Some highlights of experimental ADS programs in Europe

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GUINEVERE collaboration

SCK·CEN, Belgium
CNRS/IN2P3, France
CEA/DEN, France

1st International Workshop on Accelerator-Driven Sub-Critical Systems & Thorium Utilization, Sep 27-29 2010, Virginia Tech
Overview

• Introduction to ADS

• MUSE experimental program
  • MUSE-4

• GUINEVERE project
  • motivations, objectives
  • civil engineering
  • reactor : design & construction
  • accelerator : design & construction
  • accelerator commissioning
  • outlook

• MYRRHA project
  • overview

Not a overview on European programs! Much more than the scope of this talk
**ADS concept**

- **ADS**: Accelerator Driven System
- Sub-critical reactor \(\Rightarrow\) external neutron source to maintain the chain reaction

- Reactor driven by the source via the accelerator beam
- Allow a fuel with large amounts of minor actinides (impossible in critical reactors because of the small fraction of delayed neutrons)

A.Billebaud, ADS Experimental Workshop, Torino, 2010
First experimental ADS programs

• Mid 90’s: FEAT and TARC experiments (renewal of ADS concept)
  Fast Energy Amplifier Test, C.Rubbia et al. (CERN, 1995)
  Transmutation by Adiabatic Resonance Crossing, C.Rubbia et al. (CERN, 1996)

  ➔ Validate ADS concepts with spallation targets (high energy p on Pb and U)
    - energy amplification
    - transmutation

• End of 90’s : researches structure around key points of ADS aiming at a feasibility demonstration ➔ EURATOM FP5

  ➔ R&D on related technologies
  ➔ Mock-up experiments for physics modeling and simulation validation
  ➔ Neutron source and sub-critical core coupling
  ➔ Spallation target
  ➔ Nuclear Data
  ➔ Fuel
  ➔ Design

A.Billebaud, ADS Experimental Workshop, Torino, 2010
Main issues in ADS reactor physics

- **Modeling/simulation code validation**
  - Models and codes designed mainly for critical thermal reactors
  - No predictive models for fast sub-critical reactors
  - Codes need for validation/performance evaluation

- **Monitoring of $k_{\text{eff}}$ or reactivity, $\rho$ (safety issue)**
  - To guaranty a criticality margin allowing the power control of the reactor through the simple law:
    
    $$P_{\text{th}}(t) = C \frac{I(t)}{\rho(t)}$$

    Safety criterium:
    
    $$-5000 \text{ pcm} < \rho < -3000 \text{ pcm}$$

    ➔ Need for absolute reactivity online monitoring during reactor operation (with no reference to a critical state)

    ➔ Mock-up experiments
Genesis of MUSE experiment

- CEA/DEN (Cadarache) and CNRS collaboration, mid 90's
  - Study of a coupled system without any power and thermal effects
  - Separate the neutron source issue from the sub-critical core physics: use of a well known neutron source

- Experimental program “MUltiplication d’une Source Externe” aka MUSE with MASURCA reactor

- 1996: MUSE-2 experiment used a simple Cf source
- 1998: MUSE-3 experiment used a Genie 26 neutron generator by SODERN (F)
- This pulsed generator revealed several aspects detrimental to kinetics data:
  - long pulse, long falling time, bad repeatability, too much H in MASURCA

- Need for a cleaner neutron generator

A.Billebaud, ADS Experimental Workshop, Torino, 2010
Experimental setup for MUSE-4

- Neutron production via deuteron irradiation of Tritium or Deuterium targets
  \[ d + T \rightarrow n \ (14 \text{ MeV}) + \alpha \]
  \[ d + D \rightarrow n \ (2.6 \text{ MeV}) + \text{He}_3 \]

- Electrostatic deuteron accelerator GENEPI-1

- **GENEPI-1 developed by** Laboratoire de Physique Subatomique et de Cosmologie (LPSC, former ISN), Grenoble, from CNRS/IN2P3
MUSE-4 : GENEPI-1 at MASURCA

