A REFERENCE CONCEPT FOR ADS ACCELERATORS*

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France

*Work accomplished within the  
European Commission Contract N° FIKW-CT-2001-00179, "PDS-XADS"
Cumulated $CO_2$ emissions from different means of electricity production

<table>
<thead>
<tr>
<th>Production Mode</th>
<th>grams $CO_2$ /kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro-electricity</td>
<td>4</td>
</tr>
<tr>
<td>Nuclear</td>
<td>6</td>
</tr>
<tr>
<td>Wind</td>
<td>3-22</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>60-150</td>
</tr>
<tr>
<td>Combined-cycle gas turbine</td>
<td>427</td>
</tr>
<tr>
<td>Natural gas direct-cycle</td>
<td>883</td>
</tr>
<tr>
<td>Fuel</td>
<td>891</td>
</tr>
<tr>
<td>Coal</td>
<td>978</td>
</tr>
</tbody>
</table>

Range reflects the assumption on how the large amount of energy for making the systems are generated!

Source: SFEN, ACV-DRD Study
Change in CO₂ emission from all fossil sources between 1973 and 2000 vs. Share of nuclear power in electricity production

Data: Change from ORNL, Marland et al. Nuclear Share from EIA, DOE
Nuclear energy makes 880 TWh/y (35% of EU's electricity), but LWR produce important amounts of high level waste

Nuclear Waste from present LWR’s (Light Water Reactors)
- is highly radiotoxic \((10^8 \text{ Sv/ton})\)
- at the end of present-type nuclear deployment about 0.3 Mt tons, or \(3 \times 10^{13} \text{ Sv}\), compare to radiation workers limiting dose of 20mSv
- the initial radiotoxicity level of the mine is reached after more than 1 Mio years
- worldwide, at present 370 "1GW\textsubscript{el} equiv. LWR" produce 16% of the net electricity

• Geologic time storage of spent fuel is heavily debated
  - leakage in the biosphère?
  - expensive (1000 €/kg), sites? (Yucca mountain would hold 0.07 Mio tons!!)
  - public opposition

• Long term Energy Concerns
  - availability of oil, gas, coal (and uranium!)
  - global warming induced by fossil fuels
The Yucca Mountain Dilemma

- In the United States, the current plan is to send all spent nuclear fuel to the Yucca Mountain Repository. The challenge they are faced with is that new repositories will be needed as nuclear energy continues or grows.
Neutron consumption per fission ("D-factor") for thermal (red) and fast (blue) neutron spectra

- D ≥ 0 implies a source of neutrons is required,
- whereas D < 0 implies excess neutron self-production

Where should we buy the needed fast neutrons?
ADS: Accelerator Driven (subcritical) System for transmutation

Both critical reactors and sub-critical Accelerator Driven Systems (ADS) are potential candidates as dedicated transmutation systems.

Critical reactors, however, loaded with fuel containing large amounts of MA pose safety problems caused by unfavourable reactivity coefficients and small delayed neutron fraction.

ADS operates flexible and safe at high transmutation rate (sub-criticality not virtue but necessity!)
Burning and breeding efficiency of different reactor types

- The ADS is most efficient at Minor Actinide Transmutation

Pu Production Rate (grams / GWh)  MA Production Rate (grams / GWh)

Figures: M. Capiello & G. Imel (ANL) (ICRS-10/RPS2004)
FP5 PDS-XADS*: Working Packages


A collaboration between Industrial Partners and Research Organisations

**F**: Framatome-F CNRS CEA
**I**: Ansaldo INFN ENEA CRS4
**RFA**: Framatome-D FZK FZJ UFra
**Esp**: CIEMAT Empresarios UPM
**B**: SCK IBA Tractebel
**UK**: NNC BNFL
**Pt**: ITN
**S**: KTH
**Sui**: PSI
**PL**: UMM
**NL**: NRJ
**Eur**: JRC

coordinateur général : Framatome (B.Carlucc, B.Giraud)
coordinateur accélérateurs: CNRS-IN2P3 (A.C. Mueller)

IAEA Symposium on Utilization of Accelerators, Dubrovnik, Croatia, June 5-9 2005
The PDS-XADS Accelerator Group (WP3)

