Overview of achieved coupling experiments on zero power facilities

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The scientific and technological challenges relative to the integration, in a nuclear power facility, of the three main components of an ADS (an accelerator delivering a high-energy particle beam, a heavy metal spallation target acting as a neutron source when bombarded by ions and a subcritical multiplying medium possibly comprising significant amounts of MA and/or LLFP) are numerous. Their resolution requires going through several stages with tests successively at low, intermediate and high power and, in a first step, to consider separately the "accelerator / target spallation" and "neutron source / subcritical multiplying medium" systems. This is the direction taken in Europe in the early 2000s after first tests at low power at CERN and in France were successfully achieved (FEAT in 1994, TARC in 1996 and MUSE-1/2/3 experiments in 1995, 1996 and 1998). The objective of presentation is to give an overview of "neutron source / subcritical multiplying medium" coupling experiments at low power that were performed since.

This talk starts with a few words about the interest of zero power reactors for ADS research and a reminder of the objectives and main lessons drawn from experiments evoked above. Then, we present a review of initiatives launched world-wide with the aim to conduct low-power experiments involving the coupling of a subcritical core with an external neutron source, mostly provided by D-D / D-T generators. We give main features of experiments that were completed (list below) before focusing a bit more on major programs (the MUSE-4/GUINEVERE/FREYA suite and the Yalina-B experiment in Europe, the ADS R&D activities at KURRI/KUCA in Japan), their most significant characteristics (neutron spectrum, characteristics of the source, experimental program content) and their main outcomes. In particular, the major accomplishments with respect to the representativity of the experiments and the key issue of the control and monitoring of subcritical levels are underlined. The overview is extended to initiatives that have not gone beyond the stage of opportunity or feasibility study (in Brazil, Czech Republic and UK). The main features of larger projects (RACE, TRADE plus, SAD) that had to stop prematurely are also reminded. Last, some highlights on possible next steps are given.

Country	Project	Period	Facility	Operator	Type of facility	Core	Neutron source
Belarus	Yalina-Thermal	2000 - 2005	YALINA	JIPNR	Subcritical assembly (keff < 0,98)	Thermal	252Cf, Am-Be, D-D/D-T generator (NG-12-1)
	Yalina-Booster	2005 - 2008				Fast/Thermal	
Belgium	GUINEVERE, FREYA	2006 - 2016	VENUS-F	SCK	Zero power critical assembly	Fast	Am-Be, D-D/D-T generator (GENEPI 3C)
Brazil	-	2014	IPEN-MB-01	IPEN	Zero power critical assembly	Thermal	Am-Be
China	NBRPC	2005 -	VENUS-1	CIAE	Subcritical assembly (keff < 0,98)	Fast/Thermal	^{252}Cf, Am-Be, D-D/D-T generator (CIAE PNG)
France	MUSE-1	1995	MASURCA	CEA	Zero power critical assembly	Fast	^{252}Cf
	MUSE-2	1996					^{252}Cf
	MUSE-3	1998					D-T generator (Sodern Genie 26)
	MUSE-4	1999 - 2004					D-D/D-T generator (GENEPI 1)
India	-	2013 -	PURMINA BRAHMMA	BARC	Subcritical assembly (keff ~ 0,85 - 0,9)	Thermal	D-D/D-T generator (CIA PNG)
Italy	TRADE phase I (RACE-T)	2004 - 2006	ENEA RC-1	ENEA	TRIGA (1 MW MarkII)	Thermal	^{252}Cf
							Commercial D-T generator
Japan	FCA XX1-1	2001	FCA	JAEA	Zero power critical assembly	Fast	^{252}Cf + W test zone
Japan	KART, Lab project	2002 -	KUCA	KURRI	Zero power critical assembly	Thermal	D-D/D-Tgenerator
							100 MeV protons / W target
USA	RACE	2004 - 2007	ISU subcritical assembly	ISU-IAC, UNLV, UT, TAMU	Subcritical assembly (keff ~0,90)	Thermal	20-25 MeV electrons (LINAC) + W-Cu target
			UT NETL		TRIGA (1 MW Mark II)	Thermal	

Coupling experiments achieved on zero power facilities since 1995

Some references:

