Review of ADS efforts world-wide

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1) ADS projects

As an important effort on ADS is taking place worldwide, the risk exists that Europe could lose its leadership in a field it has pioneered in the 1990's, especially at CERN. Three major projects, all driven by proton linacs (linear accelerators), are presently at the forefront of the field:

- MYRRHA [1], at SCK•CEN, in Mol, Belgium, which should be the flagship of accelerator-driven systems, with a proton linear accelerator (600 MeV, 2.5 mA) driving a subcritical core cooled with a eutectic lead–bismuth mixture, designed to produce a thermal power of 50 to 100 MW;
- ADANES [2] developed by the Chinese Academy of Sciences, both at the Institute of High Energy Physics (IHEP) in Beijing and at the Institute of Modern Physics (IMP) in Lanzhou. The project includes notable innovations in target design and the goal is to reach 1000 MW of electrical power by 2032. A site for the first prototype was recently chosen by the Chinese Government in Huizhou city, in the Guangdong Province;
- HISPA [3] at the Bhabha Atomic Research Centre in India, concentrating on the development of a high-power proton linac, with as first stage, a 30 mA, 20 MeV injector, and the goal of reaching 30 MW of beam power with 1 GeV protons. This project is carried out in cooperation with the USA.

For what concerns the United States, Argonne National Laboratory (ANL) has designed and constructed a thermal neutron ADS facility using a 100 kW, 100 MeV electron accelerator [4] for the Kharkov Institute of Physics & Technology (KIPT) in Ukraine. The facility is in the start-up phase, which is expected to be completed by the end of 2017. This activity is supported by the Russian Research Reactor Fuel Return (RRRFR) program of the United States Department of Energy. The facility is planned to produce medical isotopes, train young nuclear professionals, support the Ukraine nuclear industry, and provide capability for performing reactor physics, material research, and basic science experiments. It is suitable for studying accelerator driven systems and performing basic neutron research, including a cold neutron source. Other USA R&D activities are being carried out to study and investigate various aspects of ADS including monitoring and controlling the system subcriticality. The utilization of ADS for transmuting minor actinides and long-lived fission products are being carried out by different institutes. One of these concepts is based on the use of mobile fuel with liquid lead.

In Russia, a proposal exists by iThEC [5] and INR Troitsk [6] to refurbish a 600 MeV accelerator and make use of existing spallation neutron facilities, to carry out the first fast neutron ADS experiment of significant power ($\geq$ 1 MW), in order to characterize ADS and demonstrate the safety advantages. Recently, NRC Kurchatov Institute has started discussions of an ADS experiment at IHEP Protvino.

Among the other countries involved in ADS-related activities, are Japan [7], where ADS research was restarted as a consequence of the Fukushima accident, and South Korea with the HYPER project [8], to name only the most significant activities.

Europe is building the most powerful spallation neutron source, the ESS [9], at Lund, in Sweden, also based on a linac. The ESS proton beam power will reach 5 MW. The Paul Scherrer Institute (PSI) [10], one of the CYCLADS [11] partners, has developed the first and successful MW spallation neutron source (MEGAPIE) [12]. These neutron spallation projects provide Europe with the most advanced expertise on target technology for ADS. Therefore, with the innovative accelerator proposed with CYCLADS, Europe would have all the elements of an ADS in hands.

The MYRRHA project is suffering from insufficient funding, in particular because the linac solution adopted for the accelerator turns out to be very expensive. A recent estimate is 550 MEuros [13]. This illustrates the strategic importance for Europe of the new accelerator option proposed with CYCLADS, based on a single stage superconducting cyclotron, at a time when the rest of the world is investing major efforts in ADS.

2) Cyclotron projects

The highest power cyclotron in the world [14] is in operation at PSI, its 590 MeV proton beam has reached a power of 1.4 MW. However, it was not initially designed to drive an ADS, therefore, it is not optimized for such use, as it is dedicated to research. A lot of expertise was accumulated at TRIUMF in Canada, which operates a warm magnet cyclotron with 520 MeV protons, since December 1974. At the Proton Driver Efficiency workshop [15] held at PSI in February 2016, it was unanimously recognized that circular concepts are cost efficient, using robust RF cavities, which provide high efficiency, and that low beam losses at extraction are possible.

Several significant cyclotron proposals are currently being discussed:

– Pulsed high-power beam, for neutrino production, the H_2^+ DAEdALUS Cyclotron [16];

– Superconducting Ring Cyclotron [17], at RIKEN, in Japan, to accelerate a broad spectrum of ions, up to uranium, at 400 MeV per nucleon;

– 800 MeV Superconducting Strong-Focussing Cyclotron [18], at Texas A&M, USA. It is a two-stage cyclotron (100 MeV injector and 800 MeV booster). The reliability and the high power are achieved through 3 stacks of superconducting cyclotrons operated in parallel.

The compactness of cyclotrons produces an additional important indirect economic advantage for the easiest installation inside the reactor building and the easiest interface management with the subcritical system. This economic advantage is exalted by the combination with a subcritical system that leverages many of the innovations introduced by Hydromine in the LFR-AS-200 project, innovations whose interest has also been confirmed recently during the International Conference FR17 [19, 20].

In this context, the CYCLADS cyclotron is unique. Its original layout, compared to the other cyclotron-based projects, allows to reduce the investment costs while increasing the overall efficiency and the reliability of the facility. It combines, in an innovative way, the advanced features of some of the other projects in the world, with the additional advantage of benefitting from the unique expertise of PSI [10], AIMA [21], and INFN [22], leading world experts in this domain, which is a major asset for the project, and minimizes technical risks.

