Accelerator Driven Systems for Th Utilisation in India: Physics Studies and Developments

S.B.Degweker, Anil Bajpai, Arun Singh, Biplab Ghosh and Y.S.Rana

Theoretical Physics Division

Bhabha Atomic Research Centre, Mumbai, India

2nd International Workshop on ACCELERATOR-DRIVEN SUB-CRITICAL SYSTEMS & THORIUM UTILIZATION

December 11-14, 2011

ADS Program Objectives: Th utilisation

- World Nuclear Scenario
  - Plenty of U available
  - Large fissile Pu availability
    - Little incentive for breeding
  - Large waste volumes
    - Strong incentive for waste transmutation
  - Little incentive for Th use

- Present Indian Scenario
  - Very limited U availability
  - Small fissile Pu base
    - Strong incentive for breeding
  - Small volumes of waste
    - Less incentive for waste transmutation immediately
    - Likely to change with expected large scale expansion nuclear power program
  - Large Th deposits
    - Strong incentive for Th use
    - Low transuranic waste generation.
  - Three stage program
    - PHWRs: Pu for fast reactors
    - FBRs: Pu and Th breeding
    - Th-U233 fuelled reactors
- ADS can achieve
  - Faster breeding of U233 for use in critical reactors
  - Self sustaining Th-U cycle
  - Simplification of Th utilisation: once through cycle

ADS Reactor Physics: Theoretical activities

- **Computer codes used for ADS studies**
  - **Inhouse development**
    - McBurn: A Monte Carlo Burnup Code
    - BURNTRAN: A transport theory burnup code
    - DIFSUB: Space time kinetics code
    - ATES: 3D transport theory code
  - Other codes (high energy transport)
    - Fluka

ADS Reactor Physics: Theoretical activities

- **Other Theoretical studies on ADS**
  - – Reactor Noise in ADS
  - – Methods for determining alpha modes
    - Useful in deciding detector locations in pulsed neutron and noise experiments for sub-criticality measurement
  - – Noise simulator
    - For planning and analysis of noise experiments
  - – Simulation of pulsed neutron and noise experiments

ADS Reactor Physics studies

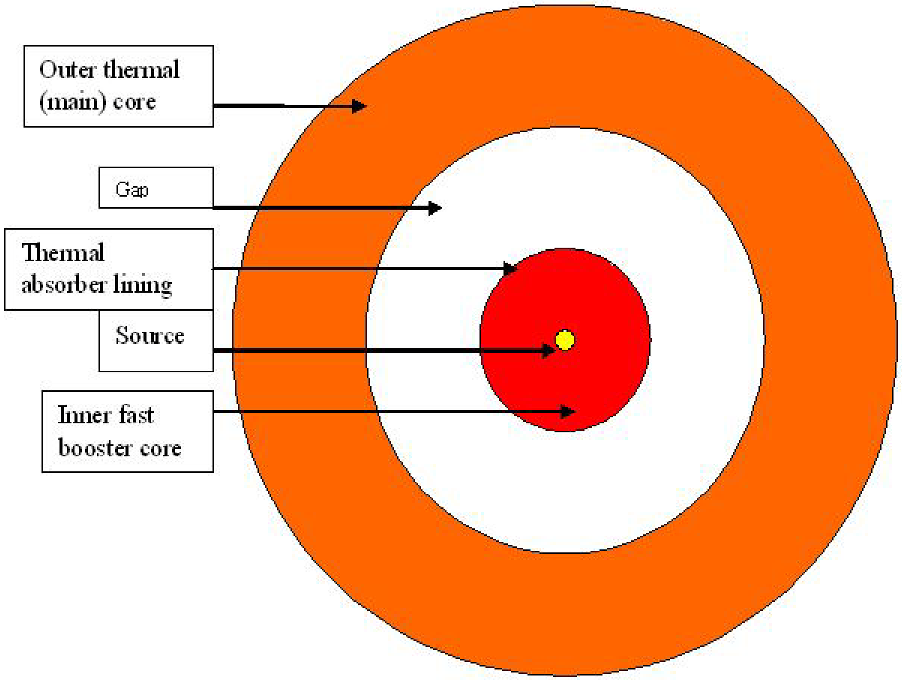
- Studies on Th Utilisation in ADS
  - One-way coupled ADS concept
  - Studies on starting ADS with naturally available fuel
  - Th Utilisation in Heavy Water Moderated ADSs
  - Th Utilisation in fast spectrum ADSs
  - Breeding U-233 in ADSs for use in critical reactors
- Experimental ADS facilities and studies
  - The Purnima Sub-critical facility
  - Proposal For A Sub-Critical Research Reactor Driven By An Electron Linac

