OVERVIEW OF ACTIVITIES ON ACCELERATOR DRIVEN SUBCRITICAL SYSTEM IN INDIA

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ABSTRACT

An experimental programme to design and study external source driven subcritical assembly has been initiated at Bhabha Atomic Research Centre, India. This program is aimed at understanding neutronics of accelerator driven system (ADS) at low power level. In this series, an experimental thermal subcritical core BRAHMMA (BeO Reflected And HDPe Moderated Multiplying Assembly) driven by a D-D/D-T neutron generator has been developed. This facility has been designed for the purpose of investigating the static and dynamic neutronic properties of accelerator driven sub-critical systems. The subcritical core consists of natural uranium fuel with high density polyethylene (HDPe) as moderator and beryllium oxide as reflector. The paper discusses detailed experiments that have been carried out in BRAHMMA for reactivity estimation using pulsed neutron source (PNS) techniques and neutron noise techniques. The PNS measurements include Area Ratio (Sjöstrand), Slope-Fit and Source Jerk methods. The effect of spatial location of detector on reactivity measurements and their correction has been studied. The spatial correction factors (Bell Glasstone) have been evaluated for various detector locations, both for D-D and D-T neutrons. Noise techniques have been explored for measuring the prompt decay constant α. Feynman-α and Rossi-α measurements for both continuous and pulsed sources are presently underway. The experimental noise measurements are influenced by the higher harmonics and hence necessary corrections have to be applied to extract the fundamental mode. The problem is also compounded for such a deep subcritical system. However, a novel technique has been developed to reduce the modal contamination in the noise measurements for deep subcritical systems. Following the successful implementation of BRAHMMA which is a thermal assembly, low-power experimental fast ADS based on Th-Pu MOX (Thorium –Plutonium Mixed Oxide) fuel has been proposed for the next stage of ADS programme to study the issues related to higher actinide transmutation using ADS. Design concept and issues related to a Th-Pu MOX fast subcritical assembly driven by intense D-T neutron generator for mock-up studies of waste transmutor ADS will be briefly discussed.

KEYWORDS
Accelerator Driven Subcritical system; BRAHMMA, Reactivity

1. INTRODUCTION

India's nuclear energy programme has been based on energy self-sufficiency using available natural resources. Since the early days of Indian nuclear energy programme, its modest uranium reserves but vast thorium reserves dictated that the country's primary objective would be thorium utilization. Indian thorium reserve accounts for approximately 30% of the world's total thorium reserve whereas uranium reserve is only a fraction of it. Therefore, since the inception of India nuclear energy programme, thorium has been at the centre of India's nuclear power industry to ensure a stable, sustainable and self-sufficient nuclear energy programme. Thorium fueled reactor have additional advantage of low radiotoxicity and this has an added advantage in the context of large scale planned expansion of nuclear programme. Thorium, however, unlike uranium, does not contain isotope which can sustain fission chain reaction but it needs to be converted into a fissile isotope – ^{233}U. Thus use of thorium requires an additional stage to first convert it into fissile isotope to sustain chain reaction. This led the forefathers of Indian nuclear energy programme to propose a three stage plan for a sustainable nuclear energy program. In the first stage, natural uranium would be used to fuel heavy water moderated reactors. Plutonium, extracted from the spent fuel of these thermal reactors, would drive fast reactors in the second stage that would contain thorium blankets for breeding ^{233}U. In the final stage, this ^{233}U would fuel thorium burning reactors that would breed and fission ^{233}U in-situ. This three stage roadmap still defines the core of India's civil nuclear power program.

The first stage has progressed well despite some constraints and several PHWR and some light water reactors are already operational and several more are in advanced stage of construction. As for the second stage, a fast breeder test reactor which is essentially a demonstration of fast reactor technology has been in operation since 1985. The Fast Breeder Test Reactor (FBTR) has not only served as a test bed for fuel development but has also generated a small amount of power for the electrical grid since 1997. The second 500 MWt Prototype Fast Breeder Reactor (PFBR) is likely to be commissioned soon. Work has been going on various aspects of first stage and second stage nuclear fuel cycle. In preparation to using third stage of nuclear fuel cycle, several preparatory developments have been undertaken, This involves experimental zero power reactors such as PURNIMA-II using ^{233}U as fuel to KAMINI reactor which is ^{233}U fuelled reactor being used for neutron radiography of irradiated fast reactor fuel elements. The Prototype Fast Breeder Reactor (PFBR) is likely to be commissioned soon. There is also significant research going on in developing high breeding ratio metallic fuel fast breeder reactor.