References:

[1] Didier De Bruyn, Hamid Aït Abderrahim, Peter Baeten, and Paul Leysen, *The MYRRHA ADS Project in Belgium Enters the Front End Engineering Phase*, Physics Procedia 66 (**2015**) 75 – 84

[2] Luo, P., Wang, S.-C., Hu, Z.-G., Xu, H.-S., Zhan, W.-L., *Accelerator-Driven Subcritical Systems—A Promising Solution for Cycling Nuclear Fuel*, Physics, *45*(9), 569–577 (**2016**), DOI: 10.7693/wl20160903

[3] P. Singh, *India ADS Programme*, EuCARD2 Workshop on Status of Accelerator Driven Systems Research and Technology Developments, CERN, 7-9 February 2017, https://indico.cern.ch/event/564485/contributions/2379331/

[4] Zelinsky, A. Y., et al., *NSC KIPT Neutron Source on the Base of Subcritical Assembly Driven with Electron Linear Accelerator*, Proc. of IPAC2013, Shanghai, China, THPFI080 (January **2013**)

[5] iThEC, international Thorium Energy Committee**,** Rue François-Dussaud 17**,** 1227 Geneva, Switzerland, http://www.ithec.org/

[6] Sidorkin, S. F., Rogov, A. D., Ponomarev, L. I., Koptelov, E. A., *Proposal of the ADS Research Stand Based on the Linac of the Institute for Nuclear Research of the Russian Academy of Sciences*, in Thorium Energy for the World, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27–31, 2013), Springer, (**2016**), DOI 10.1007/978-3-319-26542-1

[7] Sasa, T., *The Japanese Thorium Program*, in Thorium Energy for the World, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27–31, 2013), Springer, Berlin (**2016**)

[8] Won S. Park, Uncheol Shin, Seok-Jung Han, Tae Y. Song, Byung H. Choi, Chang K. Park, *HYPER (Hybrid Power Extraction Reactor): A system for clean nuclear energy*: Nuclear Engineering and Design (**2000**), 199, 155-165; 10.1016/S0029-5493(99)00066-7; *PEFP: Proton Engineering Frontier Project* (**2002-2012**), now KOMAC, since 2013: KAERI, International Topical Meeting on Nuclear Research Applications & Utilization of Accelerators Vienna, Austria, May 4-8, 2009; PyroGreen Project: SNU, Progress in Nuclear Energy 58 (2012) 27-38

[9] ESS, Technical Design Report, April 23, 2013, ESS-doc-274 http://eval.esss.lu.se/cgi-bin/public/DocDB/ShowDocument?docid=274

[10] Paul Scherrer Institute (PSI), Villigen, Switzerland, https://www.psi.ch/

[11] CERN, AIMA Dev, ASG, ENEA, HNE, iThEC, N-21, PSI, *Conceptual design of a Single Stage Cyclotron for High Power Applications (CYCLADS)*, Proposal submitted to FETOPEN-01-2016-2017: FET-Open research and innovation actions, in the framework of the Horizon 2020 EU Research and Innovation programme

[12] Latgé, C., MEGAPIE: *The World's First High-Power Liquid Metal Spallation Neutron Source*, in Thorium Energy for the World, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27–31, 2013), Springer, (**2016**), DOI 10.1007/978-3-319-26542-1

[13] Hamid Aït Abderrahim, Private communication

[14] Grillenberger, J., Seidel, M., *High Intensity Proton Beam Production with Cyclotrons*, Proc. of the Workshop on Applications of High-Intensity Proton Accelerators, Raja, R. (ed.), World Scientific, Singapore (**2010**)

[15] Joachim Grillenberger, *Cyclotrons*, Proton Driver Efficiency Workshop, Feb. 29 to March 2, 2016, Paul Scherrer Institut (PSI), Villigen, Switzerland

[16] L. Calabretta, et al., *Preliminary Design Study of High-Power H2+ Cyclotrons for the DAEdALUS Experiment*, arXiv:1107.0652 [physics.acc-ph]

[17] K. Yamada et al., *Status of the Superconducting Ring Cyclotron at Riken RI Beam Factory*, Proceedings of EPAC08, Genoa, Italy
[18] P. McIntyre, *Strong Focusing Cyclotron and Its Applications*, IEEE Transactions on Applied Superconductivity (Volume: 25, Issue: 3, June 2015)
[19] L. Cinotti, P. Brigger and G. Grasso, *Simplification, the atout of LFR-AS-200*, Id 140, Proc. Int. Conf. Fast Reactors and Related Fuel Cycles (FR17), Yekaterinburg, Russian Federation, June 26-29, 2017
[20] G. Grasso, G. Bandini, F. Lodi and L. Cinotti, *The core of the LFR-AS-200*, Id 185, Proc. Int. Conf. Fast Reactors and Related Fuel Cycles (FR17), Yekaterinburg, Russian Federation, June 26-29, 2017
[21] M. Conjat and P. Mandrillon, *Single Stage Cyclotron for an ADS Demonstrator*, Proceedings of the 21st International Conference on Cyclotrons and their Applications, Zurich September 2016; P. Mandrillon et al., Cyclotron Drivers for ADS, in Thorium Energy for the World, ThEC13 Proc., CERN Globe of Science and Innovation, Geneva, Switzerland (October 27–31, 2013), Springer, (**2016**), DOI 10.1007/978-3-319-26542-1
[22] INFN Southern National Laboratory, Catania, Italy, https://www.lns.infn.it