- Accelerator requirements for reactor studies
  - short pulse, sharp falling time
  - high current peak intensity, wide source frequency range
  - no hydrogen inside the reactor core
  - geometrical constraints: limited space around MASURCA

- Many safety requirements
  - fire protection, earthquake protection
  - rules for coupled operation accelerator and MASURCA: reactor doubling time against accelerator fast frequency variation
  - neutron irradiation of equipment
  - tritium targets: T detection, glove box, air flowed suits for target handling
Design of the accelerator GENEPI-1

1. High voltage platform
2. Duoplasmatron source
3. Accelerator
4. Quadrupole Q1
5. 45° magnet
6. Quadrupole Q2
7. Quadrupole Q3
8. Thimble with 6 quadrupoles
9. MASURCA assemblies
10. Target
Pictures of GENEPI-1

Special assembly with a channel for GENEPI beam guide
GENEPI - 1 at MASURCA: operation & results

• Key dates:
  • 1996-99: design, construction and commissioning at LPSC
  • 2000: installation in MASURCA
  • 2001: first neutrons, safety tests
  • 2002: first couplings in subcritical configuration on D then T
  • 2003-2004: operation for experimental program
  • 2007: end of dismantling

→ Data on-line reactivity monitoring, limitations of MUSE-4
  & recommendations for future experiments
  [C.Destouches et al, NIM A 562 (2006), 601-609]

• European Collaboration (2000-2004) within FP5 under the “MUSE” acronym

European contract MUSE FIKW-CT-2000-00063
Motivations for GUINEVERE

- Extend and complete the MUSE-experiments on sub-critical system reactivity monitoring
- Reactor mock-up with a zero-power core representative of a fast ADS to follow up investigations in support to the design of Fast Transmutation Experimental Facility (MASURCA reactor unavailable until 2013)
- Neutron source that can be operated in various modes: pulsed, continuous and interrupted
- Need for an easily available facility in Europe
Objectives of GUINEVERE

• **SCK•CEN** initiated in collaboration with CNRS and CEA, the project GUINEVERE (Generator of Uninterrupted Intense NEutron at the lead VEnus Reactor)

• Project proposed to EUROTRANS Integrated Project (FP6) partners in 2006 (accepted in December 2006)

• Dedicated to Experimental activities on the Coupling of an Accelerator, a Target and a Subcritical blanket (ECATS)
  - Qualification of sub-criticality level monitoring; Validation of the core power / beam current relationship,
  - Start-up and shut-down procedures, instrumentation validation and specific dedicated experimentation,
  - Interpretation and validation of experimental data, benchmarking and code validation activities etc.,
  - Safety and licensing issues of different component parts as well as that of the integrated system as a whole.
GUINEVERE : a collaborative work

- SCK•CEN is providing the VENUS facility, modifying it to get a Pb-based fast facility able to operate in both critical and sub-critical modes, and is taking the licensing responsibility.

- CNRS/IN2P3 is in charge of the design and construction of the GENEPI-3C accelerator and of its installation at SCK Mol.

- CEA/DEN provides fuel and lead rodlets.

- Partners of EUROTRANS-IP support the design and the licensing of the facility and the experimental program and analysis.
Accelerator requirements for GUINEVERE

- Similar requirements as GENEPI-1/2
- Additionally, new specifications

- Beam specifications
  - Pulsed intense beam
  - Continuous beam (DC)
  - DC w/ programmable interruptions

- Accelerator design
  - Vertical coupling to the reactor
  - Accommodate reactor topology for operation & core loading/unloading
Civil engineering at SCK•CEN

- Construction of an additional floor above the VENUS bunker to host the GENEPI-3C accelerator for a vertical coupling.
Construction phase (2007-2009)