- **WP3 partners**
  - Coordinator: CNRS-IN2P3 (F)
  - Participants: Ansaldo (I), CEA (F), ENEA (I), FANP (F), F GmbH (D), IBA (B), INFN (I), ITN (P), U. Frankfurt (D)

- **Main WP3 objectives**
  - Investigation of linac and cyclotron types with the main emphasis on the XADS requirements
  - Examination of the XADS accelerator characteristics: reliability, availability, stability, power control & maintainability
  - Definition of the R&D needs
  - Choice of the reference accelerator type for XADS and for a long-term extrapolated industrial transmuter
  - Definition of the road mapping of the ADS-class accelerators

- **6 Deliverables written**
  - D9 - D47 - D48 - D57 - D63 - D80
XADS Accelerator Requirements

• Proton Beam Specifications
  - Defined by WP1
  - 600 MeV, 6 mA max. for operation
  - 10 mA for the demonstration of concept
  - 350 MeV for the smaller scale XADS MYRRHA
  - High reliability requirement: less than 5 beam trips >1 sec per year

• Additional requirements
  - 200 μs beam «holes» for on-line sub-criticality measurements
  - Safety grade shutdown

<table>
<thead>
<tr>
<th>Accelerator requirements</th>
<th>Max. Beam Intensity</th>
<th>6 mA</th>
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<tbody>
<tr>
<td>Proton Energy</td>
<td>600 MeV</td>
<td></td>
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<tr>
<td>Beam entry</td>
<td>To be defined</td>
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<tr>
<td>Beam trip number</td>
<td>Less than 5 per year for the accelerator design</td>
<td></td>
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<tr>
<td></td>
<td>Less than 50 per year for the reactor design</td>
<td></td>
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<tr>
<td>Beam type</td>
<td>CW, best solution</td>
<td></td>
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<tr>
<td></td>
<td>Pulsed, back-up solution</td>
<td></td>
</tr>
<tr>
<td>Beam power stability</td>
<td>± 2 %</td>
<td></td>
</tr>
<tr>
<td>Beam energy stability</td>
<td>± 1 %</td>
<td></td>
</tr>
<tr>
<td>Beam intensity stability</td>
<td>± 2 %</td>
<td></td>
</tr>
<tr>
<td>Beam footprint dimensions</td>
<td>± 10 %</td>
<td></td>
</tr>
</tbody>
</table>
Choice of the Generic Accelerator Type

- **Main technical answers**
  - **Superconducting linac**
    - No limitation in energy & in intensity
    - Highly modular and upgradeable (industrial transmuter)
    - Excellent potential for reliability (fault-tolerance)
    - High efficiency (optimized operation cost)
  - **Cyclotron**
    - Attractive (construction) cost
    - Required parameters at limits of feasibility ("dream machine")
    - Compact, but therefore not modular

- **In complete agreement with findings of the NEA report:**
  - **Cyclotrons of the PSI type** should be considered as the natural and cost-effective choice for preliminary low power experiments, where availability and reliability requirements are less stringent.
  - **CW linear accelerators** must be chosen for demonstrators and full scale plants, because of their potentiality, once properly designed, in term of availability, reliability and power upgradation capability.
PDS-XADS Reference Accelerator Layout

(n.b. note similarity to EURISOL-driver)

Low energy section

Intermediate energy section

High energy section

Spallation target & sub-critical core

Beam dump

Strong R&D & construction programs for LINACs
underway worldwide for many applications

(Spallation Sources for Neutron Science, Radioactive Ions & Neutrino Beam Facilities, Irradiation Facilities)

Alex C. MUELLER

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Dubrovnik, Croatia, June 5-9 2005
Reference Accelerator: Low Energy Section

- R&D on the injector part by the WP3 partners
  - « IPHI » ECR Source & Normal Conducting RFQ (CEA-CNRS)
  - « TRASCO » ECR Source & Normal Conducting RFQ (INFN)
  - Normal Conducting IH- DTL Structure (IBA)
  - Superconducting CH-DTL Structure (U. Frankfurt)
Reference Accelerator: High Energy Section

- **R&D on SC prototypical cavities by the WP3 partners**

  - **Spoke cavities** $\beta = 0.15$ & $\beta = 0.35$ (CNRS)

