Overview of specifications and issues of ADS-drivers

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caveat emptor

- this short presentation is not a well-structured introduction to the session
- it neither is a review of the field, requiring much more time, and the focus is for high-power developing systems, thus the drivers for the coupling experiments, of utmost scientific importance, will not be treated here
- because of these time constraints it is incomplete and furthermore some transparencies will just be flashed on
- it however is a personally biased selection of facts, perception of some decisive events, and what main ingredients of reactor physics are determining for Accelerators for ADS
- partly destined to convey also some observations/messages
- but first I want to thank the organizers, Giulia, CERN, and EUCARD2 for the invitation
(some) Prehistory

1941:
Glenn Seaborg produces Plutonium by means of an accelerator

1950 – 1954:
Material Testing Accelerator (MTA) research program at Livermore,
Use of McGill cyclotron in Canada for spallation neutron yields

Late 80's:
A research group at BNL (H. Takahashi & G. van Tuyle) develops a
Concept for an ADS in today’s meaning (focused on Safety and/or
Waste Transmutation)

1991:
Detailed design of the ATW at Los Alamos by group of C. Bowman
Some Historical Highlights since the past 25 years

1993:
CERN group of Carlo Rubbia presents the "Energy Amplifier" (U-Th cycle driven by high intensity accelerator) and performs the supporting experiments FEAT (1994) and TARC (1997-1998) at the CERN PS accelerator.

During the decennia of the 1990's:
Launching of
- J-PARC in Japan
- SNS Project in US
- French Law on Research for Nuclear Waste Transmutation (CEA + CNRS + Academia!)
- European Collaborative Research substantially funded by EURATOM
- Decision of OECD-NEA Working Party on the fuel cycle for HPPA conferences
Since 1998
08:00 - 08:30  REGISTRATION

OPENING SESSION  Chairpersons: C. NORDBORG

08:30 - 08:45  - Welcome  A. TOURNYOL DU CLOS

08:45 - 09:00  - Meeting format, scope and objectives  M. SALVATORES

09:00 - 09:30  - Key note: “Utilisation and future development of high power accelerators”  C. DETRAZ

08:30 - 12:45  SESSION 1 (Invited papers): Recent developments and Ongoing Accelerator programs. Experience of relevance for ADS Chairpersons: A. MUELLER, Y. CHO

09:30 - 10:00  - Joint project of JAERI and KEK for high power proton accelerator  T. MUKAIYAMA

10:00 - 10:30  - Reliability Considerations in Design of High Power Linacs  G. LAWRENCE

10:30 - 11:00  Break

11:00 - 11:30  - Scientific issues and status of Franco-Italian collaboration in ADS  C. PAGANI

11:30 - 12:00  - Status of the proposal for a Superconducting Proton Linac at CERN  R. GAROBY

12:00 - 12:45  - Design and Status of the SNS project, and Availability consideration of the Spallation Neutron Source  Y. CHO

Extract from the program of HPPA-2
Aix-en-Provence 1999

Key issues:
Debate on the design of SNS NC or SC.
Strong opinion voiced by J.L. Laclare (SNS-MAC): SC!

Laclare, builder of ESRF, also showed how to implement reliability, and, note ESRF has today ADS-class reliability
At the same time:

(E)TWG report on ADS demanded by European Science Ministers, chaired by Carlo Rubbia (ENEA)

Triggering European ADS collaboration PDS-XADS, 
(leader Bernard Carluec Framatome) 2002-2006

and launch of word-wide collaboration for MEGAPIE
Spallation Target
Europe - Japan - Korea - US

Progress discussed and reported in HPPA-3, Santa-Fe (NM) with important findings for the suited accelerator technology:

Only SC-LINAC suited for full-scale ADS
and (existing) cyclotrons for preliminary experiments
Some memories from TWG (final session approving the report to the ministries)
And and also a tribute to nuclear data community for a "grande première" (first nTOF data from CERN)
Period 2005 -2010:

- Construction of SNS and J-PARC facilities
- China enters with strong accelerator programme
- European EUROTRANS research programme
- Success of the MEGAPIE experiment
- ESS is going from fiction to reality
- MYRRHA on the "ESFRI-list"
2006: Success of the Megapie experiment at PSI

Start of Normal User operation.

Normal user operation was started on August 21st around 8:30 and is planned to continue until the normal annual winter shut-down starting on December 23rd 2006.

The first 12 hours of proton beam is seen to the left.

590 MeV cyclotron
1.3 MW beam power
The EUROTRANS programme

- EURopean research programme for the TRANSmutation of high level nuclear waste in an Accelerator Driven System
- EU FP6 programme (2005-2010)
- 31 research agencies & industries, 16 universities
- Expands the EU FP5 project PDS-XADS (2001-2004)
- 5 Domains (Design, Coupling Experiments, Fuels, Materials and Nuclear Data)

Main GOAL of the EUROTRANS programme
- Advanced design of a 50-100 MWth eXperimental facility demonstrating the technical feasibility of Transmutation on an ADS (XT-ADS, short-term realisation)
- Generic conceptual design (several 100 MWth) of a European Facility for Industrial Transmutation (EFIT, long-term realisation)
Period 2010 - today:

- Operational Experience from running facilities SNS and J-PARC
- Construction of ESS SC-linac
- EURATOM funding for MYRRHA R&D and GUINEVERE at SCK Mol
- Construction of first stage of MYRRHA
- Construction in China of ADS-linacs at 2 sites
- PIE of MEGAPIE
- Ukraine program
- International Thorium Energy Committee
- Construction of Linac components is INDIA focused on Thorium ADS
Pictorial View of Nuclear Reactions

Fission of $^{235}_{92}U$ (below) liberating new neutrons that in turn fission other $^{235}_{92}U$ nuclei giving rise to a chain reaction.