However, it is estimated that large scale thorium utilization for power reactors will require three to four decades of commercial operation of fast breeder reactors for generating necessary feedstock of plutonium for meaningful power programme using thorium. As there is a delay before direct thorium utilisation in the three-stage programme, parallel to the sequential three-stage programme, India is looking at reactor designs that allow more direct use of thorium. This has led to several parallel approaches being adopted for accelerated use of thorium in Indian nuclear energy programme. Four options under consideration are the Indian Accelerator Driven Systems (ADS), Advanced Heavy Water Reactor (AHWR), Compact High Temperature Reactor and Molten Salt Reactor.

Out of the above options, the design for AHWR is ready for deployment. AHWR is a 300 MWe vertical pressure tube type, boiling light water cooled and heavy water moderated reactor, using uranium–thorium mixed oxide (MOX) fuel or and plutonium–thorium MOX fuel. It is expected to generate 65% of its power from thorium and can also be configured to accept other fuel types in full core including low enriched uranium (LEU) and uranium–plutonium MOX.

The second parallel programme of accelerated use of thorium is in the form of Accelerator driven subcritical system. It uses surplus neutrons of spallation reaction to first breed thorium to fissile fuel and then to use it for sustainable chain reaction. There is an active programme of Accelerator Driven subcritical system in India and it envisages various stages and components. The first stage is studying its feasibility and various physics aspect due to its distinguishing features from critical reactors. The second parallel stage is high current accelerator development with Low Energy High Intensity Particle Accelerator (LEHIPA) as first phase and high energy high current (~1 GeV, 10 mA) as second phase of this programme. The third part is target development.

2. SUBCRITICAL PHYSICS

Source driven subcritical systems [1, 2] have several attractive features such as superior safety, waste transmutation, etc. over critical reactors, yet there are several physics issues, which need to be addressed before such a system can be launched on a commercial scale. Some important physics issues relate to (a) asymmetric flux distribution – the presence of (central) non fission source whose spatial and energy distribution affects neutron multiplication in the system and hence the power of the system, (b) importance of source neutrons – understanding relative importance of the source neutrons with respect to the fission neutrons generated in the subcritical system plays an important role in performance of ADS; a higher relative importance of source neutron can help bring down accelerator current requirement but may have other issues related to source dominated system, (c) the transient behavior of subcritical system at different subcriticality level vary in response and needs to be studied while designing ADS.

Power produced in ADS is directly proportional to the strength of external source and inversely to the degree of sub-criticality. Accurate monitoring of subcritical reactivity value is thus one of the central operational and safety issues of a future ADS. The reactivity variations under no circumstances should lead either to criticality or delayed criticality. This quantity needs to be accurately monitored for sustained and safe operation of subcritical reactor. However, conventional methods of subcriticality monitoring are no longer valid in ADS. Unlike critical reactors, the subcritical system has higher modes besides fundamental mode. In a critical reactor, point kinetics approximation is used to infer about the prompt decay constant and reactivity of the system. However, for subcritical systems, the point kinetic approximation no longer holds. The total subcritical flux can be approximated by a series of eigen modes with the fundamental mode being the pre-dominant one. Any experimental measurement of the system parameters will be influenced by the higher harmonics and hence necessary corrections have to be applied to extract the fundamental mode. For subcritical system, development of new online methods for monitoring of subcriticality level is therefore required. Moreover, the accuracy of the existing methods such as Sjöstrand area ratio method or noise methods strongly depends on the detector position even when the system behaviour is point kinetic. Therefore development of accurate reactivity measurement technique is quite important.