  ![Spoke cavities image]

  - **Elliptical cavities** $\beta = 0.5$ & $\beta = 0.65$ (CEA-CNRS-INFN)

  ![Elliptical cavities image]

  ![Graph showing Eacc max=16.2 MV/m]

  ![Graph showing XADS Goal]
Reference Accelerator: Beam Line Transport

- The doubly achromatic beam line concept + beam scanning method meets the specifications:
  - of the Gas-cooled XADS (circular footprint, Ø160)
  - of the LBE-cooled XADS (rectangular footprint, 10×80)
  - of MYRRHA (quasi-circular footprint, Ø72)
Reliability Analysis

- **Assessments using the «Failure Modes and Effects Analysis» (FMEA) method**

  - System design
    - Design Review
  - Technical design
  - Reliability Block Diagram (RBD)
  - ITERATIVE PROCESS
  - Failure Modes and Effects Analysis (FMEA / FMECA)
  - Fault Tree Analysis (FTA)
  - Reliability studies:
    - MTBF, MTTR, A, R, etc.
  - Data sources (MTBF, MTTR)
  - Benchmarks based on other experiences

- **Reliability engineering is a discipline for estimating, predicting and controlling the probability of occurrence of system faults**

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Main Conclusions on Reliability

- The **cyclootron option** for PDS-XADS does not seem to offer a sufficient perspective of reaching the requested reliability level.

- **No showstopper** to reach high availability & high reliability with the XADS reference linac if **over-design & redundancy** are used.

- **Fault tolerance** has been identified as key element in order to guarantee reliability by design and operation:
  - Identification of the main component faults & estimate of their effect on the beam (not always straightforward).
  - Identification of strategies (and proper hardware systems) to deal with faults.
  - Plans for the accelerator commissioning and maintenance.
  - Reliability/availability allocation need to be examined with the constraints of legislation (safety aspects) & radioprotection.
Fault scenarios and recovery  

see talk Lucija Lukovac

Fault tolerance in the independently phased SC sections is a crucial point because a few tens of RF systems failures are foreseen per year.

1. Consequences of the failure of a superconducting RF cavity
   → A RF system failure induces phase slip (non relativistic beam)
   → If nothing is done, the beam is always LOST

2. Linac retuning after the failure of a RF cavity or of a quadrupole
   → Local compensation philosophy is used
   → In every case, the beam can be transported up to the high energy end without beam loss

Cavity #n is faulty

Cavities #n-2, #n-1, #n+1, #n+2 are retuned to recover the nominal beam energy & phase at point M
The feedback systems has to provide the necessary energy stability, dealing with faults in order to reach the project goals (less than 5 beam trips per year)

Fast digital RF system can implement fault tolerance with respect to cavity fault by dealing fault set tables

Beam diagnostics is also an area of prime importance

The maintenance strategy has to guarantee the reliability of the machine for more than 20 years

It should guarantee the long-term validity of the linac prime criteria:

- Over-Design / Redundancy / Fault Tolerance

Need for an expert system:

- Detecting faulty or out-of-order equipment
- Planning of subsequent maintenance & management of the intervention time according to radioprotection
Reliability & Maintenance

- The maintenance strategy is presently under investigation, assuming 3 months of operation / 1 month of maintenance

