Overview of Activities on Accelerator Driven Subcritical System in India

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Plan Of Talk

1. Linkages of Present study to Indian Nuclear Programme

3. SUBCRITICAL SYSTEM DESIGN - BRAHMMA -BeO Reflected And HDPE Moderated Multiplying Assembly

4. OTHER IMPORTANT ACTIVITIES RELATED TO ADS PROGRAM

5. Summary & conclusions

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Historically Indian Nuclear Program is guided the fact that

In India, availability of uranium has not been estimated to be sufficient to sustain large scale nuclear programme whereas thorium as fertile fuel is abundantly available.

Long-term goal of Indian nuclear energy policy since inception has been to harness thorium reserves which will last sustain nuclear power program for centuries.

World Thorium Resources

USGS Estimates in tonnes(2011)	
Country	**Reserves**
India	**963,000**
United States	**440,000**
Australia	**300,000**
Canada	**100,000**
South Africa	**35,000**
Brazil	**16,000**
Malaysia	**4,500**
Other Countries	**90,000**
World Total	**1,913,000**

Indian Nuclear strategy is determined based on these facts –differs from other countries.

Ref: S.B.Degweker, Pitambar Singh, P.Satyamurthy and **Amar Sinha**.-, International Thorium Energy Conference October 27-31, 2013 CERN in Geneva, Switzerland

Differences?

Indian Nuclear development program is based on indian nuclear Scenario which is quite different from world nuclear scenario particularly with respect to nuclear advanced countries.

India has large thorium reserve compared to relatively limited resources of uranium which is not the case with many nuclear advanced countries. In World scenario (nuclear advanced countries) , there is a large stockpile of fissile Plutonium and also large amount of nuclear waste. There is little incentive for thorium use. Same is not the case with India.

- **Abundance of Thorium not only provides a greater incentive for large-scale use of thorium, but also calls for deployment of thorium based systems much earlier than that contemplated by others.**

Thorium, however, can not be used directly as nuclear fuel and some intermediate stage is required to convert it to fissile. This is the crux of problem and there is an intensive effort to find a solution for it

The long-term Indian Nuclear programme since inception is devised to suit this unique position of large avalability of Thorium and limited avalability of uranium. The key factors for sustainable resource utilization are

- **Adoption of closed fuel cycle**
- **Use of Breeder Reactors**
- **Development of self-sustaining thorium based reactors**

3 stage program

- PHWRs: Pu for fast reactors
- FBRs: Pu and Th breeding
- Th-U233 fuelled reactors

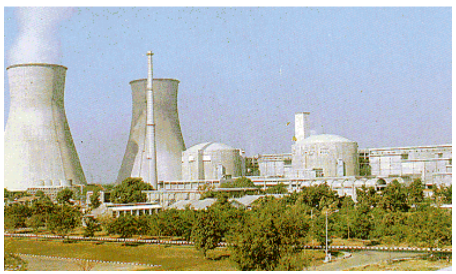
First Stage: Well established
(Commercial Operation under NPCIL)

TARAPUR-1&2

RAJASTHAN-1to 6

MADRAS-1&2

NARORA-1&2



KAKRAPARA-1&2

KAIGA-1 to 4

TARAPUR 3&4

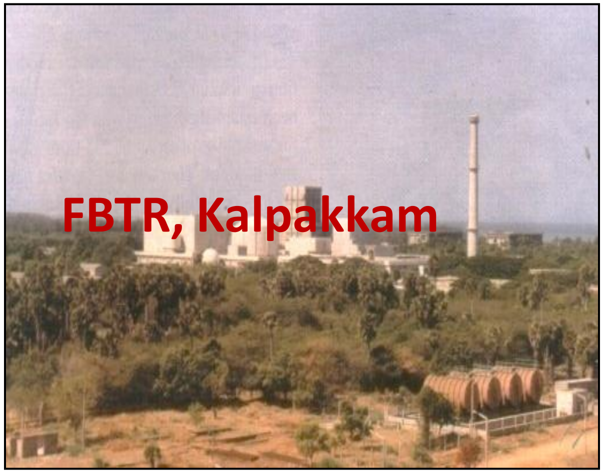
KK 1&2 (2x1000 MWe)

Several more under advanced stage of construction & some are in planning stage

P.K. Vijayan- http://www.itheo.org/ Indian Nuclear Power Programme - Role of Thorium and the Challenges (2015)

Second Stage : Well Underway

- IGCAR, Kalpakkam established to focus on fast reactor programme



- **Fast Breeder Test Reactor (FBTR) is under operation since 1985.**
  FBTR fuel has set world record for performance (165000 MWd/t)
- **500 MWe Prototype Fast Breeder Reactor (PFBR) likely to be commissioned shortly**
- **R&D on advanced FBR fuel to achieve shorter doubling period.**

PR VASUDEVA RAO -www.jaea.go.jp/04/turuga/0425_international.../PRVRao-Monju_250413_r.pdf

Preparation for third stage

Thorium resource and experience with thorium

- Since beginning of nuclear program in India, research has been carried out in some form for Thorium. In fact since early 90's experimental reactor using U-233 have been working in India

- Work has been carried out on all aspects of thorium fuel cycle.

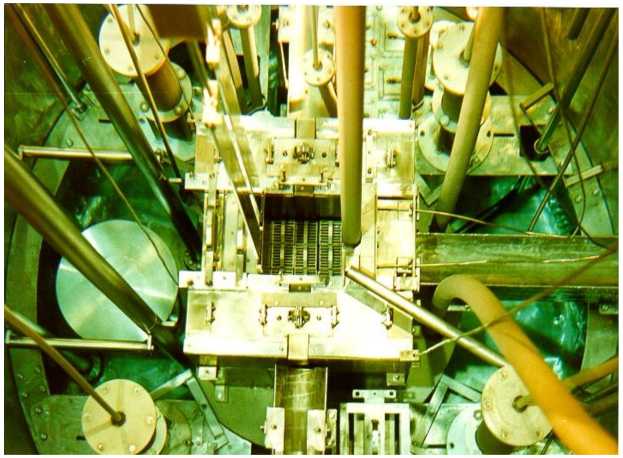
India's early 3rd stage initiative include small scale activities in relevant technologies for entire thorium fuel cycle. These include

1. PURNIMA -II (Smallest reactor with just 400 gms of ^{233}U in uranyl nitrate solution reflected by BeO) 1984

2. PURNIMA-III -^{233}U-Al alloy

3. KAMINI (Kalpakkam Mini Reactor-1996 criticality-30 kWt -1997)- upgraded version of PURNIMA-III. ^{233}U-Al alloy (Plate type Fuel) -The only U-233 fuelled reactor in the world currently in operation.

Aim: U-233 fueled test reactor, a neutron radiography for fast reactor fuel and activation analysis.



KAMINI

OPTIONS ON ACCELERATED USE OF THORIUM

Parallel approaches:

As there is a long delay before direct thorium utilisation in the sequential three-stage programme, the country is looking at reactor designs that allow more direct use of thorium in parallel with the sequential three-stage programme.

(a) An option, parallel approach such as the high-temperature gas-cooled reactor, the molten salt reactor, or the various accelerator driven systems

(b) Following options under active consideration are the

(i) Advanced Heavy Water Reactor (AHWR- ^{233}**U-Th MOX and Pu-Th MOX fuel**) – This is a near term deployment option

(ii) Accelerator Driven Systems (ADS),

and

(iii) Compact High Temperature Reactor as well as studies on

(iv) Molten Salt Reactor

P.K. Vijayan- http://www.itheo.org/ Indian Nuclear Power Programme - Role of Thorium and the Challenges (2015)

What Role ADS can Play?

- Faster breeding of U233 for use in critical reactors
- Simplification of Th Utilisation: once through cycle
- Solution to nuclear waste problem

India has a phased approach to develop an ADS system, including critical facility measurements to validate relevant neutronic data, design and construct linear accelerator facilities, and development of a molten, heavy metal spallation target. Work on Low Energy High Intensity Proton Accelerator (LEHIPA) is being undertaken in staged manner.

Program for ADS development in India

Reactor Physics

- Theoretical studies
- Experimental facility and studies -Purnima laboratories
- Fuel Cycle and Conceptual Design Studies for Th utilization

Naturally available fuel, heavy water moderated ADS, Fast Spectrum ADS, MSBR

Technological Development

- High energy and high current proton accelerator
- Development of 30 mA 20 MeV Linac injector (LEHIPA)
- Development of High energy Linac (1 GeV)
- Spallation target and materials
- • Thermal hydraulics computational tools development for LBE target simulations.
- Experimental loops for validation of thermal hydraulics codes and corrosion studies on window materials.

Why an experimental facility for ADS?

What is Different in subcritical Physics?