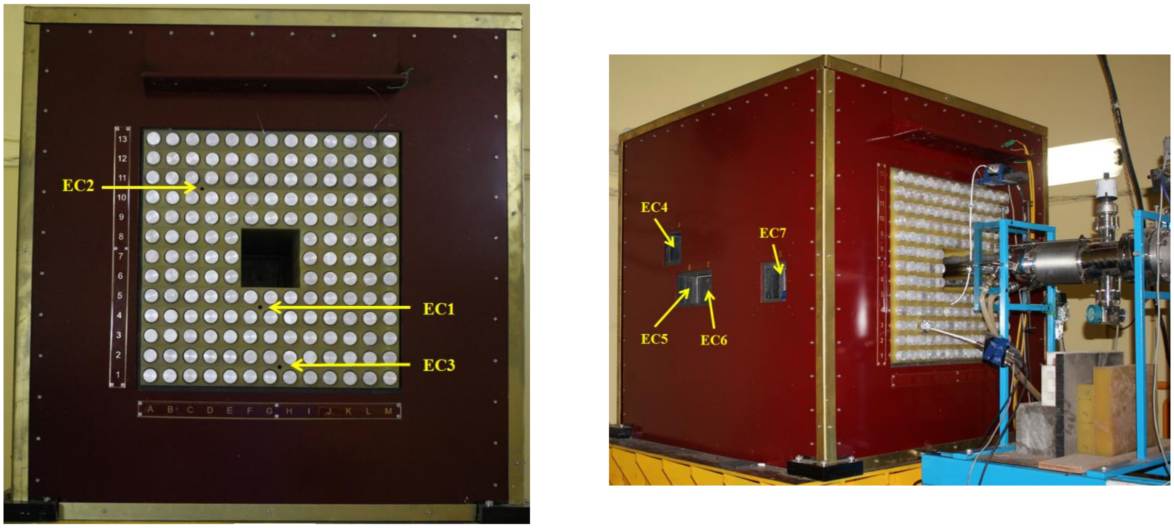
Though there have been extensive theoretical studies on ADS, it is necessary that such results be tested experimentally. In addition to such experiments that can be carried out in “zero power” facilities, it is also necessary to carry out experiments at different sub-criticality levels with feedback effects in facilities with significant power. They will be important to understand the changes in the reactor kinetics of ADSs at large sub criticality that is determined primarily by the source and at low sub criticality that is determined by feed-back effects. An important part of the experiments is to evaluate methods for assessment and monitoring of the sub-criticality level of ADSs. Several facilities and experiments have been set up or modified for the purpose of carrying out such experiments. This has been the reason for current research on ADS being pursued in several countries and it involves mainly an experimental feasibility study with the use of subcritical assemblies/test facilities: MUSE, YALINA [3-5] – thermal and booster, VENUS-1, KUCA and GUINEVERE.

3. INDIAN STUDY OF SUBCRITICAL PHYSICS

As a part of the ADS programme in India, a subcritical assembly named BRAHMMA (BeO Reflected And HDPe Moderated Multiplying Assembly) [6, 7] driven by an indigenously developed deuteron accelerator has been designed, developed and commissioned at Bhabha Atomic Research Centre, India. This facility provides an opportunity to study various physics issues related to accelerator driven sub-critical systems (ADS) on a low power scale. The subcritical assembly can be driven either by D-D neutron (2.45 MeV) or D-T neutron (14.1 MeV) or some isotopic source for study of source related parameters. The uniqueness of the system is its modular design where subcriticality level can be varied by using different fuel such as low enriched uranium (LEU). The other unique feature is the use of Beryllium oxide (BeO) as reflector which has resulted in a compact system. The facility consists of a sub-critical core and deuteron accelerator based neutron source. They are described in the following sections.

3.1. BRAHMMA Subcritical Core

The subcritical core (Fig.1) consists of metallic natural uranium as fuel, high density polyethylene (HDPe) as moderator and beryllium oxide (BeO) as reflector. The core consists mainly of high density polyethylene sheets with a maximum of 160 fuel channels. The fuel rods are arranged in a 13x 13 square HDPe lattice with a 48 mm pitch (centre-to-centre distance between two fuel rods). The central 3 x 3 part of the lattice serves as the cavity for inserting the neutron source. The neutron producing target is located at the center of the core. Behind the target, a lead block of thickness 100 mm is used to soften the energy spectrum of the monoenergetic D-T neutrons. The use of polyethylene sheets makes the system modular. The assembly can be re-configured to achieve higher keff either by increasing the amount of fuel or by replacing some of the natural uranium fuel rods by enriched uranium.



(a) (b)

Figure 1. (a) Front view (b) Side view of BRAHMMA. The positions of the axial and radial experimental channels are also shown

One of the unique features of the core is the use of BeO as reflector. Beryllium oxide has excellent properties as reflector material and also makes the system compact. The core is surrounded (on four sides perpendicular to the incident beam) by beryllium oxide of 200 mm thickness. The core is finally surrounded by an outer layer of 50 mm of borated polyethylene (1% boron by weight) followed by 1.5 mm of cadmium to isolate the system from scattered neutrons from the surrounding.