ADS Reactor Physics studies

- Studies on Th Utilisation in ADS
  - One-way coupled ADS concept
  - Studies on starting ADS with naturally available fuel
  - Th Utilisation in Heavy Water Moderated ADSs
  - Th Utilisation in fast spectrum ADSs
  - Breeding U-233 in ADSs for use in critical reactors
- Experimental ADS facilities and studies
  - The Purnima Sub-critical facility
  - Proposal For A Sub-Critical Research Reactor Driven By An Electron Linac

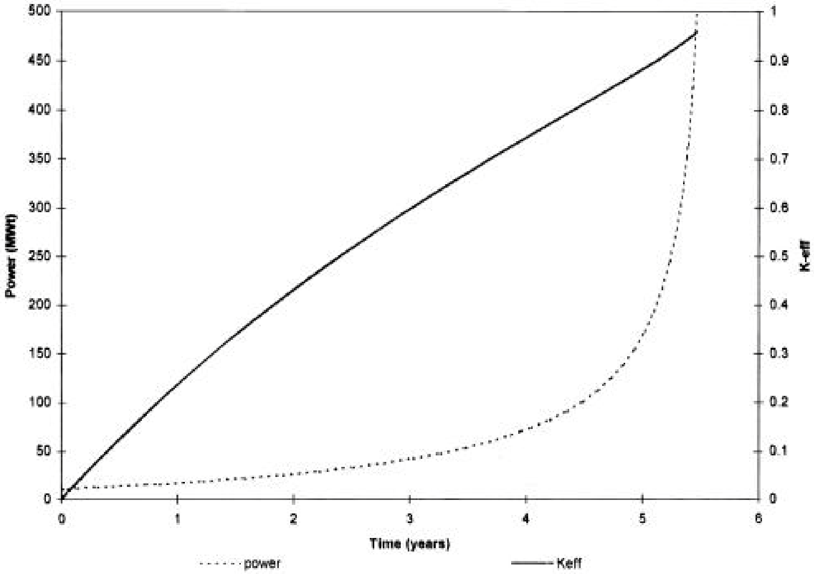
Th Utilisation in ADS: One way coupled ADS

- Power in ADS is inversely proportional to sub-criticality and directly proportional to neutron source strength
- In the control rod free concept, the operating k_{eff} is limited to the range 0.95-0.98
- This requires accelerator beam power of about 10 MW
- The one-way coupled booster-reactor concept can reduce this requirement five fold
  - Inner fast core with source at centre boosts the neutron source
  - These neutrons leak into the outer thermal (PHWR/AHWR) core where they undergo further multiplication
  - This cascade multplication gives very high energy gain
  - Due to the absorber lining and the gap very few neutrons return to the booster – i.e. there is a one way-coupling between the two
  - The one-way coupling ensures that the overall k_{eff} is limited to the desired value
  - Consequently, accelerator power requirement for 750 MW(t) is ~ 1-2 MW
- Similar ideas have been studied in Russia
  - As an example, there is a recent proposal for a waste transmuting ADS driven by an electron accelerator