The Physics and Technology of ADS is quite different from that of critical reactors.

- **Role of K_{eff}** - **The power in an ADS is very sensitive to the value of k_{eff} , - accurately predict this parameter over the entire length of the burnup cycle.**

- **Source Importance: unlike critical reactor , where only source of neutron is fission neutron, sub critical neutrons have additional source neutrons which have different spatial and energy distribution . This distribution changes from generation to generation. – concept of a new term K_s besides K_{eff}**

- The stationary **spatial flux distribution** and the neutron spectrum in ADS is different from critical reactor

- The **dynamic response** of ADS to transients and perturbations are quite different from that of the critical reactors.

Challenges in measurements

- **In a subcritical reactor, measurement of reactivity based on source multiplication can be contaminated by higher modes. To extract true k_{eff} from these measurements can be a challenge.**

- **Conventional methods of reactivity determination may not correctly predict true values and since in sub critical system power depends on this parameter , development of accurate methods are needed.**

- There are several methods of measurement of subcriticality- **neutron source multiplication method (NSM), pulse neutron method, stochastic methods such as Feynman-alpha or Rossi-alpha and frequency analysis method by Mihalczo.**

- **These methods have to be changed for subcritical system** particularly for source dominated **deep subcritical systems**. Noise measurement techniques are **based on assumption of Poisson Distribution of source neutr**on – this may not be valid for source driven systems

Simulation Experiment

- Physics Demonstrator
  - Zero Power

(simulate ADS using a variety of neutron sources D-D, D-T, isotopic, photoneutron, coupled to small thermal or fast subcritical assembly)-understand & validate measurement techniques

- Technology Demonstrator
  - High Power

Major Components of Source Driven Purnima Subcritical Assembly

The strategy adopted for design first Experimental ADS was to keep subcritical system as simple and clean as possible, avoid major safety issues and couple it to existing neutron generator with modification of pulsing etc.

The idea has been to learn and build capability in subcriticality measurement and other ADS relevant techniques at various level of criticality using a simple and clean design.

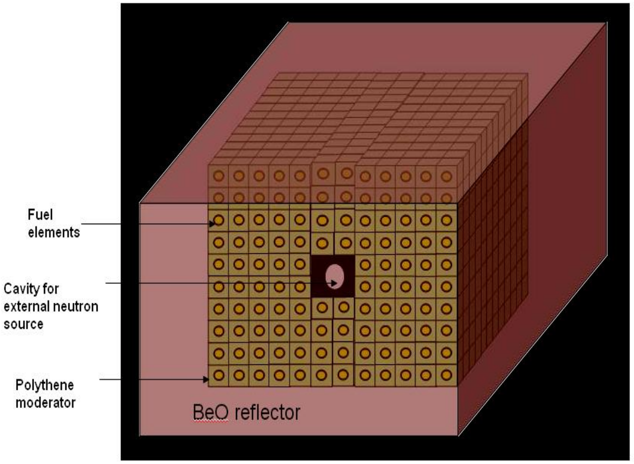
Proposed Stages of Program –

1. Design with natural Uranium –High Density Polyethylene (HDPE) Keff ~ 0.89)

Future Proposals

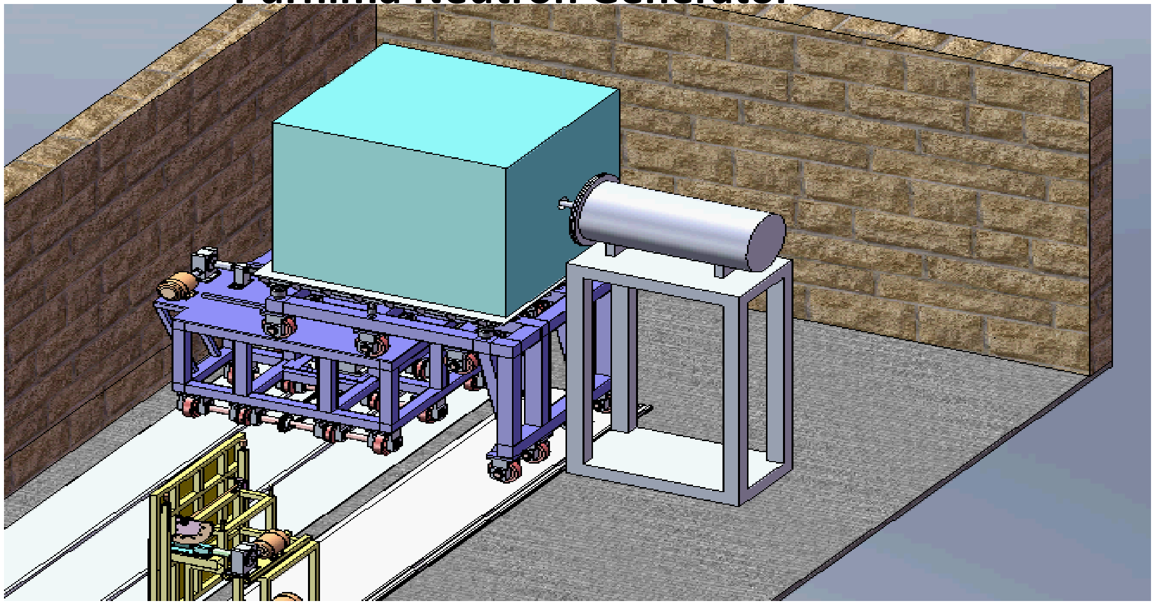
2. Upgrade Design with enhanced Keff
3. work on Fast ADS

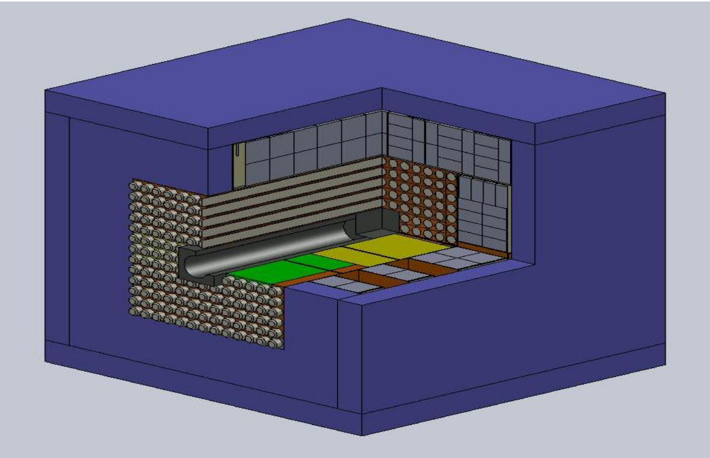
Components of Experimental ADS



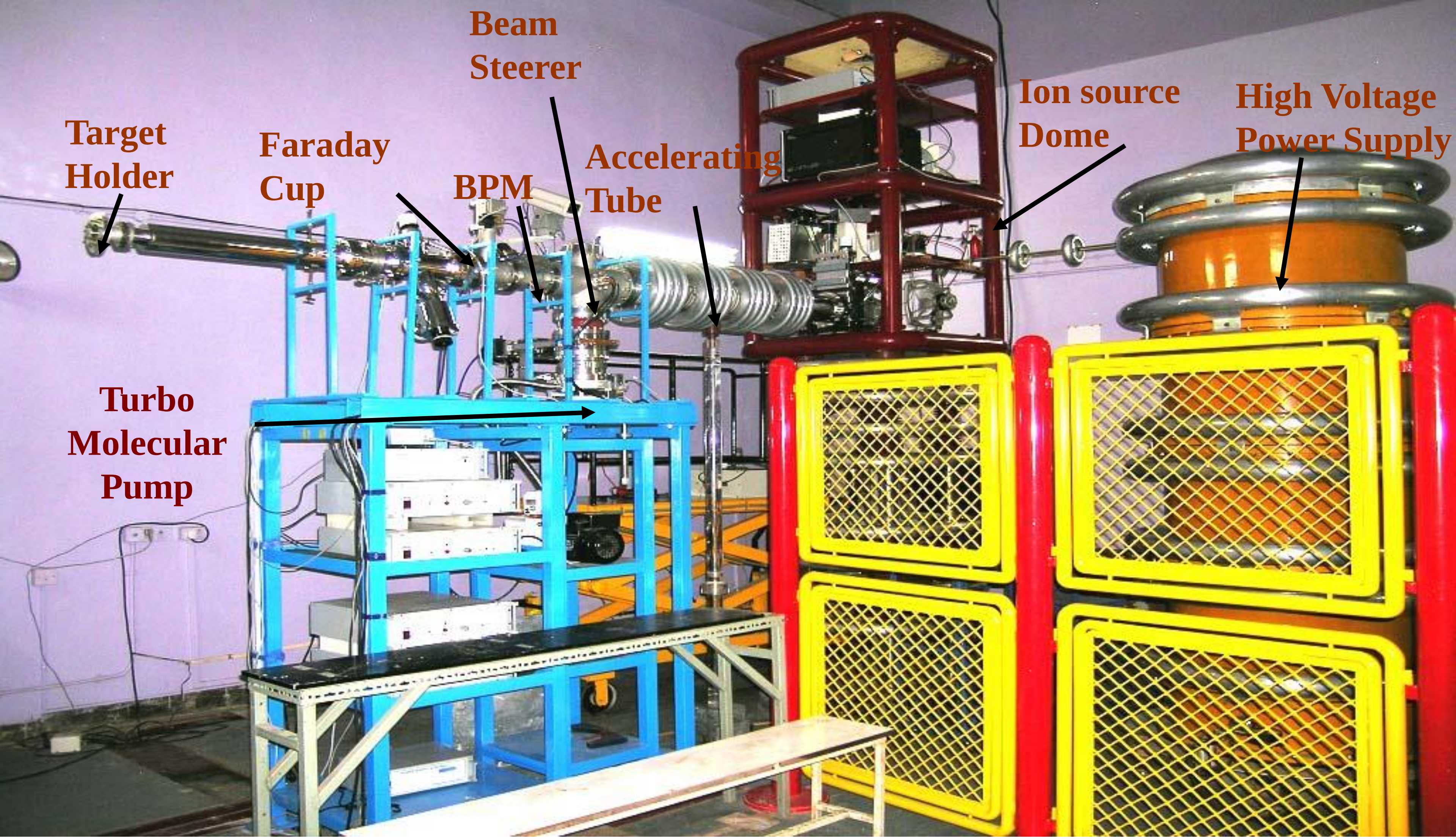
3D view of geometry used in Keff calculation