3.2. Experimental Channels

Seven experimental channels (EC) are located at different axial and radial positions. The relative positions of the experimental channels are such that their influence on each other is minimized. The experimental channels are as follows:

1. Three axial experimental channels (EC1, EC2 and EC3) of diameter 10.0 mm have been provided at radial distances of 122, 238 and 265 mm respectively for measurement. EC1 is close to the source whereas EC3 is near the reflector.
2. Four experimental channels (EC4, EC5, EC6 and EC7) of diameter 7.2 mm have been provided in the moderator/reflector region along the radial direction. Channels EC5, EC6 and EC7 are located in the mid-elevation plane and run up to the cavity only. Since the experimental channels are small, some new neutron detectors have been developed. These include miniature He-3 and fibre optic detectors.

3.3. Neutron Generator

The coupling with the subcritical core is provided by deuteron accelerator based neutron generator. It is a 300 kV deuteron accelerator. The D+ ions are produced in an RF ion source, which are extracted, focused, accelerated and bombarded on the target. The target is maintained at ground potential. The deuteron ions impinge on titanium-tritium (TiT) or titanium-deuterium (TiD) targets providing 14.1 MeV or 2.45 MeV neutrons via T(d,n)4He or D(d,n)3He reactions respectively. The design of this system also required two major developments - neutron generator and detector. For the neutron generator, we have incorporated some features like DC and pulsed operation, online source strength monitoring using neutron tagging and programmable source modulation feature for both D-D and D-T mode operation. The accelerator can be operated in both continuous and pulsed modes. An electrostatic beam-chopper is used to generate pulsed beams. This enables the generation of neutron pulses with minimum pulse width of 10 µs and repetition rates from 1 Hz to 1 kHz. Fig.2 shows the subcritical core coupled to neutron generator.

Figure 2. Neutron Generator

4. EXPERIMENTAL MEASUREMENT

Experiments have been carried out to measure reactivity using Pulsed Neutron Source (PNS) [8-10] and neutron noise techniques. The experimental data are acquired using a set of miniature 3He detectors (Active length: 70 mm; Diameter: 6.3 mm) [11] with different sensitivities in the range from 0.1 cps/nv to 0.001 cps/nv. The signal readout electronics consists of a charge sensitive pre-amplifier with a fall time of 5 μs, shaping amplifier (1 μs time constant) with a single channel analyzer which generates 5V TTL pulses. These pulses are then fed to a multi-channel scalar (MCS). The experimental results are briefly discussed in the subsequent sub-sections.