Courtesy of SCK·CEN

Avril 2009
VENUS for GUINEVERE: set-up of a modular reactor design

- Modifying of the water moderated VENUS core
  ➔ fast lead core

Pb top reflector
Pb radial reflector
Core in metallic uranium and lead
6 $\text{B}_4\text{C}$ safety rods with fuel follower
(2 $\text{B}_4\text{C}$ control rods are not shown)
Pb bottom reflector

Courtesy of SCK-CEN
Modular fuel assemblies

- **CEA fuel rodlets**
  - U-metal
  - Enrichment 30 %
  - Diameter= 1.27 cm
  - Length= 20 cm

- **Fuel assembly**
  - 60 cm active length in height + 40 cm lead reflector
  - 8 cm in lateral dimension

\[\text{FA structure manufacturing completed}\]

Courtesy of SCK·CEN
GUINEVERE cores

- Critical configuration (CR):
  88 Fuel Assemblies
  6 safety rods (~14 $)
  2 control rods (~1.1 $)
  $\lambda = 0.39 \mu s$
  $\beta_{eff} = 748$ pcm
  Peripheral assemblies ~230 pcm

- Sub-Critical configurations:
  84 Fuel Assemblies
  - SC1 with $k_{eff} = 0.97$
  - SC2 with $k_{eff} = 0.95$
  - SC3 with $k_{eff} \geq 0.99$
  - SCL with $k_{eff} = 0.85 - 0.95$ (loading)
  - SCR with different reflectors
Safety and control rods

• Safety rod structure driving
  • 6 Safety Rods
  • 2 Control Rods (stand-alone units)

⇒ installed
Reactor vessel

• Reactor vessel
→ ready for core loading
Physics requirements for the accelerator - 1

- Intense pulsed mode
  similar as GENEPI-1

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>140 up to 240 keV</td>
</tr>
<tr>
<td><strong>Peak current</strong></td>
<td>40 mA</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>10 Hz to 5 kHz</td>
</tr>
<tr>
<td><strong>Mean current</strong></td>
<td>190 μA at 4.7 kHz</td>
</tr>
<tr>
<td><strong>Pulse FWHM</strong></td>
<td>~ 0.7 μs</td>
</tr>
<tr>
<td><strong>Pulse stability</strong></td>
<td>~ 1%</td>
</tr>
<tr>
<td><strong>Beam spot size</strong></td>
<td>20-25 mm in diameter</td>
</tr>
<tr>
<td><strong>Target</strong></td>
<td>Tritium (Deuterium) / Titanium</td>
</tr>
<tr>
<td><strong>Maximum neutron production</strong></td>
<td>~8×10⁹ n/s at 4 kHz for Tritium</td>
</tr>
<tr>
<td><strong>Neutron energy</strong></td>
<td>14 MeV (2.5 MeV)</td>
</tr>
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</table>
Physics requirements for the accelerator - 2

• Continuous modes
  • DC beam
  • DC beam with programmable interruptions

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<table>
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<tbody>
<tr>
<td>Mean current</td>
<td>160 μA to 1 mA</td>
</tr>
<tr>
<td>Beam trip rate</td>
<td>0.1 to 100 Hz</td>
</tr>
<tr>
<td>Beam trip duration</td>
<td>~20 μs to 10 ms</td>
</tr>
<tr>
<td>Transition (ON/OFF)</td>
<td>~1 μs</td>
</tr>
<tr>
<td>Beam spot size</td>
<td>20-40 mm (diameter)</td>
</tr>
<tr>
<td>Max neutron rate</td>
<td>~5 × 10^{10} n/s</td>
</tr>
<tr>
<td>Pulse stability</td>
<td>~1%</td>
</tr>
</tbody>
</table>

• Aim for a single source for pulsed & DC mode operation

⇒ Required important developments on the ion source
Machine design : version 2006

- Preliminary discussions with SCK•CEN : 2006
  feasibility, machine implementation