Purnima Neutron Generator





Modular Subcritical Core



Neutron Generator at Purnima Hall

D-D & D-T

Neutron Generator

- Neutron Generator >10^{10} n/s

- Can operate in both DC mode and Pulsed mode

- Pulsed mode 20 µs – ms to s (programmable)

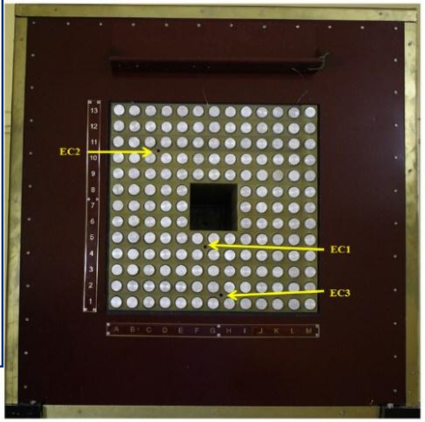
  rep rate 1Hz to KhZ

NEXT: SUBCRITICAL FACILITY

BRAHMMA

BeO Reflected And HDPE Moderated Multiplying Assembly

- Thermal ADS
- Natural uranium fuel with High density Polyethylene moderator and Beryllium oxide reflector
- 13 X 13 matrix with 160 fuel rods
- $k_{eff} \sim 0.890$
- Coupled to Purnima Neutron Generator (D-D / D-T)

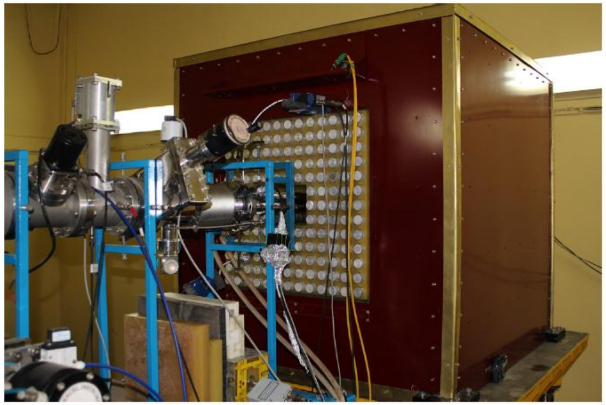


Features:

- Modular & compact
- Can be reconfigures for different core configuration
- No pressurized fluid
- No thermal effects
- Possibility of using different fuel configurations
- Testing of Codes developed for performing Noise studies

in deep subcritical system for a non-Poisson source.

It is a Deep Subcritical System using Natural uranium as fuel which is being used to study and validate codes already developed by BARC scientists. We are testing our reactivity measurement techniques experimental as well as data analysis part.

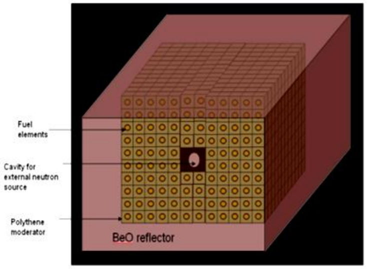


BRAHMMA Subcritical Facility

- The present facility at Purnima is a zero-power Experimental ADS
- Useful as a surrogate for investigating many of the physical characteristics and potential applications of high-power, full-scale ADS systems that are under design but remain to be built.
- Unique feature is its design is similar to “Chicago Pile” of Fermi.
- Unique feature is use of High Density Polyethylene (HDPE) as moderator
- UNIQUE feature is use of BeO as reflector in any subcritical system to make a system in less fuel
- Unique feature is its modular design which may permit increasing Keff

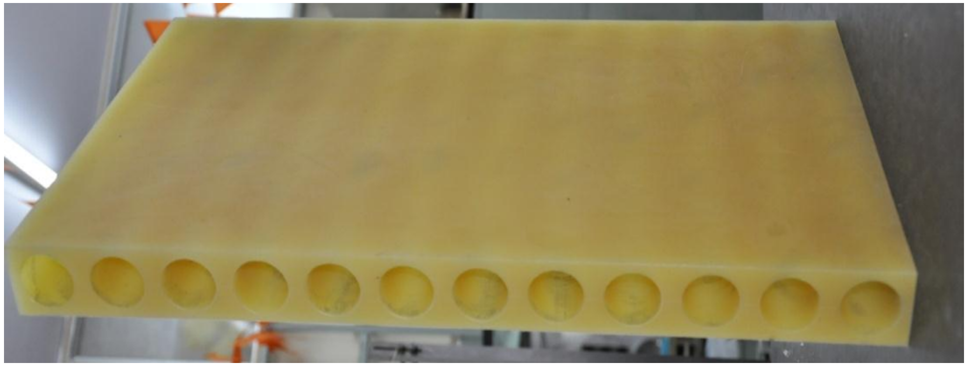
Polyethylene moderated – BeO reflected – natural uranium fuel

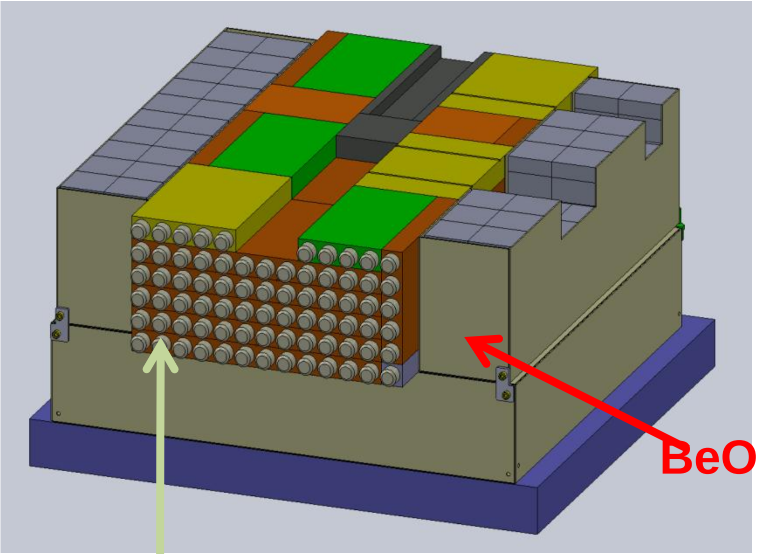
$K_{eff} = 0.890$ can be upgraded for higher Keff

