Accelerator R&D
for the
European ADS demonstrator

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On behalf of the EUROTRANS WP1.3 working group
1. The European ADS demonstrator project

2. The XT-ADS linac reference scheme
3. The reliability issue
4. Related R&D topics
5. Conclusion
1. **Overall purpose**
   - Reduce the nuclear wastes radio-toxicity, volume & heat load before underground storage
   - 2500 tons of spent fuel are produced every year by the EU reactors (25 t Pu, 3.5 t MA, 3 t LLFP)

2. **Available strategy: P&T**
   - **Partitioning**: chemical separation of Pu, MA & FP
   - **Transmutation**: use of the waste as a fuel in DEDICATED transmuter systems

3. **The ADS transmuter system**
   - A subcritical reactor ($k_{eff}<1$), in which the chain reaction is not self-sustained
   - An intense spallation source, that provides the “missing” neutrons
The EUROTRANS programme

- EURopean research programme for the TRANSmutation of high level nuclear waste in an Accelerator Driven System
- EU FP6 programme (2005-2010)
- More than 40 research agencies, universities & nuclear industries
- Expands the EU FP5 project PDS-XADS (2001-2004)
- Includes 5 distinct research Domains (see also J-M.DE CONTO TU6PFPO28)

Main GOAL of the EUROTRANS programme

- Advanced design of a 50-100 MWth eXperimental facility demonstrating the technical feasibility of Transmutation in an ADS (XT-ADS/MYRRHA, short-term realisation)
- Generic conceptual design (several 100 MWth) of a European Facility for Industrial Transmutation (EFIT, long-term realisation)
Transmutation Demonstration

1. MYRRHA/XT-ADS (ADS prototype)
   - Goals:
     - Demonstrate the concept (coupling of accelerator + spallation target + reactor),
     - Demonstrate the transmutation
     - Provide a fast-spectrum irradiation facility for material & fuel developments
   - Features:
     - 50-100 MWth power
     - $k_{eff}$ around 0.95
     - 600 MeV, 2.5 mA proton beam
     - Highly-enriched MOX fuel
     - Pb-Bi Eutectic coolant & target

2. EFIT (Industrial Transmuter)
   - Goals:
     - Maximise the transmutation efficiency
     - Easiness of operation and maintenance
     - High level of availability for a cost-effective transmutation
   - Features:
     - Several 100 MWth power
     - $k_{eff}$ around 0.97
     - 800 MeV, 20 mA proton beam
     - Minor Actinide fuel
     - Pb coolant & target (gas as back-up solution)
# Proton beam specifications

## High-power proton CW beams

### Table 1 – XT-ADS and EFIT proton beam general specifications

<table>
<thead>
<tr>
<th></th>
<th>XT-ADS</th>
<th>EFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum beam intensity</td>
<td>2.5 – 4 mA</td>
<td>20 mA</td>
</tr>
<tr>
<td>Proton energy</td>
<td>600 MeV</td>
<td>800 MeV</td>
</tr>
<tr>
<td>Beam entry</td>
<td>Vertically from above</td>
<td></td>
</tr>
<tr>
<td>Beam trip number</td>
<td>&lt; 20 per year (exceeding 1 second)</td>
<td>&lt; 3 per year (exceeding 1 second)</td>
</tr>
<tr>
<td>Beam stability</td>
<td>Energy: ± 1 %, Intensity: ± 2 %, Size: ± 10 %</td>
<td></td>
</tr>
<tr>
<td>Beam footprint on target</td>
<td>Circular 5 to 10 cm, “donut-shaped”</td>
<td>An area of up to 100 cm² must be “paintable” with any arbitrary selectable intensity profile</td>
</tr>
<tr>
<td>Beam time structure</td>
<td>CW, with 200 µs zero-current holes every $10^{-3}$ to 1 Hz, + pulsed mode capability (repetition rate around 50 Hz)</td>
<td></td>
</tr>
</tbody>
</table>