Th Utilisation in ADS: Starting ADS with pure Th

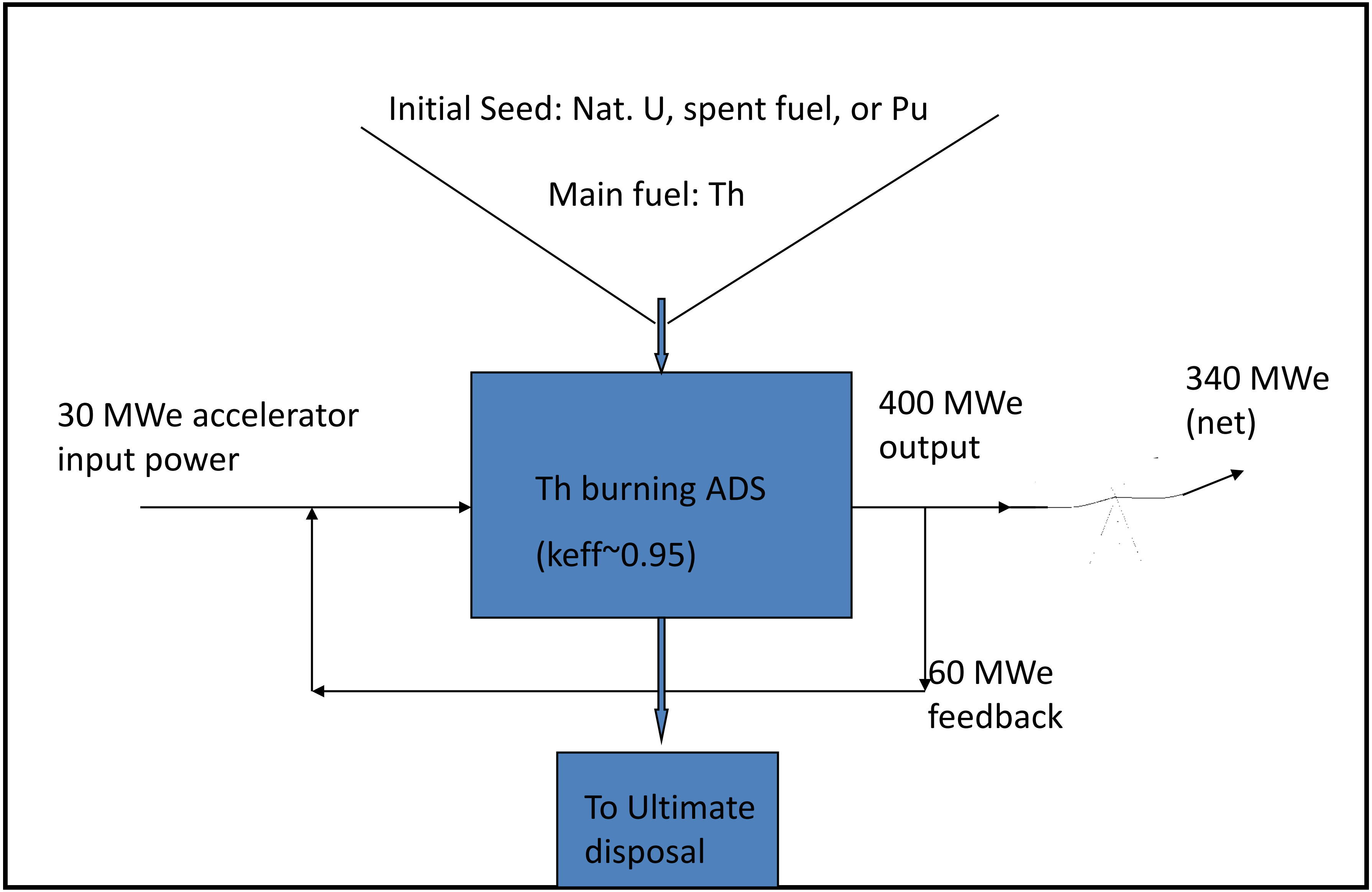
- MSR ADS concepts studied for long at Los Alamos by C.D.Bowman and coworkers
- One such scheme starts with pure Th fuel driven by a modest power (~10MW) proton beam on Pb
- They expected that such a reactor will reach full power of 200 MWe in about one year
- Our studies showed that actually it will take more than 5 years
- If however we use a mixture of Th and U we can get full power from day one
- In heavy water reactors the time required to breed the necessary U-233 is much longer ~ 20 years
- Hence using a mixture of Th and another fuel with a fissile species (say) natural U is more appropriate