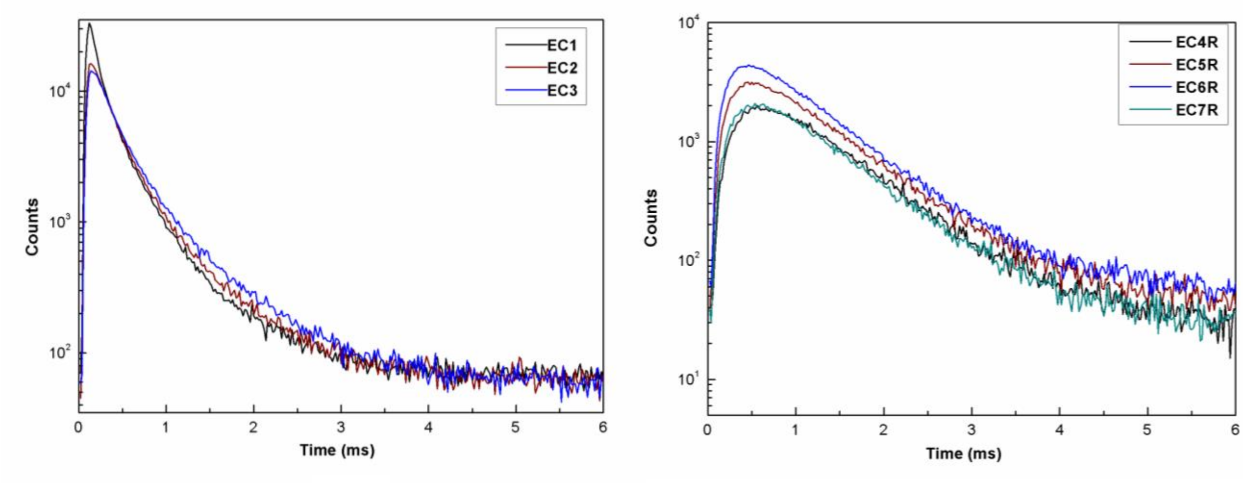
4.1 Pulsed Neutron Source Measurements

For PNS measurements, three techniques, namely – Area-Ratio (Sjöstrand and Gozani), Slope-Fit and source Jerk – have been explored. To measure the reactivity in the subcritical assembly, several miniature 3He detectors were placed at different experimental channels. For the Area-Ratio and Slope-Fit methods, the external pulsed D-T neutron source is operated with a pulse period of 10 ms (100 Hz). The neutron flux in the subcritical assembly is recorded by the detectors from a number of repetitive neutron pulses (typically 50,000 pulses) once the delayed neutron level has reached an equilibrium value.

4.1.1 Area-ratio method

In Area-Ratio method, the reactivity (in $) is given as the negative ratio of prompt neutron area and delayed neutron area. For Sjöstrand method, prompt area is calculated as the integrated neutron flux since the start of neutron pulse. However, the presence of higher order modes introduces errors in reactivity measurement. Since the higher order modes have spatial dependency, the measured local reactivity is not a true measure of global reactivity. To eliminate the contribution of higher order mode, spatial correction (as proposed by Bell-Glasstone [12]) has to be used for each detector location.

An alternate approach to calculate prompt neutron area was suggested by Gozani [10]. In this method, prompt neutron area is calculated by extrapolating the prompt part of the PNS histogram to the start time of the neutron pulse, thereby eliminating the prompt harmonic contribution from prompt neutron area. This method is also known as the Extrapolated Area Ratio Method.



(a) (b)

Figure 3. PNS histogram at (a) axial (b) radial experimental channels. The suffix R indicates the measurements are in reflector region

Figures 3(a) and 3(b) show the PNS histogram for different detector locations. Table 1 shows the experimentally measured values of reactivity using Area Ratio methods [13, 14] due to Sjostrand and Gozani.

Table I. Reactivity measured using Area Ratio method

Experimental Channel	Sjöstrand Method				Gozani Method	
	ρ^{meas} ($)	Spatial correction factor	ρ^{corr} ($)	k_{eff}	ρ ($)	k_{eff}
EC1	-28.03	0.62 ± 0.02	-17.38±0.56	0.886±0.003	-17.33±1.15	0.891±0.008
EC2	-19.04	0.92 ± 0.03	-17.52±0.57	0.885±0.003	-19.09±1.13	0.882±0.008
EC3	-16.61	0.99 ± 0.04	-16.44±0.66	0.896±0.004	-18.53±0.98	0.885±0.007

4.1.2 Slope-fit method

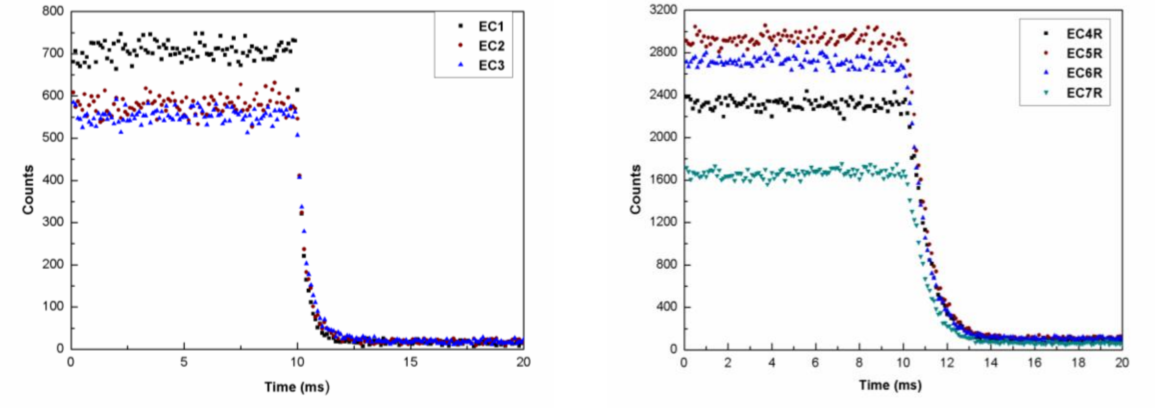
The PNS histogram (Fig. 3) obtained in the area ratio method is used to find the prompt decay constant α. The decay constant α is obtained from the slope of the prompt part of the histogram (straight line in loge plot). The effective delayed neutron fraction βeff is computed theoretically and its value is 704 ± 10 pcm. Table 2 gives the prompt decay constant and keff values measured at different axial channels.