Extremely high reliability required !!!
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SUPERCONDUCTING LINAC

Highly modular and upgradeable; Excellent potential for reliability; Very good efficiency
352 MHz RFQ characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Current [mA]</td>
<td>30</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>352</td>
</tr>
<tr>
<td>Input Energy [keV]</td>
<td>50</td>
</tr>
<tr>
<td>Output Energy [MeV]</td>
<td>3.0</td>
</tr>
<tr>
<td>Inter-Electrode Voltage [kV]</td>
<td>65</td>
</tr>
<tr>
<td>Kilpatrick Factor</td>
<td>1.69</td>
</tr>
<tr>
<td>$\varepsilon_{in}^{trans., , n., , rms , [\pi , \text{mm-mrad}]}$</td>
<td>0.20</td>
</tr>
<tr>
<td>Output Synchronous Phase [$^\circ$]</td>
<td>-28.8</td>
</tr>
<tr>
<td>Minimum Aperture [cm]</td>
<td>0.23</td>
</tr>
<tr>
<td>Maximum Modulation</td>
<td>1.79</td>
</tr>
<tr>
<td>$\varepsilon_{out}^{x, , n., , rms , [\pi , \text{mm-mrad}]}$</td>
<td>0.21</td>
</tr>
<tr>
<td>$\varepsilon_{out}^{y, , n., , rms , [\pi , \text{mm-mrad}]}$</td>
<td>0.20</td>
</tr>
<tr>
<td>$\varepsilon_{out}^{z, , rms , [\text{MeV-deg}]}$</td>
<td>0.09</td>
</tr>
<tr>
<td>Electrode Length [cm]</td>
<td>431.8</td>
</tr>
<tr>
<td>Beam Transmission [%]</td>
<td>99.9</td>
</tr>
</tbody>
</table>

352 MHz DTL characteristics

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Gaps ($\varphi, [^\circ]$)</th>
<th>Length [cm]</th>
<th>$W_{out}$ [MeV]</th>
<th>$Eacc^*$ [MV/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebuncher I</td>
<td>2 (-90°)</td>
<td>~7</td>
<td>3.0</td>
<td>2.79</td>
</tr>
<tr>
<td>RT-CH</td>
<td>11 (0°)  8 (40°) 8 (0°)</td>
<td>~160</td>
<td>5.2</td>
<td>2.72</td>
</tr>
<tr>
<td>Rebuncher II</td>
<td>2 (-90°)</td>
<td>~7</td>
<td>5.2</td>
<td>5.11</td>
</tr>
<tr>
<td>SC-CH I</td>
<td>3 10 (0°) 4 10 (40°) 8 (0°)</td>
<td>~90</td>
<td>7.5</td>
<td>3.99</td>
</tr>
<tr>
<td>SC-CH II</td>
<td>4 10 (0°) 12 (40°)</td>
<td>~105</td>
<td>10.4</td>
<td>3.97</td>
</tr>
<tr>
<td>SC-CH III</td>
<td>4 12 (0°) 12 (40°)</td>
<td>~130</td>
<td>14.3</td>
<td>3.98</td>
</tr>
<tr>
<td>SC-CH IV</td>
<td>4 12 (40°)</td>
<td>~145</td>
<td>18.3</td>
<td>3.96</td>
</tr>
</tbody>
</table>

* $Eacc$: active acceleration gradient.