- Financing approved : Dec 2006

- French collaboration within the IN2P3 institute of CNRS
  - LPC Caen
  - IPN Orsay
  - IPHC-DRS Strasbourg
  - LPSC Grenoble
Machine design: version 2008

- Ions source at HV
- Selection (dipole)
- Focusing (electrostatic quadrupoles)
- Shielding
- Target
Ion source

- Duoplasmatron: production of Deuterons: well adapted to pulsed mode
- Developments for DC operation: ionization efficiency D+ ~ 40%
  → 60% beam lost before target

- DC mode specifications mostly reached
  ✓ 1 mA D+
  ✓ Programmable interruptions
  ✓ ON/OFF transitions ~ few μs

Drop time ~ 2-3 μs
Dipole magnet - 1

- Deflect the beam towards core & perform magnetic separation
- Magnet features: C design, 0.5 m radius, 0.2 T, 30° faces
- Translation system for dipole + short V line
- Water cooled with stringent precautions against leaks
  - Deported cooling unit
  - Coil, cooling system waterproof
  - Water & electrical connections

Dipole magnet (in position)
Dipole magnet (out position)
Dipole magnet - 2

- Ion collector connected to the chamber ($D_2^+$, $D_3^+$ out of source)
- Recoil telescope facing the target
- Shielding against neutron production (protection of upper level)

Total beam
($D^+$, $D_2^+$, $D_3^+$)

Magnet chamber

window for 180° n monitor

deuteron collector

Selected beam
($D^+$)
Vertical beam line insertion

- Target within the thimble to be inserted at core center
- Machine sections mobile for periodic target changes & core maintenance
  - Dipole magnet to grant access to the V line
  - Vertical beamline to be lifted up
- V line & shielding embedded in support structure, guided at upper & lower level
**Tritium target**

- **Target holder:** copper disk
  - Material: high purity copper OFHC
  - Diameter: 60 mm
  - Thickness: 1.5 mm
  - Back side:
    - Pin fin size: 2.4x2.4x7 mm³
    - Diameter of pin area: 40 mm

- **Thin layer of TiT (12 Ci)**
  - Titane deposit: 1100 µg/cm², diameter: 40 mm
  - Tritium loading (by impregnation): 12 Ci
  - Titanium hydride ρ=4.2 g/cm²
  - T/Ti ~ > 1.5

- Mounted on beamline termination (thimble)
Target cooling

- **Requirements**
  - Beam power to be evacuated up to 250 W (DC mode), reactor not cooled
  - Temperature to be kept minimal to limit Tritium desorption: $T < 60 \degree C$
  - No Hydrogen within core (neutron slowdown in fast core)
  - Limited room available for cooling (2x2 FA)

- **Cooling system developed based on compressed air**
  - Cooler & drier system (6 bars)
  - Diffuser at target’s back fed by 4 inlets
Neutron monitoring - 1

• Neutron production
  \[ d + T \rightarrow n \ (14 \text{ MeV}) + \alpha \]

• Monitoring of alpha particles associated to neutron production
  Performed within beam pipe and under direct solid angle
  Semiconductor Silicon detector, mounted on thimble above the reactor
  Provides absolute neutron monitoring

~ 1 m for GUINEVERE

TiT Target
• Direct monitoring of 14 MeV neutrons
  To detect neutrons: conversion into proton via (n,p) reactions in an H material
  Consisting of 3 Silicon detectors, located atop the dipole magnet
  High energy protons stop in 3rd detector
  ➔ triple coincidence for identification
  ➔ discriminated from reactor fission neutrons
GENEPI-3C commissioning @ LPSC

- Machine fully assembled and tested at LPSC before transfer to Mol

- Validate motions & guiding of mobile sections
  - Magnet horizontal translation
  - Vertical beam line lift
- Validate safety interlock system
- Validate machine operation
  - Individual equipment and remote control
- Validate beam dynamics
  - Beam transport through the machine
  - Beam size on target (emittance), dummy targets only
- Validate target cooling
  - Reactor core mock-up at expected operating temperature
Commissioning at LPSC – July, August 2009