Country	Project	Period	Facility	Some references
Belarus	Yalina-Thermal	2000 - 2005	YALINA	**H. Kiyavitskaya & al.**, 'YALINA Facility to study neutronics of ADS and Fast Reactors', The IAEA TWGM on Fast Reactors and Accelerator Driven Systems (ADS)", Obninsk , Russia, 25-29 May 2015 **C. Berglof**, 'On Measurement and Monitoring of Reactivity in Subcritical Reactor Systems', Doctoral Thesis in Physics Stockholm, Sweden 2010
	Yalina-Booster	2005 - 2008		
Belgium	GUINEVERE, FREYA	2006 - 2016	VENUS-F	**A. Billebaud & al.**, "The GUINEVERE Project for Accelerator Driven System Physics", Proceedings of Global 2009, Paris, France (September 6–11, 2009) **J.L. Lecouey & al.**, "Estimate of the reactivity of the VENUS-F subcritical configuration using a Monte Carlo MSM method", Annals of Nuclear Energy 83 (2015) 65–75 **N. Marie & al.**, "Reactivity monitoring using the area method for the subcritic al VENUS-F core within the framework of the FREYA Project", Second International Workshop on Technology and Components of Accelerator Driven Systems (TCADS 2), Nantes, France **S. Chabod & al.**, "Reactivity Measurement at GUINEVERE Facility Using the Integral kp Method, PHYSOR 2014, The Role of Reactor Physics Toward a Sustainable Future, Kyoto, Japan, September 28th–October 3rd **T. Chevret & al.**, "Reactivity Measurement of the Lead Fast Subcritical VENUS-F Reactor Using Beam Interruption Experiments, PHYSOR 2014, The Role of Reactor Physics Toward a Sustainable Future, Kyoto, Japan, September 28th–October 3rd. **FREYA - Final publishable summary report**, FREYA (Fast Reactor Experiments for Hybrid Applications), FP7, Contract n°269665
Brazil	National Program	2014	IPEN-MB-01	**E Gonnelli & al.**, 'An alternative experimental approach for subcritical configurations of the IPEN/MB-01 nuclear reactor', XXXVII Brazilian Meeting on Nuclear Physics (available at http://iopscience.iop.org/1742-6596/630/1/012007) **R. Kuramoto & al.**, "Rossi-α Experiment in the IPEN/MB-01 Research Reactor", Brazilian Journal of Physics, vol. 35, no. 3B, September, 2005
	IPEN-MB-01 subcritical facility	Abandonned		**J.R.Maiorino & al.**, "The utilization of a compact neutron generator to drive a sub critical core of the IPEN-MB-01 facility for reactor physics experiments", Brazilian Journal of Physics, vol. 35, no. 3B, September, 2005 **J.R. Maiorino & al.**, "The Utilization of a Cyclotron CV-28 in Basic and Applied Nuclear Research and in an Experimental Accelerator Driven System Zero Power Lead SubCritical Facility", Brazilian Journal of Physics, vol. 34, no. 3A, September, 2004
China	NBRPC	2005 -	VENUS-1	**S. Yongqian & al.**, 'China ADS sub-critical experimental assembly—Venus-1 and preliminary experiment', Front. Energy Power Eng. China 2007, 1(2): 150–157
Czech Republic	LA-0	Abandonned	LR-0	**R. Mach & al.**, "Nuclear Waste Transmutation Program in the Czech Republic", Proceedings of the International Workshop - Nuclear Methods for Transmutation of Nuclear Waste: Problems, Perspectives, Cooperative Research -, Copyright ⍰ by World Scientific Publishing Co. Pte. Ltd.
France	MUSE-1	1995	MASURCA	**R. Soule** & al., 'Neutronic Studies in Support of Accelerator-Driven Systems: The MUSE experiments in the MASURCA Facility', Nuclear Science and Engineering, Volume 148, Number 1, September 2004n Pages 124-152 **The MUSE experiments for sub critical neutronics validation**, EURATOM FP5, Contract n°FIKW-CT-2000-00063, Deliverable 8,- Final report (https://cordis.europa.eu/pub/fp5-euratom/docs/projrep_muse_en.pdf)
	MUSE-2	1996		
	MUSE-3	1998		
	MUSE-4	1999 - 2004		
India	BRAHMMA	2013 -	PURMINA BRAHMMA	**A. Sinha & al.**, 'Experimental subcritical facility driven by D-D/D-T neutron generator at BARC, India', Nuclear Instruments and Methods in Physics Research B 350 (2015) 66–70
Italy	TRADE (RACE-T)	2004 - 2006	ENEA RC-1	**R. Rosa & al.**, "RACE-T Experimental Activities - An overview of the subcritical measurements preliminary to the accelerator coupling experiment", International Conference on Research Reactors: Safe Management and Effective Utilization, Australia, Sydney, 5 – 9 November 2007 **C. Jammes & al.**, "Absolute Reactivity Calibration of Accelerator Driven Systems after RACE-T Experiments", **C. Jammes & al.**, "Comparison of reactivity estimations obtained from rod-drop and pulsed neutron source experiments", Annals of Nuclear Energy, 32 (2005), p. 1131–1145
	TRADE plus	Abandonned		**C. Rubbia & al.**, "The TRADE Experiment: Status of the Project and Physics of the Spallation Target", PHYSOR 2004 -The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)
Japan	FCA XX1-1	2001	FCA	**T. Yamane & al.**, "Subcritical experiments in uranium-fueled core with central test zone of tungsten", Proceedings of PHYSOR 2004: The Physics of Fuel Cycles and Advanced Nuclear Systems - Global Developments; Chicago, IL (United States); 25-29 Apr 2004
Japan	KART, Lab project	2002 -	KUCA	The last one : **M. Yamanaka & al.**, "Effective Delayed Neutron Fraction in Accelerator-Driven System Experiments with 100 MeV Protons at Kyoto University Critical Assembly", Journal of Nuclear Science and Technology 54(3) 293-300 Jan 2017
Russia	SAD	Abandonned	JINR/Dubna	**V.N.Shvetsov & al.**, "The subcritical assembly at DUBNA (SAD): coupling all major components of an accelerator driven system (ADS) for nuclear waste incineration", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment Volume 562, Issue 2, 23 June 2006, Pages 883–886
U.K.	Reconversion of CONSORT Research Reactor	Abandonned	CONSORT	**H. Owen & al.**, "Steady-State Neutronic Analysis of Converting the UK CONSORT Reactor for ADS Experiments", Annals of Nuclear Energy Volume 38 Issue 12, December 2011, Pages 2653–2660
USA	RACE	2004 - 2007	ISU subcritical assembly	**D. Beller**, "Overview of the AFCI Reactor-Accelerator Coupling Experiments (RACE) Project, Transactions of American Nuclear Society, 90, 2004 **C. Jammes & al.**, 'Experimental Results of the RACE-ISU international collaboration on ADS', Proceedings of the Eighth international topical meeting on nuclear applications and utilization of accelerators (ACCAPP'2007), July 29-August 2, 2007, Pocatello, Idaho **Sean O'Kelly**, "Accelerator Driven Subcritical Experriments at The University of Texas", Test, Research and Training Reactor meeting, Texas, Austin, 2006
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