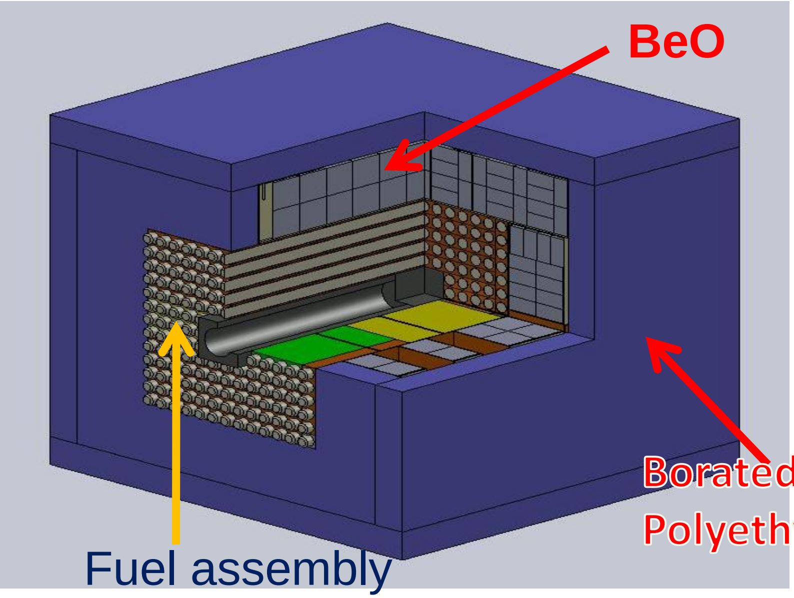


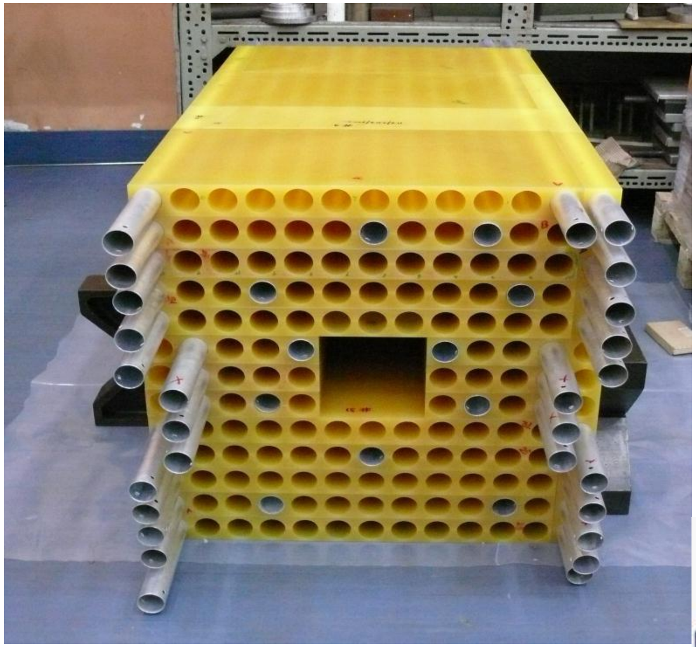
3D view of geometry used in Keff calculation

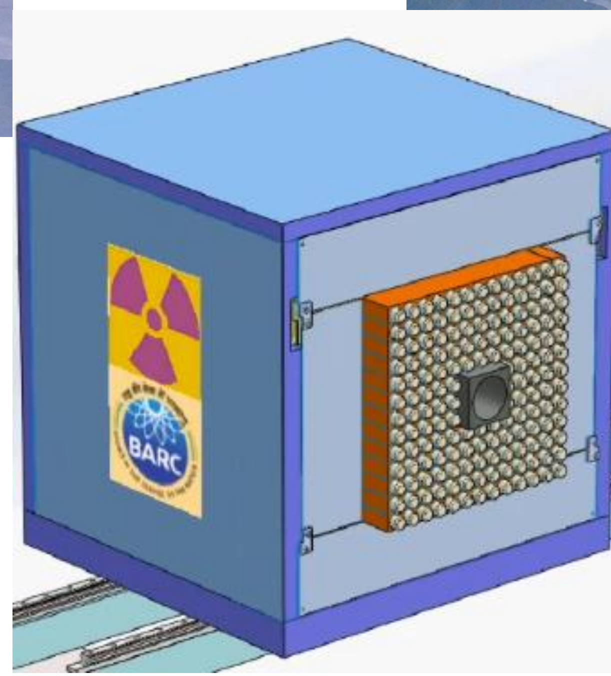
➢ **Modular structure** – can be easily assembled/disassembled with no sub-module weighing more than 500 kg





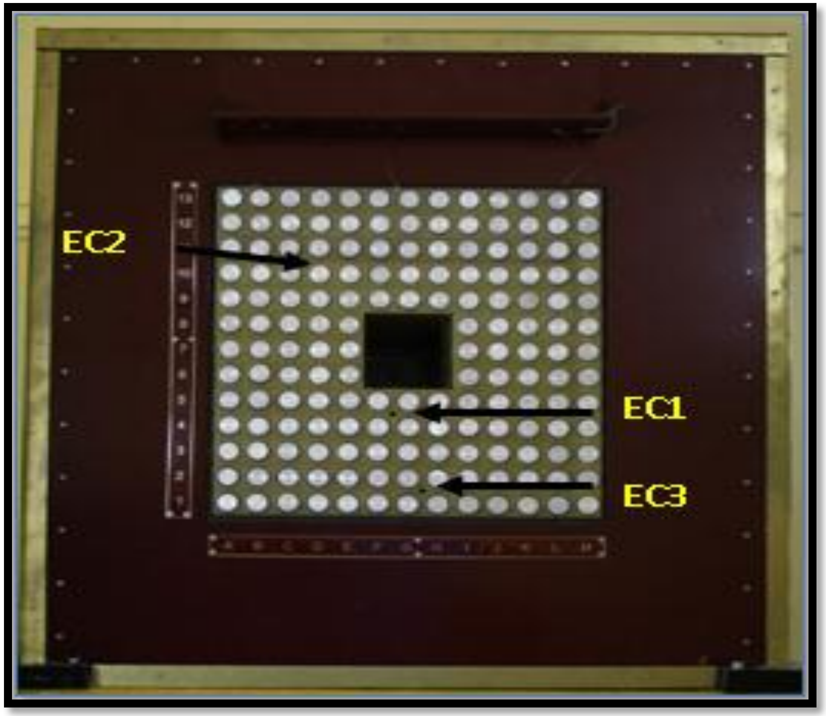





BARC

BRAHMMA- Experimental Channels

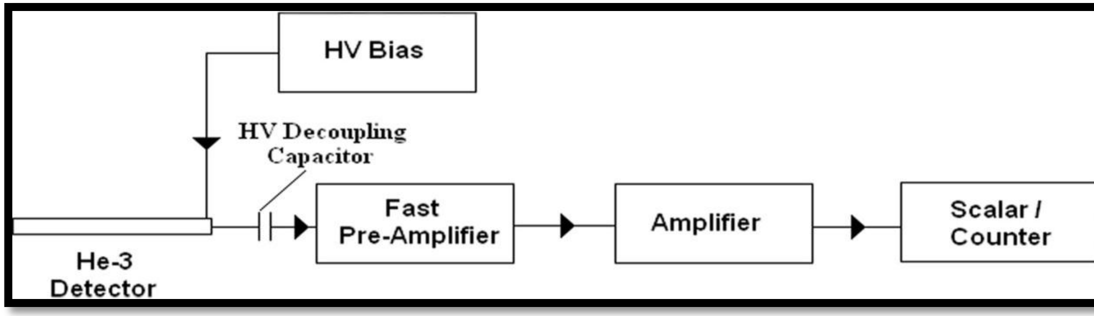
- 7 experimental channels
- 3 Axial (diameter 10mm) EC1, EC2 &EC3 located at a radial distance of 122mm, 238mm and 265 mm
- 4 Radial (diameter 7.2 mm) EC5, EC6 & EC7 located in mid elevation plane run upto cavity, EC4 located above mid elevation plane and covers full length of moderator

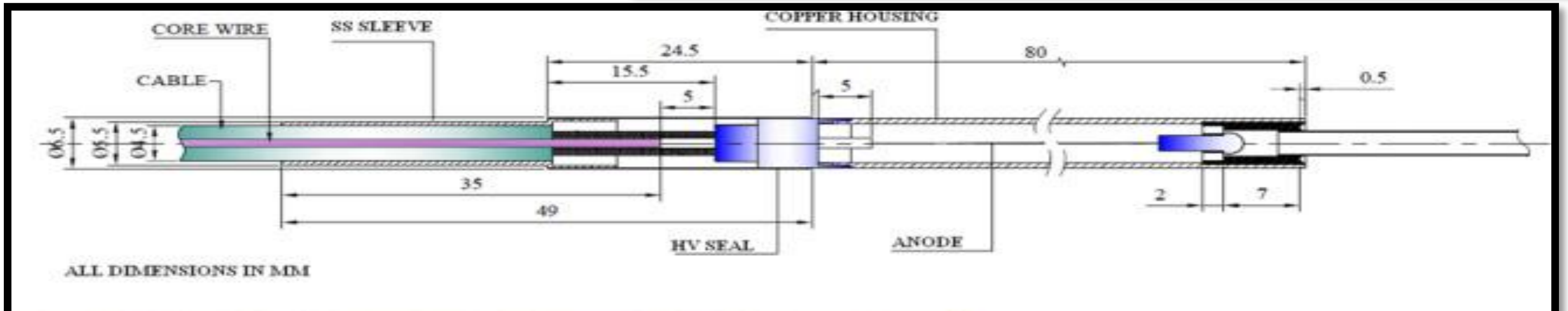


Ref: "BRAHMMA: A compact experimental accelerator driven subcritical facility using D-T/D-D neutron source", Amar Sinha, Tushar Roy**,** et al; ***Annals of Nuclear Energy,*** 75, 590–594 **(2015)**

Miniature He-3 Detectors developed for measurements in experimental channels

- Experimental channels in subcritical assembly were very narrow
- Miniature He-3 detectors were developed for measurements.