$$t = \frac{1}{s}\left[(\eta-1)x + \big((\eta-2)\xi-\lambda\big)\ln\left(1-\frac{x}{\xi}\right)\right]$$

$$k = \frac{\eta x}{x+\xi+\lambda}$$

Th Utilisation in ADS: Th burner concept



Th Utilisation in ADS: Once through Th cycle in PHWR: The thermal Th burner

- Initial fuel: Nat. U & Th
- Normal refuelling of U bundles (say 7 GWd/t)
- Th will reside longer
  - U-233 generation adds reactivity
  - Compensate by replacing some U by Th
- Th increases and U decreases
- Ultimately fully Th core
  - In situ breeding and burning Th
- Advantages
  - Use of natural fuels only
  - 140 tons U consumption during reactor life
  - High burnup of Th ~ 100 GWd/t
- Disadvantage
  - Low K ~0.9 and gain < 20 with Pb target
  - Accelerator power ~ 30 MW for a 200 MWe ADS

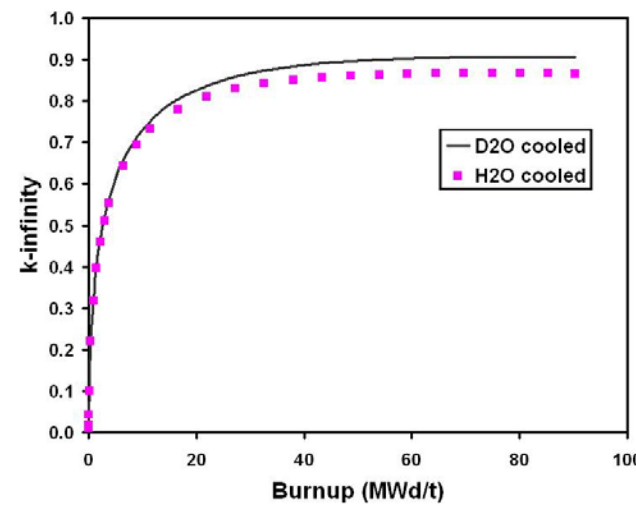
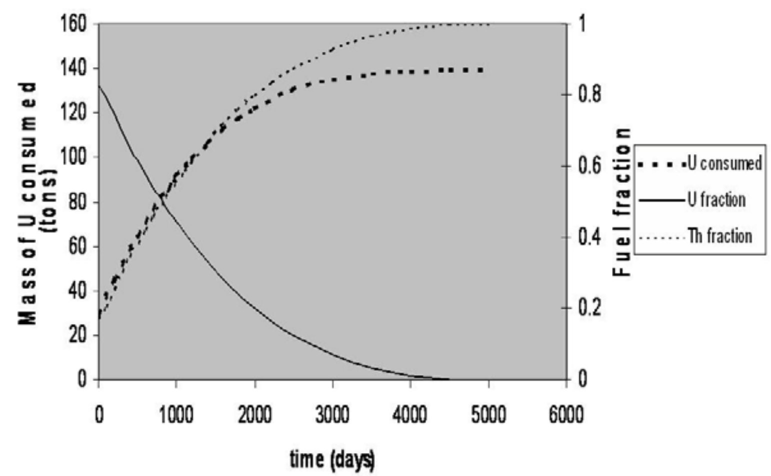
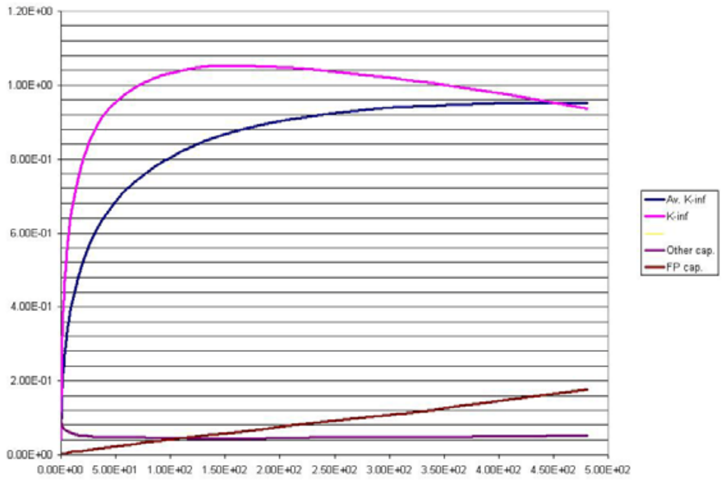