<table>
<thead>
<tr>
<th>Main Items</th>
<th>Function</th>
<th>Failure Mode</th>
<th>Prevalence rank</th>
<th>Preventive action</th>
<th>Curative action</th>
<th>Rem.</th>
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<tr>
<td>Boron nitride discs</td>
<td>Wear</td>
<td>1</td>
<td>Replace</td>
<td>6 months</td>
<td>Replace</td>
<td>24 H</td>
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<tr>
<td>Vacuum pumps</td>
<td>Wear</td>
<td>1</td>
<td>Regenerate</td>
<td>24 months</td>
<td></td>
<td></td>
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<td>Power supply filters</td>
<td>Get dirty</td>
<td>0</td>
<td>Clean</td>
<td>3 months</td>
<td>Replace</td>
<td>8H</td>
</tr>
<tr>
<td>Power supply</td>
<td>Aging</td>
<td>0</td>
<td>Overhaul</td>
<td>24 months few weeks</td>
<td>Replace</td>
<td></td>
</tr>
<tr>
<td>Cooling (water): filters, pumps</td>
<td>Wear/dirty</td>
<td>0</td>
<td>Clean</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Plasma electrode</td>
<td>Aging</td>
<td>1</td>
<td>Replace</td>
<td>12 months</td>
<td>Replace</td>
<td>24H</td>
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<tr>
<td>Magnetron</td>
<td>Out of order</td>
<td>2</td>
<td>Replace</td>
<td>24 months</td>
<td>Replace</td>
<td>2H Replace&quot;before MTBF&quot;</td>
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<tr>
<td>HV power supply</td>
<td>Out of order</td>
<td>2</td>
<td>Oil changing</td>
<td>24 months</td>
<td>Replace</td>
<td>8H</td>
</tr>
<tr>
<td>Extraction electrodes</td>
<td>Aging</td>
<td>1</td>
<td>Replace</td>
<td>24 months</td>
<td>Replace</td>
<td>48H</td>
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<td>Security devices</td>
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<tr>
<td>Water flow controller</td>
<td>get dirty</td>
<td></td>
<td>cleaning</td>
<td>12 months</td>
<td>Replace</td>
<td>2H</td>
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<tr>
<td>Temperature controller</td>
<td>Out of order</td>
<td></td>
<td>Systematic tests</td>
<td>12 months</td>
<td>Replace</td>
<td>8H could be doubled</td>
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<tr>
<td>Emergency stop</td>
<td>Out of order</td>
<td></td>
<td>Systematic tests</td>
<td>12 months</td>
<td>Replace</td>
<td>1H</td>
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<tr>
<td>DGP T</td>
<td>Out of order</td>
<td></td>
<td>Systematic tests</td>
<td>12 months</td>
<td>Replace</td>
<td>8H</td>
</tr>
</tbody>
</table>
XADS: Safety Aspects & Radioprotection*

- **Legal framework**
  - Recommendations: ICRP publication 60
  - European Directive 96/29/Euratom
  - European Union: analysis of national legislations
    - Belgium
    - France
    - Germany
  - Very similar requirements from national legislations for an XADS facility, in particular:
    - Public enquiry
    - Decommissioning plan
  - Belgium: more restrictive definition of «radiation worker»

- **Accelerator shielding philosophy based on the ALARA principle**
  - *As Low As Reasonably Achievable*

*study performed within "Deliverable D48" by Paul Berkvens and S.Palanque relying on Moyer's model*
**XADS-Accelerator Shielding Design**

- **Conservative beam losses assumptions**
  - Normal beam losses
    - RFQ: 3%
    - Intermediate energy: 10 nA/m
    - High energy: 1 nA/m
  - Unwanted beam trips
    - $P > 1 \times 10^{-2}$ year$^{-1} \rightarrow$ included in the normal beam losses
    - $P < 1 \times 10^{-2}$ year$^{-1} \rightarrow$ “accidental beam losses” case

- **ALARA shielding design criteria**
  - $< 1$ mSv/year
  - I.e. $< 0.5$ µSv/h (2000 h/year)
  - Occupancy factor = 1

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600 MeV XADS: Shielding for Normal Operation and for Commissioning

Figure 6.1 – Minimum earth profile above a 60 cm concrete tunnel (blue curve) corresponding to a beam loss rate of 1 nA m\(^{-1}\) at 600 MeV for a residual dose rate of 0.5 mSv h\(^{-1}\). Red curve: corresponding realistic earth profile. Dose rates are calculated for a beam loss rate of 100 nA m\(^{-1}\) at 600 MeV.
Iron shielding for a 600 MeV beam dump as a function of the beam power, required to reduce the dose rate outside a 60 cm concrete building, covered with 550 cm of earth, below 0.5 μSv h⁻¹.

Radioactivity produced per meter along the high-energy part of the accelerator for a 1 nA m⁻¹ beam loss, as a function of the decay time, for 4 different values of the irradiation time.