- Classical 4-vane RFQ with moderated Kp
- DTL booster using CH structures (KONUS beam dyn.)
- 17 MeV gained in less than 15 metres
**Superconducting Linac**

### System Specifications

<table>
<thead>
<tr>
<th>Section number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Energy [MeV]</td>
<td>17</td>
<td>90</td>
<td>190</td>
<td>450</td>
</tr>
<tr>
<td>Output Energy [MeV]</td>
<td>90</td>
<td>190</td>
<td>450</td>
<td>610</td>
</tr>
<tr>
<td>Cavity Technology</td>
<td>Spoke 352 MHz</td>
<td>Elliptical 704 MHz</td>
<td></td>
<td></td>
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<tr>
<td>Structure β</td>
<td>0.35</td>
<td>0.47</td>
<td>0.65</td>
<td>0.85</td>
</tr>
<tr>
<td>Number of cavity cells</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>60</td>
<td>30</td>
<td>42</td>
<td>16</td>
</tr>
<tr>
<td>Focusing type</td>
<td>NC quadruple doublet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavities/Lattice</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Synch Phase [deg]</td>
<td>-40 to -18</td>
<td>-36 to -15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lattice length [m]</td>
<td>2.5</td>
<td>4.1</td>
<td>5.7</td>
<td>8.4</td>
</tr>
<tr>
<td>Section Length [m]</td>
<td>50</td>
<td>61</td>
<td>80</td>
<td>34</td>
</tr>
<tr>
<td>&lt;gradient&gt; [MeV/m]</td>
<td>1.4</td>
<td>1.6</td>
<td>3.4</td>
<td>4.7</td>
</tr>
</tbody>
</table>

- Modular, independently-phased accelerating structures
- Moderate gradients (50mT $B_{pk}$, 25MV/m $E_{pk}$) & energy gain per cavity
- Overall length: about 225 metres
- Final beam line guarantees the position of the beam spot and ensures that only particles of nominal energy are delivered (doubly-achromatic lines)

- Also guarantees the required “donut-shape” distribution at the target (redundant beam scanning)

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Beam dynamics

Less than 10% emittance growth in the whole 17 MeV front-end
(RFQ simulations with PARMTEQM, DTL simulations with LORASR)

Less than 5% emittance growth in the 17-600 MeV SC linac section
(simulations with TRACEWIN)
Goal = reach a frozen advanced design by 2010...

Optional (at least 2 ion sources)
... with assessed start-to-end beam dynamics

**TraceWin (CEA)**
- Envelope code with 1st order space charge
- Interacting with GenLinWin for the SC linac longitudinal optimization

*Benchmarked with: Transport (CERN), Beta (CEA), Path (CERN)*…

**Partran (CEA)**
- Multiparticle code, with 3D space charge routines.
- Coupling with TOUTATIS (CEA) for RFQ multiparticle simulations

*Benchmarked with: Lions (GANIL), Impact (LANL), Dynamion (GSI), Parmila (LANL), Alodyn (INFN), Path (CERN)*…

**Code package crucial capabilities**
- "Close to real" beam tuning procedures using simulated diagnostics
- Use of 3D field maps for most of the elements (focusing magnets, RF cavities), high-order aberrations taken into account for the others (dipoles)
- Possibility to perform statistical error studies
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The reliability requirement

- **Beam trips longer than 1 sec are forbidden** to avoid thermal stresses & fatigue on the ADS target, fuel & assembly & to provide good availability.
  SPECIFICATION : less than 5 per 3-month operation cycle (MYRRHA / XT-ADS)

- **Reliability guidelines have been followed during the ADS accelerator design**
  
  1. Strong component design ("**overdesign**")
     - All components are derated with respect to technological limitations
     - For every linac main component, a prototype is being designed, built and tested
  
  2. Inclusion of **redundancies** in critical areas
     - Possible doubled front-end (hot stand-by injector), solid-state RF power amplifiers where possible…
  
  3. Enhance the capability of **fault-tolerant** operation
     - “Fault-tolerance” = ability to pursue operation despite some major faults in the system
     - Expected in the independently-phased superconducting linac (for both RF faults and QP doublets faults)
**Local compensation method**

**CONTEXT:** We have a strongly non-relativistic beam, and any energy loss will imply a phase slip along the linac, increasing with the distance, that will push the beam out of the stability region -> BEAM LOSS

**GOAL:** Recover most of the SCRF cavities fault conditions without stopping/loosing the beam more than 1sec

**STRATEGY:**
- “Local compensation method” in the case of a RF unit or cavity failure: adjacent cavities are retuned to provide the missing energy gain to the beam
- Requires independently-powered RF cavities, good velocity acceptance, moderate energy gain per cavity & tolerant beam dynamics design
- FAST retuning to be performed using pre-tabulated set-points databases stored into the digital LLRF FPGAs
In every case, with an appropriate retuning, the beam can be transported up to the high-energy end without any beam loss (100% transmission, small emittance growth), and within the nominal target parameters.