Neutron spatial flux profile measurement in compact subcritical system using miniature neutron detectors
Nuclear Instruments and Methods in Physics Research A, 772, 118–123 **(2015)**

Experimental Measurement with BRAHMMA

Reactivity measurements

- **Pulsed neutron techniques (Area Ratio method, Slope Fit method, Source-jerk)**
- **Noise measurements (Feynman-α, Rossi-α)**

Spatial correction for modal effects

K-source Measurements

- **Measurement of Source multiplication**

Fundamental mode extraction

- **Noise measurements (new technique for suppression of higher harmonics)**

Development of special detectors to be used for measurements

- **Miniature He-3 gas filled detectors**
- **Optical fiber detector**

Flux measurements

- **Axial and radial flux profile measurement in various experimental channels**

PNS Measurements

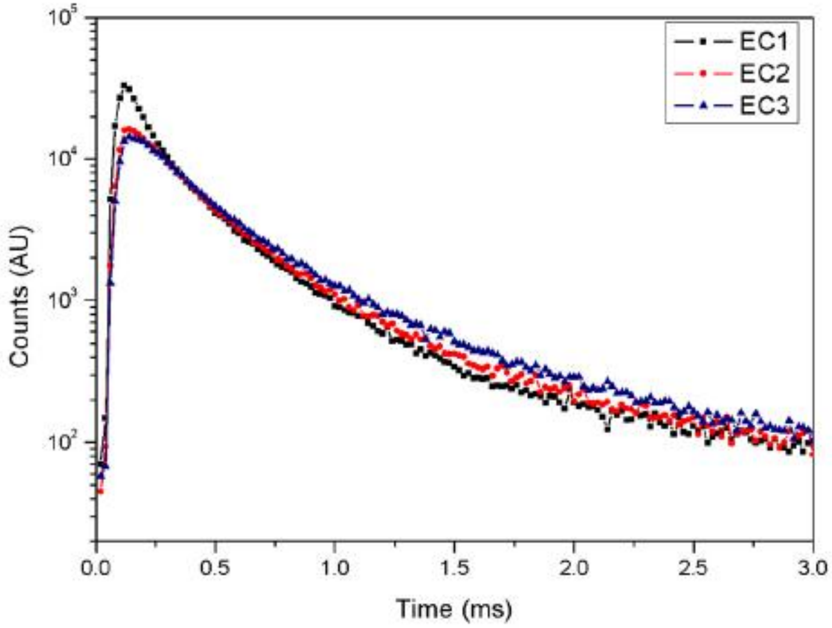
➢ **Pulsed Neutron Source Techniques**

✓ Area Ratio Method
✓ Source Jerk Method
✓ Slope Fit Method

Area Ratio Method /Sjostrand Method

- Several neutron pulses are injected in the system. After a large number of neutron pulse an equilibrium level of delayed neutron precursors is obtained in the system.
- The decay of the neutron flux with time is measured by ^{3}He detector and histogram is plotted.
- Reactivity is obtained by the ratio of the prompt and delayed areas

$$\rho \text{ (in \$)} = - A_{prompt} / A_{delayed}$$

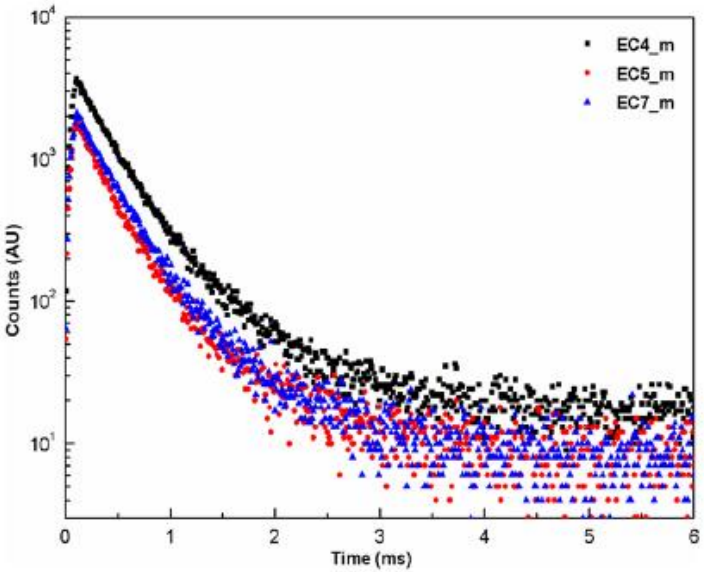


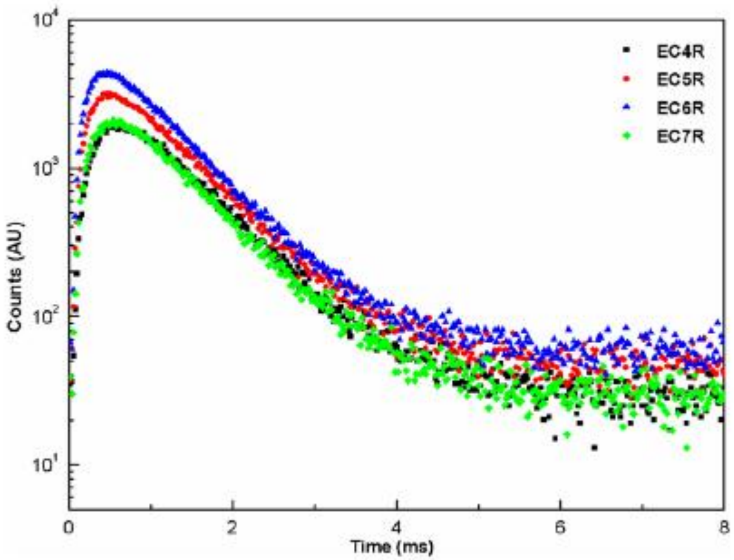
PNS histogram (core)

Slope Fit Method

The prompt decay constant ***α*** may be obtained from the slope of the prompt part in the PNS histogram.

$$\alpha = (\rho - \beta_{eff})/\Lambda$$





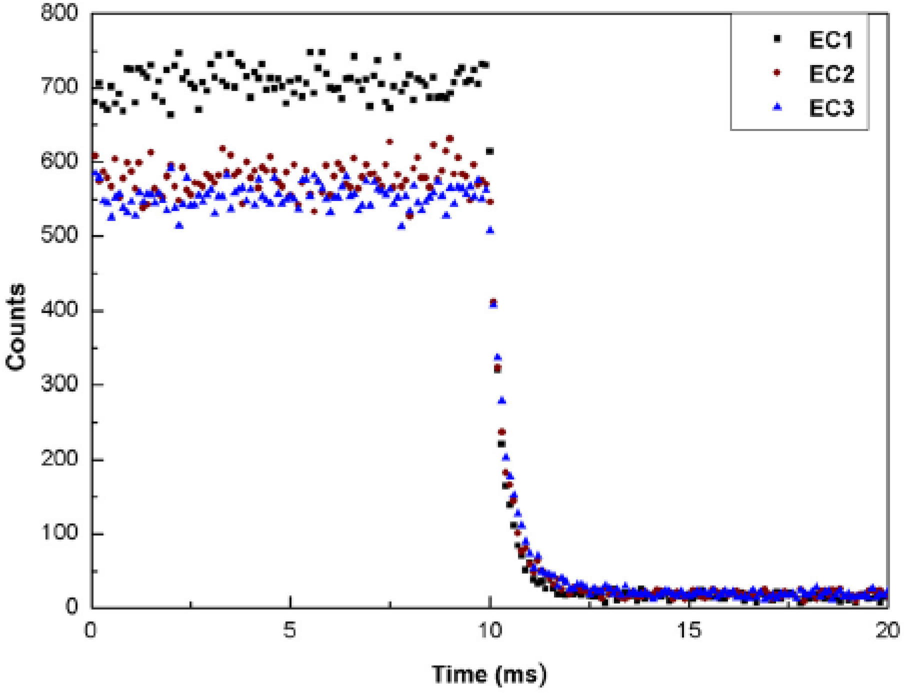
Measured α and k_{eff} Values in Axial Experimental Channels