Dose rates at 50 cm from the beam axis, along the high-energy part of the accelerator for a 1 nA m⁻¹ beam loss, as a function of the decay time, for 4 different values of the irradiation time.
Safety Aspects: Application to MYRRHA @ Mol

- **Tunnel design for a 350 MeV XADS linac**
  - Shielding calculations @ 350 MeV, 1 nA/m, 0.5 μSv/h
  - Chicane access design
  - Shielding for normal losses also copes with « accidental losses »

- **The 350 MeV MYRRHA machine**
  - Location on the SCK•CEN site, Mol, Belgium

Calculations by P. Berkvens & S. Palanque

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Long-term operation of the injector

Construction & test of intermediate energy cavities

Full demonstration of the high energy section cryomodule

Fault tolerance: numerical simulation code & digital RF control system design
A possible Scenario using ADS to support Generation-III (and even Gen-IV!) reactors

Figure:  
M. Capiello & G. Imel (ANL)  
(ICRS-10/RPS2004)
From FP5 PDS-XADS to FP6 EUROTRANS

**FP5**
- XADS (Pb-Bi)
  - 80 MW(th)
  - 110 W/cm
  - single batch loading

**FP6**
- Design Concepts
  - XADS (Gas)
    - 80 MW(th)
    - 250 W/cm
    - single batch loading
  - MYRRHA (Pb-Bi)
    - 50 MW(th)
    - 500 W/cm
    - multi batch loading

**European Transmutation Demonstration (ETD)**
- advanced design
- conceptual design, economics, scalability

**Objectives**
- **XADS**
  - Demonstration of technological feasibility of an ADS system

- **XT-ADS**
  - Short-term demonstration of transmutation on a sizable scale and of the ADS behaviour
  - < 100 MW(th)
  - 250 - 300 W/cm
  - multi batch loading

- **EFIT**
  - Long-term transmutation on an industrial scale
  - Several 100 MW(th)
  - 250 - 300 W/cm
  - multi batch loading
EURopean Research Programme for the TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System

FZK
AAA
ANSALDO
Nexia Solutions
CEA
CIEMAT
CNRS
CRS4
CSIC
EA
ENEA
ENEN
FANP SAS
FZJ
FZR

GSI
IBA
INFN
INRNE
ITN
JRC
NRG
NRI
OTL
PSI
SCK-CEN
Suez-Tractebel
FANP GmbH
NNC
The accelerator within EUROTRANS-DM1

WP1.3: ACCELERATOR

GOAL:
HPPA development, and in particular, qualification of the reliability of the prototypical components

CO-ORDINATING CONTRACTOR:
CNRS (F) – Alex C. Mueller

<table>
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<tr>
<th>DM1 DESIGN WP1.3 - Accelerator</th>
<th>TOTAL WP1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cons. k€</td>
</tr>
<tr>
<td>P5-CEA (F)</td>
<td>170</td>
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<tr>
<td>P8-CNRS (F)</td>
<td>180</td>
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<td>P13.4-IAP-FU (D)</td>
<td>75</td>
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<td>P13.12-UPM (SP)</td>
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<td>P31-FANP GmbH (D)</td>
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<td>Total WP1.3</td>
<td>1103</td>
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</tbody>
</table>

1 PM = 10k€

RED: Loading Organization in this Work Package
GOAL:
The injector IPHI, developed by CEA and CNRS, will be used for a long run test to demonstrate on a real scale the reliability of the injector part.

CO-ORDINATING CONTRACTOR:
CEA (F) – Raphaël Gobin

MILESTONES:
M1.3.1: Specifications for the long test run (+9)
M1.3.2: Injector operational for test (+18)
M1.3.3: Experimental tests accomplished (+36)
M1.3.4: Final report: results and analysis (+39)

DELIVERABLES:
D1.3.1: Preliminary short report. Specifications of the long test runs (CEA, +9)
D1.3.2: Intermediate progress report on injector status and proposed test schedule (CEA, +18)
D1.3.3: Final report on results and analysis (CEA, +39)
Intermediate-energy Section

**TASK 1.3.2**

**GOAL:**
Evaluation of room-temperature cavities and superconducting cavities performances, reliability and cost. Determination of the energy transition from where on doubling of the injector is no longer required for reliability.