Fig. 4 U and Th fractions in ADSS for 7 GWd/t U burnup



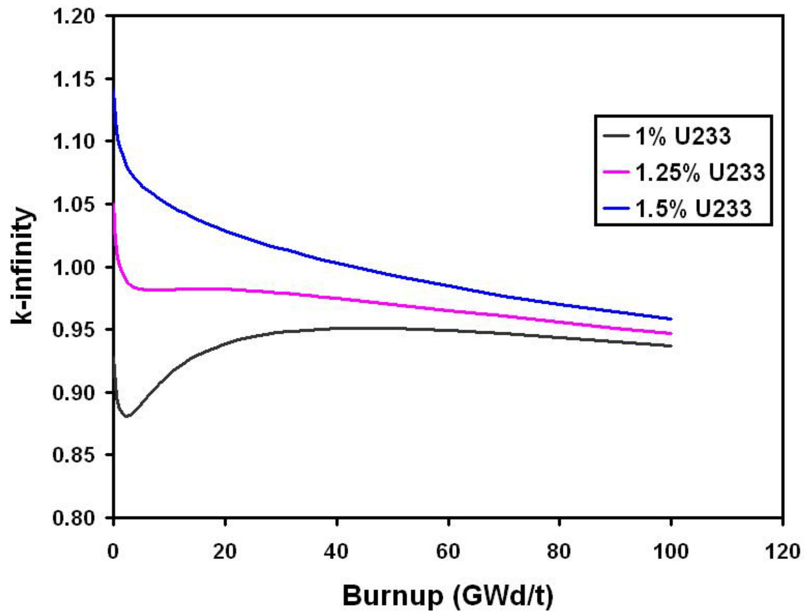
Once through Th cycle: The fast Th burner ADS

- Advantages
  - Good breeding properties of fast reactors
    - Lower parasitic capture on FPs and structures
    - Higher value of $\eta\ \varepsilon$
- Disadvantages
  - Higher U-233/Th ratio required ~ 0.1 [against 0.015]
    - Greater loss of U-233 when fuel is discharged needing higher breeding rate
    - Requires initial fissile charge of fissile material
  - Very long irradiation time and high fluence exposure
- Will need
  - Minimum possible absorption in structures and coolant
  - Higher discharge burnup ~ 400 GWd/t
  - On power fuelling facility with good shuffling
- Metallic fuel gives higher value k~0.95
  - Coolant Na, Pb



Th Utilisation in PHWR ADSs: Recycling

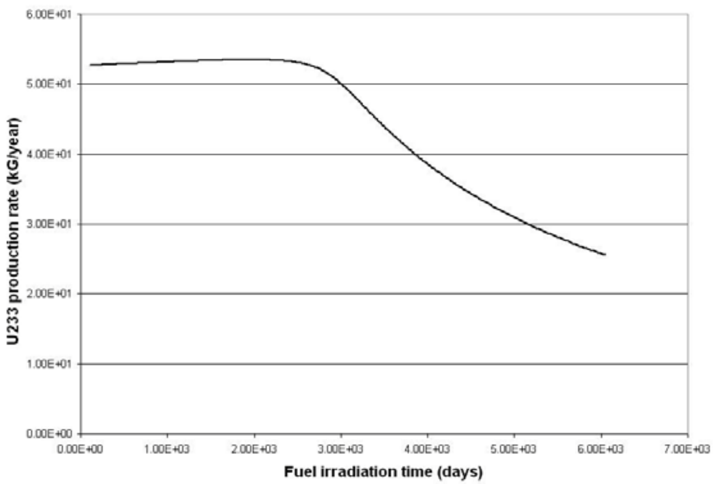
- Self sustaining cycles in Heavy Water Moderated ADSs
  - Very difficult for critical reactors
    - Very low burn-ups
  - For ADS mode PHWR
  - With D2O coolant
    - K~0.95
    - burn-up 50 GWd/t
    - Energy Gain is ~ 40
    - 30 MW beam for 1200 MW(t) reactor
  - Boiling H2O coolant
    - Burnup ~ 23 GWd/t
    - Gain ~ 40
  - Power distribution