Table II. Reactivity measured using Slope Fit method

Experimental channel	α (ms^{-1})	k_{eff}
EC1	-2.246 ± 0.112	0.887 ± 0.005
EC2	-2.318 ± 0.116	0.884 ± 0.005
EC3	-2.346 ± 0.117	0.883 ± 0.005

4.1.3 Source jerk method

Figures 4(a) and 4(b) show the PNS histogram for different detector locations. Table 3 gives the keff values measured at different axial channels using Source Jerk method.



(a) (b)

Figure 4. PNS histogram for Source Jerk at (a) axial experimental channels (b) radial experimental channels. The suffix R indicates the measurements are in reflector region

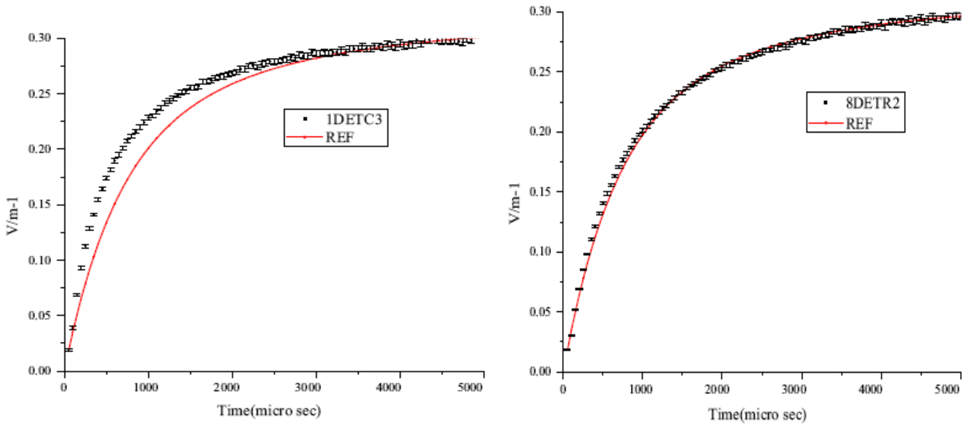
Table III. Reactivity measured using Source Jerk method

Experimental channel	ρ^{meas} (\$)	Spatial correction factor	ρ^{corr} (\$)	k_{eff}
EC1	-25.87	0.62 ± 0.02	-16.04 ± 0.51	0.894 ± 0.003
EC2	-17.39	0.92 ± 0.03	-16.00 ± 0.52	0.894 ± 0.003
EC3	-15.69	0.99 ± 0.04	-15.53 ± 0.62	0.897 ± 0.004

4.2 Neutron Noise Measurements

Measurement of reactivity using neutron noise measurement in a subcritical system is affected by contamination of higher harmonics (other than the fundamental mode). We have proposed and experimentally verified a novel technique [15] for measurement of the fundamental prompt neutron decay constant using neutron noise method that is practically free from any contamination due to higher modes. The experiment involves placing detectors symmetrically in the core at the common zeros of first set of higher symmetric modes and using the combined output of these detectors for noise analysis.

For experimental measurement, a maximum of eight He-3 neutron detectors were used in the experiments. The combined signal from all the detectors was fed to the neutron pulse time stamping data acquisition system (for details, see [15]). Figure 5 shows the Feynman Y-curve for single detector (no modal correction) and 8-detector configurations. It can be seen that significant reduction in modal contamination is achieved in the 8-detector configuration as the detector locations have been strategically chosen to cancel out the effect of higher harmonics.



(a) (b)

Figure 5. Feynman Y-curve for (a) single detector (b) 8-detector configuration

5. FUTURE WORK

In the next stage of experimental ADS in India, it is planned to increase k_{eff} of the system using enriched fuel in some of the channels and study the various physics parameters discussed above at different values of k_{eff}. There is also a program to have staged development of experimental Fast ADS using some novel design using thorium-plutonium MOX fuel.

6. CONCLUSIONS

An overview of the Indian programme on Accelerator Driven Subcritical system is presented in this paper. It discusses the motivation and objectives of our ADS programme. It also describes BRAHMMA subcritical facility and various experimental results carried out at this facility. It also outlines some future directions in experimental ADS development.

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