Beam profiler: characterizations

Thimble, insertion channel mock-up:
Thermal tests

Alternative terminal setups
Beam transport

• Beam transported for
  • Intense pulsed beam: ~40 mA on target
  • DC beam: 150 µA to ~1.2 mA
with optimization: 8 reference settings

• Some beam diagnostics commissioned

• Beam profile measured on profilometer at line end

✓ reference settings ready for operation at SCK•CEN
High current DC beam: operation

- Validation of
  - Target cooling ($P \approx 250 \text{ W air-cooled}$)
  - Magnet collector cooling ($P_{\text{lost}} \approx 400 \text{ W air-cooled}$)
- Vacuum chamber pressure
  - measurements consistent with design values
- High voltage operation
  - some discharges occurred

✓ no major problem detected
Dismantle and transfer

- Dismantling & packing of whole machine: sep. 09
- Transfer to SKC·CEN, Mol (Belgium): oct. 09
  - 3 trucks
  - 16 tons of equipment
  - Estimated cost ~ 1 M€
Delivery and re-assembly at SCK•CEN

+ some breakage
Vertical beam line handling
Vertical beam line storage
Vertical beam line motion
Accelerator - upper level
Beam line insertion into the core upper level
Beam line insertion into the core
Beam line insertion into the core lower level
VENUS-F bunker and beamline
Motion picture
Official inauguration: March, 2010

The GUINEVERE facility
was inaugurated by
Minister Paul Magnette and
Minister Sabine Laruelle on
March 4, 2010
GENEPI-3C commissioning at SCK·CEN

- Safety report for accelerator operation at SCK·CEN obtained by steps: Jan-Aug 2010

- Some debug: incorrect connections, fix breakages

- Transported beam through the machine with mostly LPSC settings
  - DC mode: 1 mA on target
  - Pulsed mode: ~25 mA

- Some instability on long high current runs
  - Discharges ➔ to be investigated

- Maximum beam current in pulsed mode too low
  ➔ To be investigated
GENEPI-3C commissioning at SCK•CEN

- Target and collimator cooling validated

- Neutron production
  - First neutron production: Sep 2010
  - Preliminary measurements analysis: few $10^9$ n/s as expected!
Main key dates

- Stop of VENUS reactor: 1-4-2007
- Removal of internal parts of VENUS: 1-7-2007
- Conceptual design of core: 1-10-2007
- Transport of fuel from CEA to SCK-CEN: 1-11-2007
- Accelerator room construction: 1-9-2009, Final stage 1-4-2009
- Building and commissioning of GENEPI at LPSC: 01-6-2009
- Transfer of GENEPI from CNRS to SCK-CEN: 1-10-2009
- Installation new components in VENUS: 1-11-2009
- Royal Decree for GUINEVERE-experiment: January-2010
- Fuel assembly construction: May-2010
- Commissioning accelerator: September 2010
- Commissioning reactor (non-nuclear): September-October 2010
- Criticality: October-November 2010
- Coupling with sub-critical core: December 2010
GUINEVERE outlook

- Experimental program to follow within framework of European programs FP7 FREYA (physics) & MAX (accelerator)

- GUINEVERE will provide a unique experiment with a continuous beam coupled to a fast (sub)critical assembly allowing
  - Validation of the methodology for measuring the sub-criticality level
  - Investigation and validation of the operational procedures for an ADS
  - Validation of neutronic codes
  - Safety and licensing issues related to a fast spectrum ADS

- It provides a zero power experimental facility (critical as well) for fast lead system studies and related further developments

- In particular it can act as a zero-power facility for the further design of the MYRRHA project

⇒ GUINEVERE as a mini-MYRRHA
Multipurpose fast spectrum irradiation facility

Multipurpose Hybrid Research Reactor for High-tech Applications

Courtesy of Prof. Baeten, SCK-CEN, pbaeten@sckcen.be or myrrha@sckcen.be
## Applications of MYRRHA