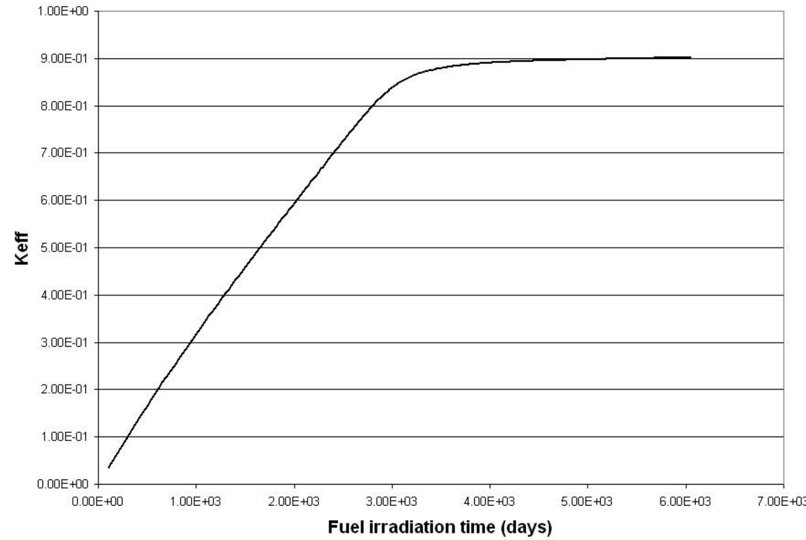


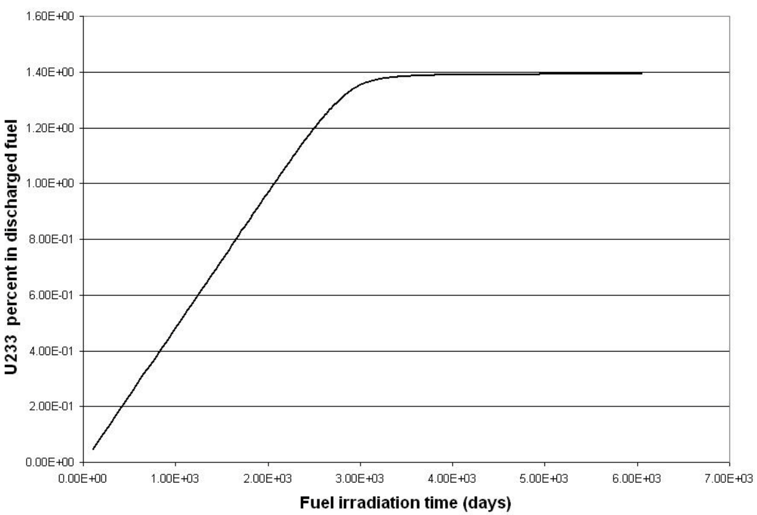
Accelerator breeding of U233 for use in critical reactors