- from 4 to 8 surrounding cavities are used
- 20 to 30% margin on RF powers and accelerating fields is required
- OK for all energies from 5 to 600 MeV, but significantly more difficult below 15 MeV

Elliptical cavity is lost at 90 MeV

Situation after retuning
Tolerance to focusing faults

Same philosophy can be applied to quadrupole failures

- The situation is less critical: if a quadrupole fails, beam losses occur, BUT if the whole doublet fails, no loss: it is thus recommended to have 1 power supply per doublet

- After a QP doublet failure, a (slow) additional retuning of neighboring doublets is recommended to decrease mismatching
Fast fault-recovery scenario

OK... but retuning should be performed in less than 1 second in the case of a failure event

Simulation code development

- Based on TraceWin (CEA)
- For all the linac cavities, a RF cavity model with control loop is included
- Very powerful tool, able to analyze the effect of time-dependent perturbations while simulating the whole beam behavior (long. + transv. planes)

Definition of a reference “fast fault-recovery scenario”

- detect (or anticipate) the RF fault (via dedicated diagnostics & interlocks) & trigger beam shut-down
- update the new LLRF field and phase set-points of the correcting cavities (data have been determined & stored in FPGAs during commissioning)
- detune the failed cavity (w/ piezo-actuators) and cut off the failed RF loop
- trigger beam re-injection once steady state is reached

Figure 12: Transverse beam distribution at 220 μs, in red are plotted the losses
GOAL of the ANALYSIS

- Estimate the number of malfunctions of the XT-ADS accelerator that cause a beam/plant shutdown, per period of operation (3 months = 2190 hours)

- Analyse the influence of MTBFs (Mean Time Between Failures), MTTRs (Mean Time to Repair), and of the degree of redundancy & fault-tolerance on the results

- Goal MTBF: better than 500 hours

WORK PERFORMED SO FAR (to be continued)

- Reliability Block Diagram analysis using the Relex© software
  - performed by INFN & ENEA (PDS-XADS, 2004)

- Home-made Monte-Carlo simulations using Matlab
  - performed by Empresarios Agrupados (EUROTRANS, 2008)
**CLASSICAL LINAC DESIGN**
- “all-series” (simplified) components
- every component failure leads to a global system failure
- poor MTBF, mostly due to the ~150 RF units

**RELIABILITY-ORIENTED DESIGN**
- same components MTBFs
- duplicated injector with fast switching magnet
- fault-tolerance in the SC linac

If a RF accel. unit (or QP doublet) fails, a certain number of RF units are immediately retuned around the failed cavity (these sources can not be used to compensate another failure); the failed RF unit is then fixed after 1 MTTR
★ What we learned from our RELIABILITY ANALYSIS

✦ # expected beam shutdowns from simulations
  - Classical linac: ~100 per 3 months mission time
  - Including fault-tolerance in the SCRF linac: ~15 per 3 months mission time
  - Also including injector redundancy: ~ 5 per 3 months mission time

✦ “analysis of the analysis”
  - The obtained *absolute* figures remain highly questionable
    (very few reliable MTBF data, high complexity of the system not fully modeled)
  - Fault-tolerance & redundancy can really improve the situation, by about one order of magnitude (but of course, @ a certain cost)
What we learn looking @ other high power facilities

- Very poor reliability is generally observed
  - Tens of beam trips / day
  - Machines are not really designed for this issue, SNS is still young (room for improvement)
  - Critical areas are usually: RF & High Voltage, ion sources & injectors, support systems (water cooling, mains), C&C and interlocks
  - High-current pulsed machines are considered as less reliable than CW ones

- Nevertheless, some facilities reach very interesting performance
  - Very promising recent improvements at J-PARC
  - Light sources facilities are more focused on reliability: ESRF (Grenoble, France) obtains routinely a MTBF of several days, and is still in progress

Figure 1: Evolution of the Mean Time Between Failures.