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

Source Jerk Method/ Beam Trip Method

- Source is operated in a steady state - steady state flux n_0
- The source is switched off (Beam Trip)
- Prompt jump of the flux to lower level n_1
- Reactivity is obtained as

$$\rho \text{ (in \$)} = (n_1 - n_0)/n_1$$



PNS histogram (core)

Area Ratio Method /Sjostrand Method

Technique	Detector Location	ρ^{meas} ($)	Spatial Correction Factor	ρ^{corr} ($)	k_{eff}^{corr}
Area ratio	EC1	−28.03	0.62 ± 0.02	−17.38 ± 0.56	0.886 ± 0.003
	EC2	−19.04	0.92 ± 0.03	−17.52 ± 0.57	0.885 ± 0.003
	EC3	−16.61	0.99 ± 0.04	−16.44 ± 0.66	0.891 ± 0.004
	EC4R	−12.10	1.28 ± 0.05	−15.49 ± 0.60	0.897 ± 0.004
	EC5R	−16.25	1.00 ± 0.04	−16.25 ± 0.65	0.892 ± 0.004
	EC6R	−14.99	1.11 ± 0.04	−16.64 ± 0.59	0.890 ± 0.004
	EC7R	−12.59	1.38 ± 0.05	−17.37 ± 0.62	0.886 ± 0.004

Ref: "Pulsed Neutron Source Measurements in BRAHMMA Accelerator Driven Subcritical System", Tushar Roy, et al, ***Nuclear Science & Engineering***, 184,584-590 **(2016)**

Ref: "Experimental subcritical facility driven by D-D/D-T neutron generator at BARC, India", Amar Sinha , **Tushar Roy**, et al; ***Nuclear Instruments and Methods in Physics Research B,*** 350, 66-70 **(2015)**

Ref: "Reactivity measurement using Area-Ratio Method in BRAHMMA subcritical system", Nirmal Kumar Ray, Tushar Roy, **et al;** ***Nuclear Technology***, 197, 110-115 **(2017)**

Spatial Correction Factor

Why ??

- Reactivity of a subcritical assembly measured by PNS techniques is spatially dependent.
- To remove this spatial dependence ⟶ correct the measured reactivity by a spatial correction factor.
- We are basically obtaining global reactivity from the measured local reactivity
- The Bell and Glasstonne Spatial Correction factor for Area Ratio Method may be evaluated using following expression.

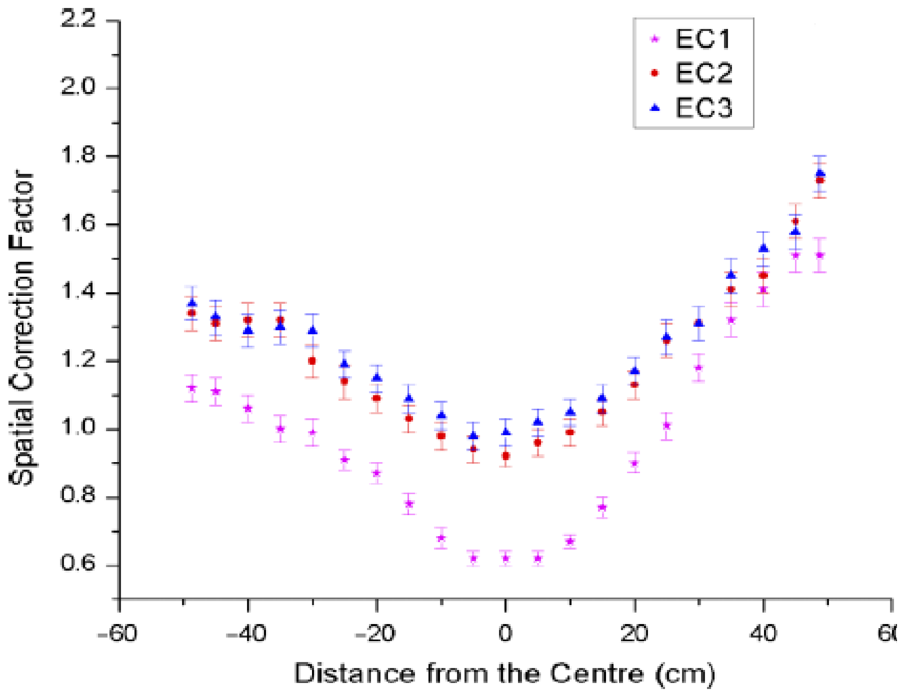
$$f = \left(\frac{\rho_{cri}}{\rho_{src}}\right) = -\left(\frac{A_d}{A_p}\right)\left(\frac{1}{\beta_{eff}}\right)\left(\frac{1-k_{eff}}{k_{eff}}\right)$$

Prompt area has contribution both from fission and source neutrons while delayed area has contribution only from source neutrons.

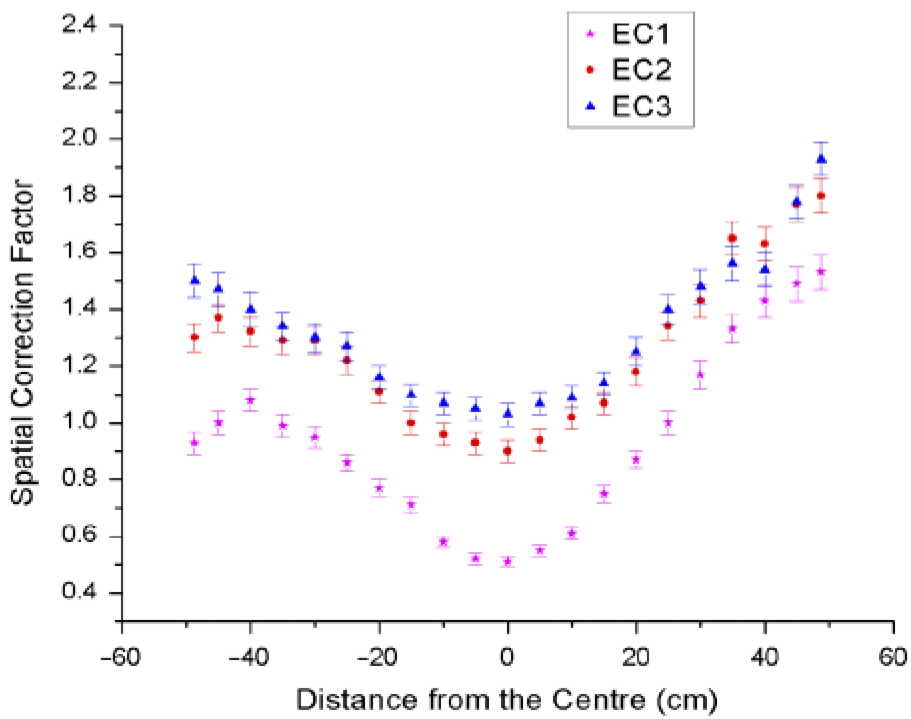
So close to the source where the contribution of source neutrons to prompt area is more value of f is less

Spatial Correction Factor

Axial variation



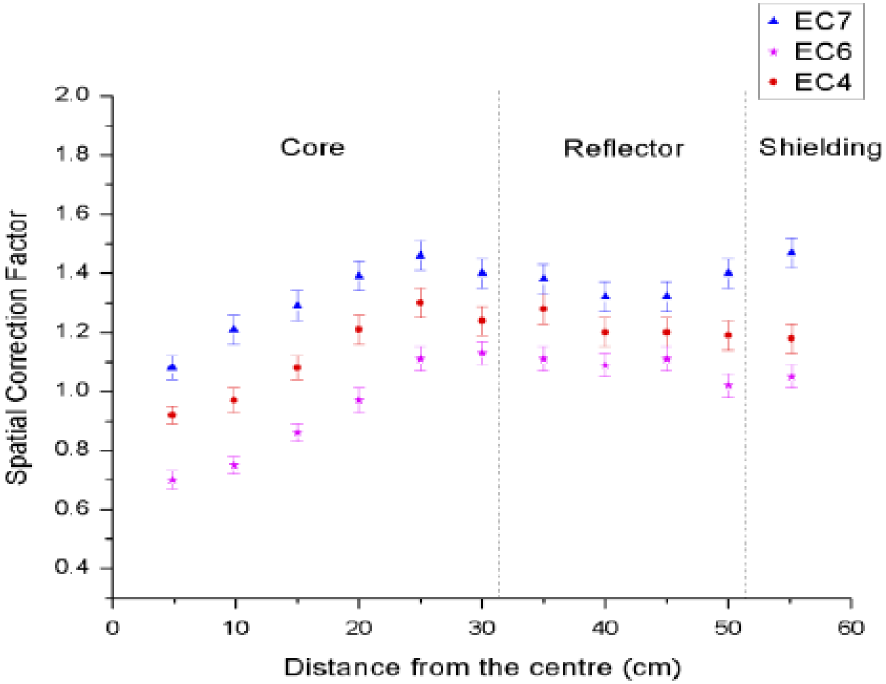
D-T source



D-D source

Spatial Correction Factor

Radial variation



D-T source

Ref: "Evaluation of Spatial Correction Factors for BRAHMMA Subcritical Assembly", Shefali Bajpai, Tushar Roy, et al; ***Nuclear Science and Engineering*, 181**, 361–367 **(2015)**