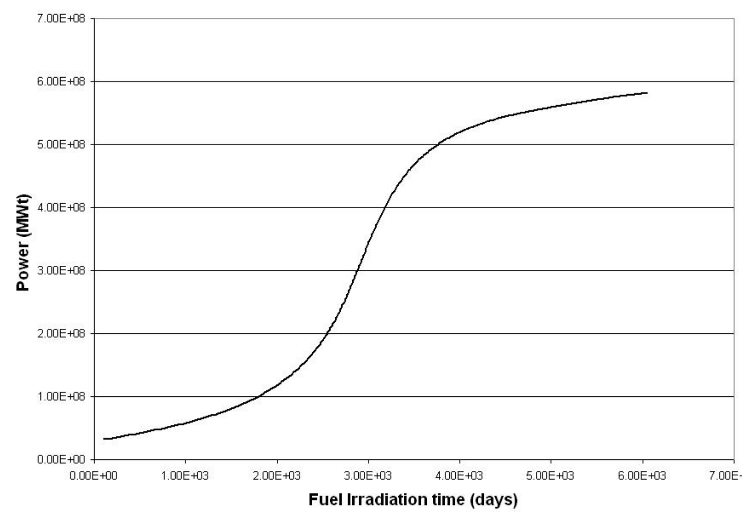
- Energy requirement per neutron
  - Spallation by high energy protons on Pb: 40MeV
  - Photo neutrons using electrons: 2 GeV
  - Clearly favours proton accelerators
- How far do we irradiate Th before discharging?
  - Interesting nonlinear problem with interplay of various factors
    - Loss due to burning of U233
    - Breeding gain due to fission of U233
    - Losses to fission product captures
    - Shows bi-stability in some situations
  - Good choice of irradiation time
    - Power production for accelerator and grid
    - No significant loss of U233 production rate
  - Long irradiation time limit takes us to the Th burner limit
- Compared to thermal systems, fast systems
  - Can go to much higher concentrations of U233
    - Reprocessing costs are reduced
  - Better breeding properties, Lower parasitic capture
  - Higher K
  - Greater power generation in power producing system
  - However longer irradiation times and higher fluence
- Production rate ~ 2kG per mA of 1 GeV p on Pb

U233 production rate, U233 fraction, power, and keff, for thermal blanket driven with 30 MW proton beam on Pb