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<tr>
<th>Challenge</th>
<th>Solution</th>
<th>MYRRHA contribution</th>
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<tbody>
<tr>
<td><strong>Fission</strong></td>
<td></td>
<td></td>
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<tr>
<td>High radiotoxic level waste</td>
<td>Transmutation</td>
<td>ADS demo</td>
</tr>
<tr>
<td><strong>Fission GEN IV</strong></td>
<td>Demonstrate concept</td>
<td>Build demonstrators</td>
</tr>
<tr>
<td><strong>Fusion</strong></td>
<td>Extreme operating conditions</td>
<td>Material testing &amp; development</td>
</tr>
<tr>
<td><strong>Fundamental research</strong></td>
<td>Pushing the limits of knowledge</td>
<td>Access to proton beam</td>
</tr>
<tr>
<td><strong>Renewable energies</strong></td>
<td>Efficient power electronics</td>
<td>High efficiency transistors (NTD-Si)</td>
</tr>
<tr>
<td><strong>Healthcare</strong></td>
<td>Ageing population</td>
<td>A long term source of medical radioisotopes</td>
</tr>
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Courtesy of Prof. Baeten, SCK•CEN, pbaeten@sckcen.be or myrrha@sckcen.be
MYRRHA: innovative and unique

Accelerator
(600 MeV – 4 mA proton)

Reactor
• subcritical mode (50-100 MWth)
• critical mode (~100 MWth)

Spallation source
Fast neutron source

Multipurpose flexible irradiation facility

Lead-Bismuth coolant

~ 9 m

Courtesy of Prof. Baeten, SCK·CEN, pbaeten@sckcen.be or myrrha@sckcen.be
Reactor: core layout

- $k_{\text{eff}} \approx 0.95$ (sub-critical mode)
- MOX fuel
- 30-35% enrichment Pu
- 7 IPS positions (irradiation volume)

Courtesy of Prof. Baeten, SCK·CEN, pbaeten@sckcen.be or myrrha@sckcen.be
Accelerator - layout

Courtesy of Prof. Baeten, SCK-CEN, pbaeten@sckcen.be or myrrha@sckcen.be
ISOL@MYRRHA lay-out

**MYRRHA driver**

- Ion Source
- RFQ
- DTL
- Spoke cavities 350 MHz
- Elliptical cavities: 700 MHz, 3 sections
- Magnetic kicker

**Super-conducting section**

- 2.5 mA
- 100 μA

**MYRRHA reactor**

- 1 GeV

**ISOL@MYRRHA**

- High-resolution mass separator
- RFQ cooler and buncher
- Low-resolution mass separator

**Experiments:**
- Nuclear physics
- Condensed Matter
- Atomic physics
- Fundamental Interactions
- Life science

**Ruggedized target:** SiC/C, TiC/C, ZrC/C, La, Ta, UC/C

**Sustainable I+ ion source:** Surface Ionization, ECR, RILIS

Courtesy of Prof. Baeten, SCK·CEN, pbaeten@sckcen.be or myrrha@sckcen.be
Building layout and reactor hall
Vertical section in the reactor building

Courtesy of Prof. Baeten, SCK-CEN, pbaeten@sckcen.be or myrrha@sckcen.be
Project schedule

- 2010-2014: Front End Engineering Design
- 2014-2015: Specifications, Drafting & Tendering
- 2016-2018: Construction of components & Civil engineering
- 2019: On site assembly
- 2020-2022: Commissioning
- 2023: Progressive start-up
- 2024+: Full exploitation

For more information on MYRRHA: [http://myrrha.sckcen.be](http://myrrha.sckcen.be)

Courtesy of Prof. Baeten, SCK-CEN, pbaeten@sckcen.be or myrrha@sckcen.be
Thanks for your attention