Figure 6. Trip frequency vs. trip duration for high power proton accelerators.

★ It seems at least not completely unrealistic to approach (and ultimately reach) the ADS accelerator reliability goal. It will imply:

- to include design de-rating, redundancy & fault-tolerance in the system
- to have a few years of commissioning and training to identify and fix the weak elements

★ Approaching the goal “from the other side” would also help!

- relaxed specifications on beam trips number
- relaxed specifications on beam trips duration
- appropriate design modifications in the target/reactor system
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**Injector long reliability test run**

**IPHI status**
- SILHI ECR p source (95kV, 100mA) operational with very promising reliability
- RFQ last sections still under fabrication
- RFQ environment 95% completed

**EUROTRANS related activities**
- Once IPHI commissioned, the 3 MeV beam will be continuously operated for a 2 months period @30mA
- Sharp 200μs “beam holes” have been produced successfully pulsing the source
SC CH cavities development

- 19-gap superconducting CH-DTL prototype built & successfully tested @4K (up to 7MV/m)
  M.Busch FR5REP061

- New tests in horizontal cryostat with slow & fast tuners will come shortly

- Design of a new optimized prototype cavity suited to the XT-ADS needs (β profile, RF power needs). Construction has begun & beam tests are foreseen.
- Single spoke prototypes ($\beta$ 0.15, $\beta$ 0.35) built & successfully tested; $\beta$ 0.35 reached 12.5 MV/m ($\beta\lambda$ definition)

- CW power couplers fabricated and conditioned successfully, using a 10kW solid-state amplifier E.Rampnoux WE5PFP029

- $\beta$ 0.15 cavity successfully tested in horizontal cryostat with Cold Tuning System (incl. piezo-actuators) & digital LLRF loop

- Fast detuning procedures checked (< 5ms without significant instabilities during the transient)

- NEXT STEP, coming soon = global test @ full power (10kW)
- 5-cell $\beta$ 0.5 elliptical prototype built & successfully tested
- 150 kW CW power couplers under construction, a 80 kW IOT tube (TED) is available, to be commissioned
- Prototypical cryomodule designed, presently being built
- **GOAL1** = qualify the reliability performance of a high-energy cryomodule at full power & nominal temperature
- **GOAL2** = in the long run, provide a test bench for fast fault-recovery scenarios
Digital LLRF activities

XT-ADS DLLRF reference scheme (suited to fault-tolerance procedures)
- a FPGA chip, able to process the feedback control algorithms,
- several ADCs and DACs, to convert the received and produced signals,
- a RAM memory, used to store set-points or save operating parameters,
- a serial bus, to communicate with the general control/command system,
- a fast serial bus, to communicate with adjacent boards.

1st IPNO prototype showed very good regulation stability with spoke cavities: <1% (V) & <0.5° (ϕ) @2σ

2nd IPNO prototype is presently under validation tests

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A reliability-oriented superconducting linac has been identified as the reference solution for the European ADS Transmutation Demonstration.

An advanced design of the machine is in-work, to be frozen by 2010.

R&D activities will be pursued after the EUROTRANS contract (ends April 2010), especially on the very challenging reliability issue.

★ Beyond this, the MYRRHA machine?! ★

- Conceptual Design Team being settled @Mol, Belgium (2009-2012, supported by EU FP7)

- Goal n°1: demonstrate the transmutation

- Goal n°2: build a flexible irradiation facility as suitable replacement for the existing reactor BR2

- Timescale: fully operational in 2020

THANK YOU for your attention!