Neutron capture of $^{238}_{92}U$, followed by beta-decay of $^{239}_{92}U$ and continuation of this process leading to $^{239}_{94}Pu$ (and beyond).

(Figures from the Karlsruhe Lexikon zur Kernenergie)
**Fundamental Difference between Critical Reactor and ADS**

A critical reactor is piloted by (neutron absorbing) rods, which, **inserted**, keep the criticality below $k < 1$. See below the gradual start-up (note time!). The divergent phase stabilizes at $k=1$ because of thermal expansion decreasing reactivity. The delayed neutron fraction (from radioactive) decay ensures that the prompt criticality stays below 1.

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**Energy by Strong Interaction Controlability by Weak Interaction**

An ADS is (and has to stay!) sub-critical at all times. The thermal output $P$ is determined by the driving source $S$.

$$P \sim \frac{S}{1 - k_{\text{eff}}}$$

Effective criticality $k_{\text{eff}}$, Typically $0.92 - 0.98$

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**figure from a lecture by Frédéric Mellier**

Alex C. Mueller, EUCARD2 Workshop, CERN, 7-9 February 2017
Characteristic Numbers for a Power ADS

\[ P \sim \frac{S}{1 - k_{\text{eff}}} \]

\[ k_{\text{eff}} = 0.93 - 0.97 \]

\[ P_{\text{acc el}} = 100 \text{ MW} \]
\[ \varepsilon_{\text{Acc}} = 0.3 \]
\[ P_{\text{acc beam}} = 1 \text{ GeV} \times 30 \text{mA} = 30 \text{ MW} \]

\[ \Delta P = + 300 \text{ MW}_{\text{el}} \]

\[ \varepsilon = 0.40 \]

\[ P_{\text{th}} = 1 \text{ GW}_{\text{th}} \]

Figure redrawn after an idea by G. Van den Eyde

Alex C. Mueller, EUCARD2 Workshop, CERN, 7-9 February 2017
Fast Neutrons are needed to incinerate actinide waste (or breed U233 from Thorium)

Example: Am241 fission and capture cross sections
Pictorial: the nuclear reactions underlying Spallation

La spallation : une source de neutrons

A) Cascade dans le noyau

B) Spallation secondaire

C) Noyau chaud

D) Fission

E) évaporation

taken from the site "laradioactivite.com" (IN2P3 & EDP Sciences)
Spallation physics and technology defining accelerator parameters

Abaques Courant/Energie/Sous-Criticité pour un démonstrateur de 80 MW$_{\text{therm}}$ (simulation par ANSALDO)
High Power Accelerator Projects in the World

J-L. Biarrotte, Proc. SRF 2013

Existing NC machines
Under construction NC machines
Existing SC machines
Under construction SC machines
Planned SC machines

Mean beam current (mA)

Beam energy (MeV)
Strong R&D & construction programs for LINACs underway worldwide for many applications (Spallation Sources for Neutron Science, Radioactive Ions & Neutrino Beam Facilities, Irradiation Facilities)
Reliability as required by reactor physics, technology and safety

D. Vandeplasche, Proc. IPAC 012

Alex C. Mueller, EUCARD2 Workshop, CERN, 7-9 February 2017
The 3 principles for reliability improvement

- **Overdesign**
  - basically only possible for linacs not running against or exceeding
    - the limits of energy (relativistic effects)
    - The limits of intensity (weak focusing)

- **Redundancy**
  - basically only possible for linacs
    - because of their modularity
    - at the expense of efficiency (components used once)

- **Fault tolerance**
  - basically only possible for linacs
    - requires modularity
    - a very innovative concept
Fault Tolerance, a new concept uniquely applicable in a modular SC-Linac
- first proposed in PDS-XADS study in 2002 by Biarrotte, Mueller et al.
- experimental verification by Galambos et al with SNS in 2007

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
   → An 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

[Diagram showing cavity and quadrupole configurations]
Exotic hybride concepts?

• In contrast to cyclotrons, FFAG exhibit
  ➢ strong focusing and they overcome the relativistic limitations

• In contrast to cyclotrons, FFAG
  ➢ are pulsed machines, with intrinsically (much) lower intensity

• In contrast to cyclotrons and linac's, FFAG are
  ➢ very complicated to build
  ➢ No "real machine" existing since the 60 years after invention

• In contrast to linacs, FFAG exhibit
  ➢ no potential for implementing the 3 basic principles
  of reliability improvement

• To my assessment,
  ➢ FFAG are therefore unsuited for ADS
Accelerator choice assessment: NEA was and still is right!

- **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 well above limits of feasibility ("dream machine" = 10 mA)
    - 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 upgrading capability.
Concluding Remarks

- From early conceptional considerations and studies the field has grown to maturity with large-scale experiments, dedicated R&D, and major realisations

- The choice of the accelerator type directly depends from nuclear physics and technology

- I am eager to see the progress that will be reported at the present meeting

- Good luck for all for the future of the field that truly lends to international collaboration and as European I of course look forward to MYRRHA

- Warm thanks again to Giulia, CERN and EUCARD2