**CO-ORDINATING CONTRACTOR:**
CNRS (F) – Tomas Junquera

**MILESTONES:**
- M1.3.5: Specifications for prototypes (+6)
- M1.3.6: Prototypes ready for test (+27)
- M1.3.7: Experimental results of prototypes performances (+39)
- M1.3.8: Final report: synthesis and design proposals (+42)

**DM1 DESIGN WP1.3 - Accelerator**

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<th>Assessment of the reliability performances of the intermediate energy accelerating components</th>
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<td>P18-IBA (B)</td>
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**DELIVERABLES:**
- D1.3.4: Preliminary report. Specifications of the prototypes (IAP_FU, +6)
- D1.3.5: Intermediate report on prototype test schedules (IBA, +18)
- D1.3.6: Final report: tests results, synthesis and design proposals (CNRS, +42)
High-energy Section

GOAL:
Design, construction and test of a full prototypical cryomodule of the high energy section of the proton linac.

CO-ORDINATING CONTRACTOR:
INFN (I) – Paolo Pierini

MILESTONES:
M1.3.9: Preliminary cryomodule specifications (+9)
M1.3.10: Cryomodule design finalized (+15)
M1.3.11: Cryomodule is ready for test (+30)
M1.3.12: Exptl. results of cryomodule performances (+39)
M1.3.13: Final report: synthesis and design proposals (+42)

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<th>DM1 DESIGN WP1.3 - Accelerator</th>
<th>Task 1.3.3 Qualification of the reliability performances of a high energy cryomodule at full power and nominal temperature</th>
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<tr>
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<td>P8-CNRS (F)</td>
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<tr>
<td>P13.4-IAP-FU (D)</td>
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<td>P13.12-UPM (SP)</td>
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<td>P18-IBA (B)</td>
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DELIVERABLES:
D1.3.7: Preliminary report: specifications for the cryomodule (INFN, +9)
D1.3.8: Report on cryomodule design and schedule (CNRS, +15)
D1.3.9: Final report: test results, synthesis and design proposals (INFN, +42)
Digital RF Control

GOAL:
Modelling and VHDL analysis of a digital RF control system for fault tolerant operation of the linear accelerator. (Prototyping of an RF control unit is strongly recommended)

CO-ORDINATING CONTRACTOR:
CEA (F) – Michel Luong

MILESTONES:
M1.3.14: Preliminary RF control system specifications (+6)
M1.3.15: RF control system modelling (+24)
M1.3.16: Final report: VHDL architecture and synthesis (+42)

Task 1.3.4
Conceptual design of an RF control system for fault tolerant operation of the linear accelerator

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DELIVERABLES:
D1.3.10: Preliminary specifications of the RF control system (CEA, +6)
D1.3.11: Report on RF control system modelling (CEA, +24)
D1.3.12: Final report: VHDL architectures and synthesis (CEA, +42)
Beam Dynamics and Overall Coherence

**TASK 1.3.5**

**GOAL:**
Overall coherence of the accelerator design, including beam dynamics simulations, integrated reliability analysis, and cost estimation.

**CO-ORDINATING CONTRACTOR:**
CNRS (F) – Jean-Luc Biarrotte

**MILESTONES:**
- M1.3.17: General specifications (+6)
- M1.3.18: WP1.3 overall task review (+18)
- M1.3.19: Results of beam dynamic simulations (+30)
- M1.3.20: Reliability study experimental results (+39)
- M1.3.21: Integrated reliability analysis (+45)
- M1.3.22: Cost Analysis (+45)
- M1.3.23: Final report (+48)

**DM1 DESIGN WP1.3 - Accelerator**

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**DELIVERABLES:**
- D1.3.13: General specifications for all the tasks (CNRS, +6)
- D1.3.14: Beam dynamics simulations for fault tolerance (CNRS, +30)
- D1.3.15: Report on integrated reliability analysis of the accelerator (INFN, +48)
- D1.3.16: Final report: accelerator design, performances, costs for XT-ADS and EFIT and associated road map (CNRS, +48)

IAEA Symposium on Utilization of Accelerators, Dubrovnik, Croatia, June 5-9 2005
CONCLUSION

With the reliability-focused R&D programme within the EUROTRANS project,

the Accelerator for a EUROPEAN ADS Demonstrator XT-ADS is on the projected roadmap

Thank you all!