Noise methods

- Do not require pulsing or switching off
- Can also work if source is pulsed
- Use of the following methods has been reported
    - Feynman alpha
    - Rossi alpha
- Other possible methods
    - auto and cross correlation
    - Psd and cpsd methods
- All methods possible by
    - By recording time history of detection events
    - Off line analysis
- Difficulty
    - High degree of sub-criticality
        - High efficiency requirement
        - Contamination from higher modes
- Simulator Development and results of simulation

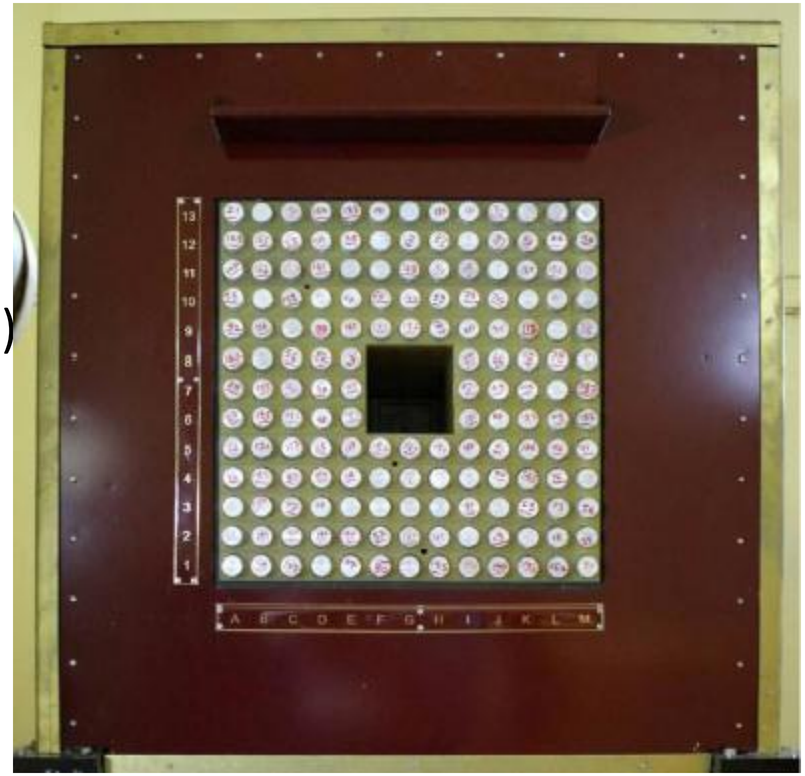
Reactor Noise in ADS: New Theory

- **Radioactive sources are Poisson sources due to**
  - Large number of radioactive atoms
  - Relatively small number decay independently
- **Accelerator sources are different**
  - Pulsing
  - CW accelerators
  - Fluctuations in intensity
    - Typically a few per cent
    - For Poisson source of 1e8 strength should be only 0.01%
  - Correlations in these fluctuations
- **And are therefore non-Poisson sources**
- **The difference is important in the interpretation of noise based measurement**
- **Requires a new theory**

Fundamental mode extraction by cancellation of higher modes

A total of 8 detectors

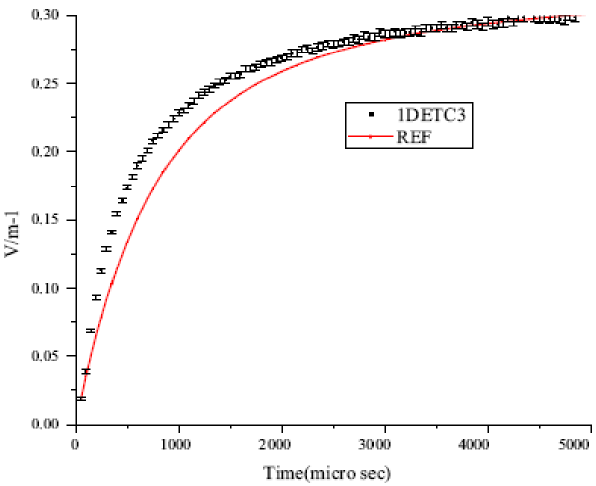
2 detectors each located at four lattice positions
B7, L7, G2, G12 (radial locations)
1/3rd from mid-plane on either side (axial locations)



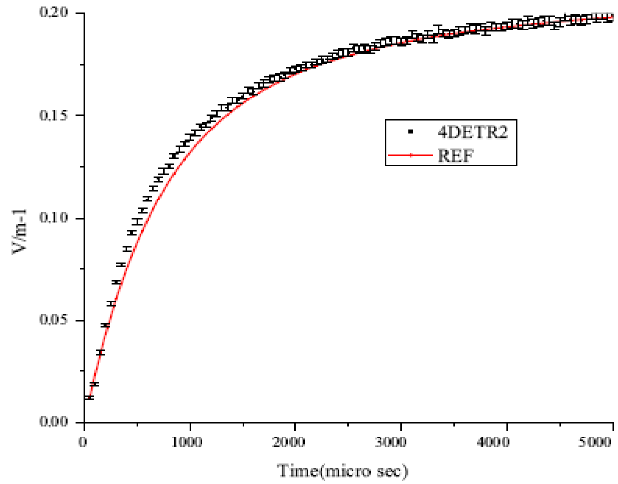
Noise measurements

Time-stamped data from all 8 detectors combined was used for experimental measurements

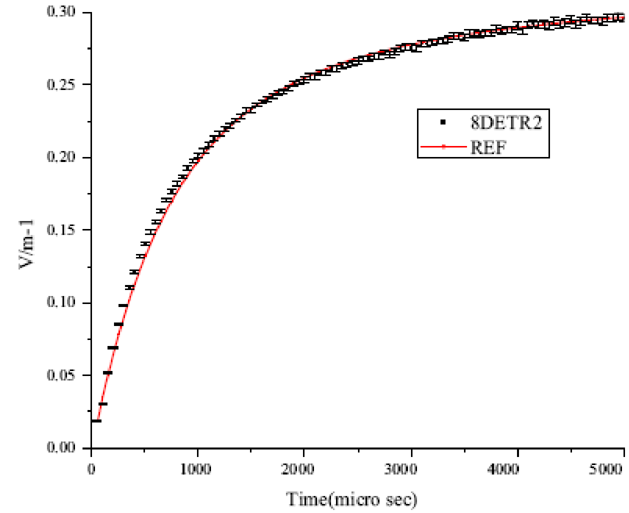
Feynman-alpha measurements



Single detector



4 detectors



8 detectors

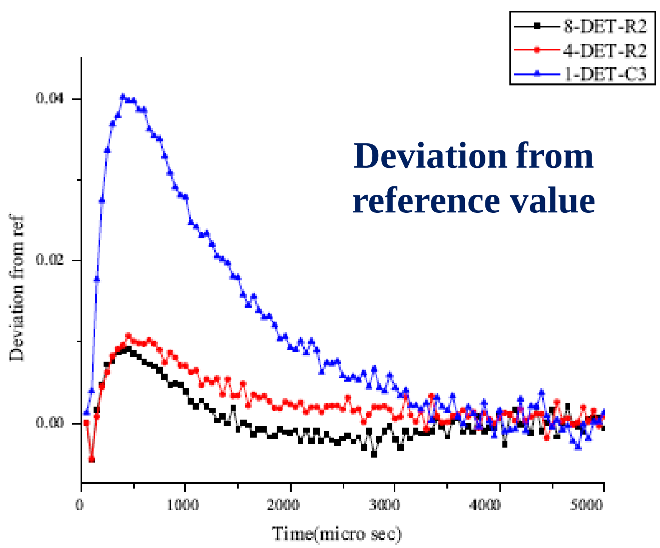


Fig. 9. Deviation of Feynman alpha curves from reference for all sets of the experiment.

Comparison between calculated and measured value of prompt neutron decay constant.

