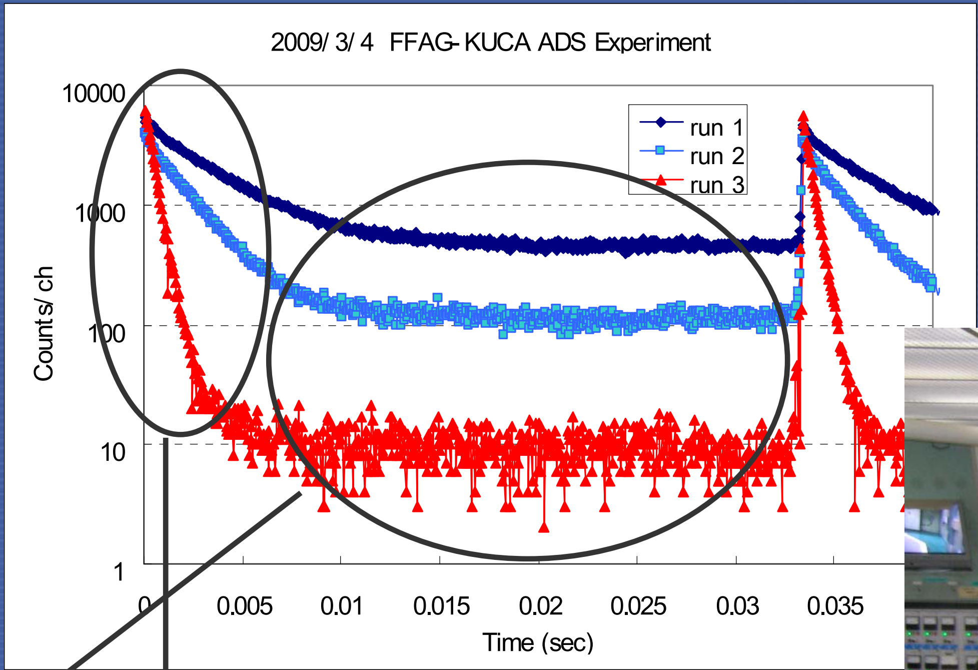
- Japan Atomic Energy Agency (JAEA) objective of R&D on ADS ➔ transmutation of long-lived radioactive nuclides
- Sub-critical core design studies: 800 MWth Pb-Bi eutectic cooled ADS
  - Four-zone core concept (limit operating temperatures below 500°C and thus improve the compatibility with Pb-Bi eutectic)
- Corrosion tests for various structural material candidates in low oxygen concentration condition at 450°C and at 550°C

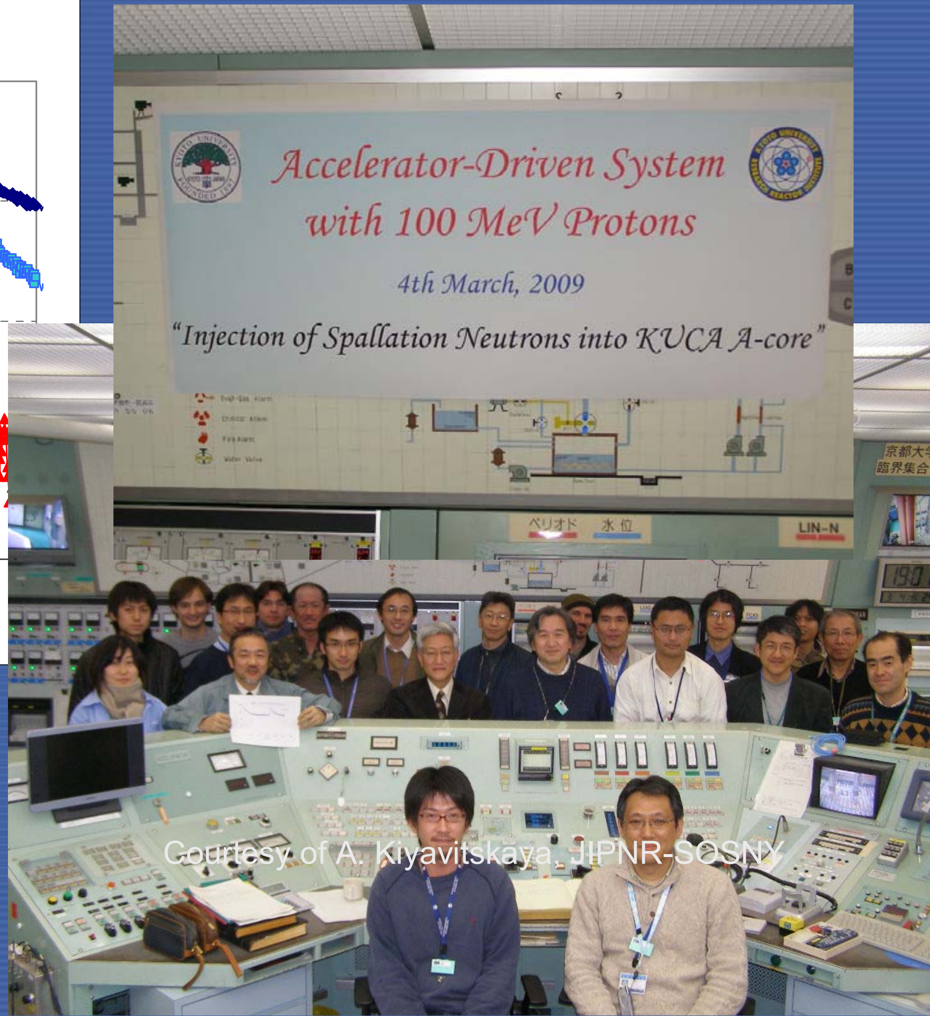
Status of ADS R&D: Japan, cont'd

- TEF (Transmutation Experimental Facility) design studies → within the framework of J-PARC (Japan Proton Accelerator Research Complex)
  - Handling of minor actinides bearing fuel
  - Remote handling system design

Subcritical Experiments at Kyoto University Critical Assembly (KUCA)

Courtesy of C.H. Pyeon, Kyoto University Research Reactor Institute





Courtesy of A. Kiyavitskaya, JIPNR-SOSNY

Spallation neutrons from target

Delayed neutrons in core

IAEA

Spallation neutrons generated by protons multiplied in KUCA

Conclusions

- Renewed interest in nuclear energy
- Sustainability → spent fuel utilization and breeding returning to centre stage → fast reactor necessary linchpin
- Significant reduction of the total Pu and minor actinides inventory → closed fuel cycle strategy → removal of minor actinides from liquid high-level waste before vitrification → achieved by combining advanced MOX fuelled LWRs and dedicated fast reactors
- Significant radio-toxicity reduction levels → innovative fuel cycles → fast neutron ADS → vastly enhanced core loadings flexibility, and ability to accommodate very high transuranics and minor actinides inventories) → drastic minor actinides depletion

⇒ **ADS an option considered for P&T**

Conclusions, cont'd

- Achieving the full potential of fast neutron system and closed fuel cycle technologies with regard to both efficient utilization of the fissile resources and waste management requires continued advances in research and technology development to ensure improved economics, and maintain high safety levels with increased design simplification
- IAEA assists Member States considering innovative fast neutron system technology options by providing an umbrella for information exchange and collaborative R&D to pool resources and expertise

For more information, please visit

http://www.iaea.org/inisnkm/nkm/aws/fnss/index.html

Thank You !