Exp. set	Prompt neutron decay constant α (m sec^{-1})		
	Auto correlation	Feynman Alpha	Reference
8 DET-R1	2.58 ± 0.056	2.62 ± 0.023	2.31
8 DET-R2	2.44 ± 0.068	2.46 ± 0.027	
4 DET-R2	2.70 ± 0.082	2.66 ± 0.025	
1 DET-C3	3.11 ± 0.145	3.58 ± 0.44	

List of important Publications on BRAHMMA subcritical system designed & developed in India

1. . **BRAHMMA: A compact experimental accelerator driven subcritical facility using D-T/D-D neutron source**- Amar Sinha, Tushar Roy, Yogesh Kashyap, Nirmal Ray, Mayank Shukla, Tarun Patel, Shefali Bajpai, P.S. Sarkar, S.Bishnoi, P.S. Adhikari-***Annals of Nuclear Energy***, **75**, 590–594 **(2015)**

2. **Reactivity measurement using Area-Ratio Method in BRAHMMA subcritical system**
Nirmal Ray, Tushar Roy, Shefali Bajpai, Tarun Patel, Yogesh Kashyap, Mayank Shukla and Amar Sinha-***Nuclear Technology***, **197**, 110-115 **(2017)**

3. **Measurement of Reactivity in a Source Driven Deep Sub-critical System using Neutron Noise Methods**-Rajeev Kumar, S.B.Degweker, Tushar Roy, K.P.Singh, Sudipta Samanta, Shefali Bajpai, Nirmal Ray, M.Yakub Ali, Tarun Patel, Mayank Shukla, Amar Sinha
Annals of Nuclear Energy, **103**, 315–325 **(2017)**

4. **Pulsed Neutron Source Measurements in BRAHMMA Accelerator Driven Subcritical System**
Tushar Roy, Nirmal Ray, Shefali Bajpai, Tarun Patel, Mayank Shukla, Yogesh Kashyap, Amar Sinha and S.C. Gadkari-***Nuclear Science & Engineering***, **184**,584-590 **(2016)**

5. **Evaluation of Spatial Correction Factors for BRAHMMA Subcritical Assembly** Shefali Bajpai, Tushar Roy, Nirmal Ray, Yogesh Kashyap, Mayank Shukla, Tarun Patel and Amar Sinha
Nuclear Science and Engineering, **181**,361-367 **(2015)**

6.**Neutron spatial flux profile measurement in compact subcritical system using miniature neutron detectors**- Mayank Shukla, Shraddha S Desai, Tushar Roy, Yogesh Kashyap, Nirmal Ray, Shefali Bajpai, Tarun Patel, Amar Sinha
Nuclear Instruments and Methods in Physics Research A, **772**, 118–123 **(2015)**.

7. **Experimental subcritical facility driven by D-D/D-T neutron generator at BARC, India**
Amar Sinha , Tushar Roy, Yogesh Kashyap, Nirmal Ray, Mayank Shukla, Tarun Patel, Shefali Bajpai, P.S. Sarkar, Saroj Bishnoi-***Nuclear Instruments and Methods in Physics Research B***, **350**, 66-70 **(2015)**

Next stage of subcritical System

- BRAHMMA – Thermal ADS Nat U-keff 0.89

- **Proposals to**
  - **(a) increase- keff in thermal system**
  - **(b) FAST ADS**

Technological development in India for ADS

- Accelerator
- Target development

Accelerator Development

Scheme for Accelerator Development for ADS

LEHIPA

High current injector 20 MeV, 30 mA

Proton IS 50 keV → RFQ 3 MeV → DTL 20 MeV

Phase 1

Design completed & fabrication is in progress

Normal Conducting: DTL/ CCDTL

Phase II

Super-conducting

200 MeV → Phase III: SC Linac

1 GeV

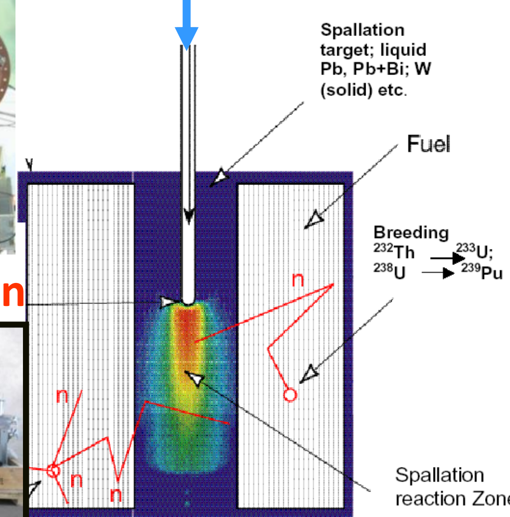
Proton beam from high power accelerator

ECR Ion Source

LEBT

RFQ

Drift Tube Linac



50 kW RF Coupler

60 kW RF System

1.3 MW Klystron

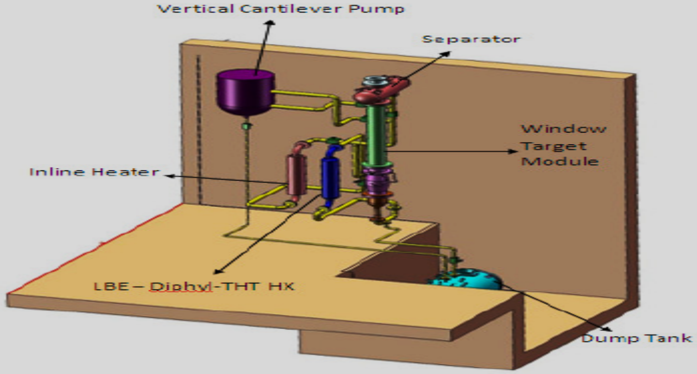
Ref: P. Singh-www.iuac.res.in/event/ijschool/17/psingh.pdf

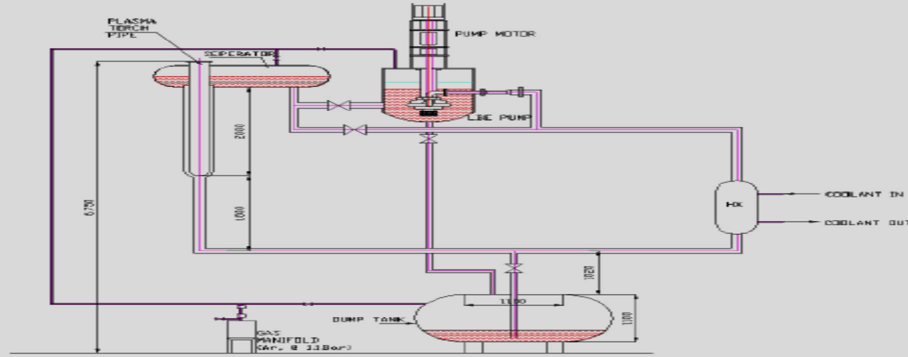
Target Development

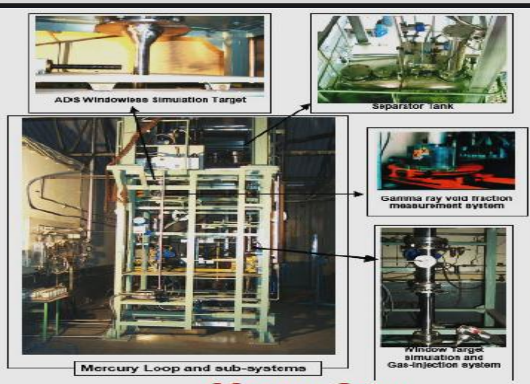
Experimental LBE Loop Facility

For Experiments on:

- Validation of thermal hydraulics code for HLM circulation.
- Pump driven 120 Kg/s LBE flow operation @ 350ºC max.
- Beam heating simulations by plasma torch or Electron beam.
- Corrosion tests- flowing HLM on samples- SS 316, T91.
- Active online oxygen monitor development.







Mercury Loop

- Simulation of Window/Windowless Target
- Velocity field mapping by UVP monitor
- Carry-under studies
- Two-phase flow studies by Gamma Ray
- Laser-triangulation for free surface measurement
- CFD code validation
- Gas-driven flow studies

LBE Corrosion Loop

Height ….. ~ 7m
Flow Rate ….. ~1.7 kg/s
Temp ….. : 550ºC and 450ºC
Velocity in the Samples : 0.6 m/s
Corrosion Tests : Charpy and tensile tests after 3000 hrs in the flow

Experimental set ups on target technology

Ref: S.B.**Degweker**, Pitambar Singh, P.Satyamurthy and Amar **Sinha**.-, International Thorium Energy Conference October 27-31, 2013 CERN in Geneva, Switzerland

Summary & Conclusion

1. Indian Nuclear Energy Programme & Role of ADS

2. ADS has exclusive niche for utilization thorium besides burning Transuranic waste

1. Transmuting transuranic (TRU) elements in the spent fuel

2. **Sustainability of nuclear power: Excess neutron in spallation breeds fissile fuel ^{233}U from thorium**

We have highlighted role of ADS in India Nuclear Programme and work being carried out in this direction

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