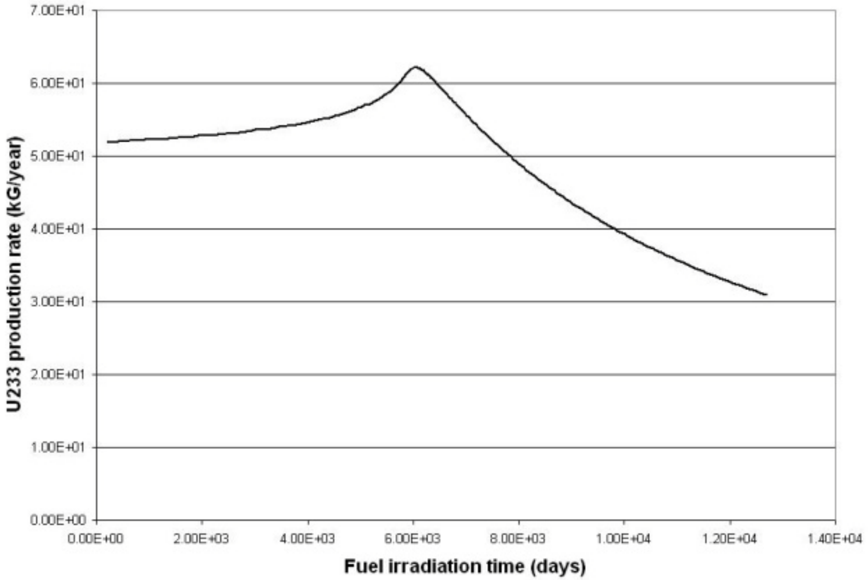


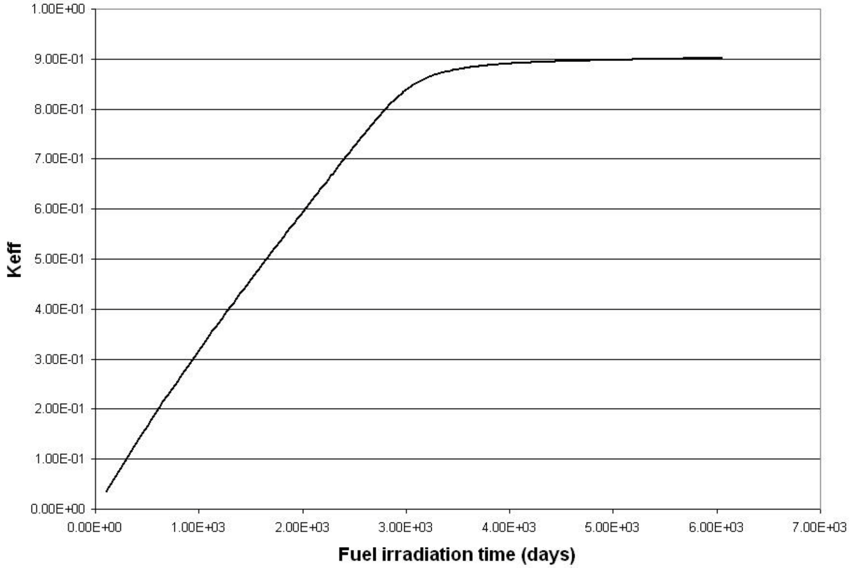


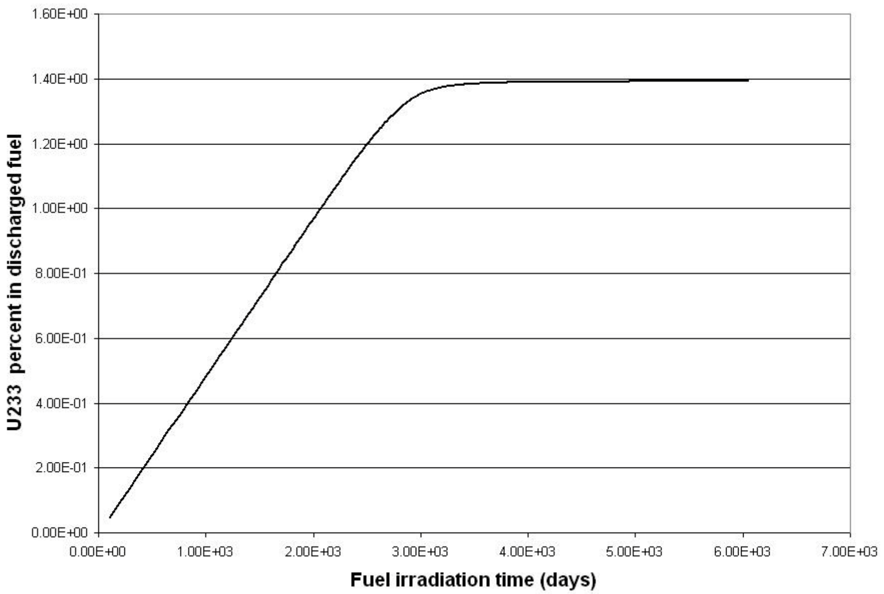


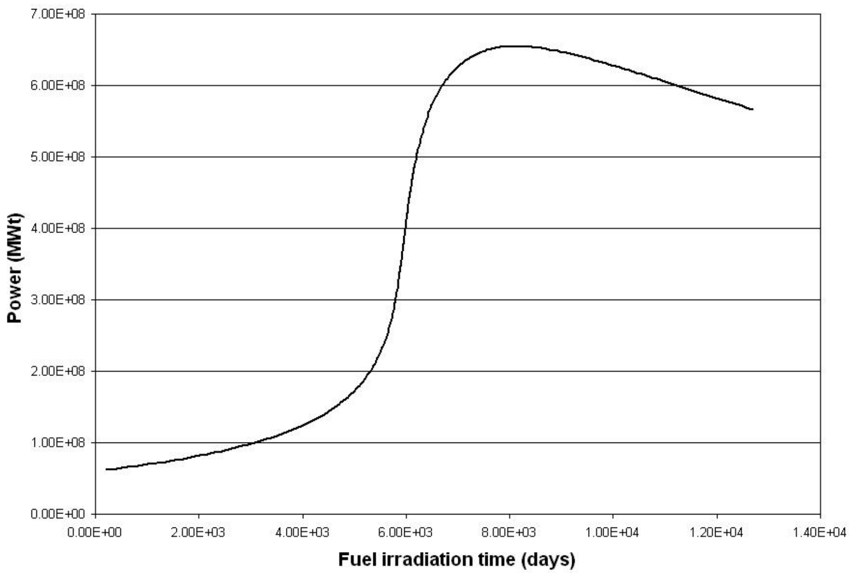


U233 production rate, U233 fraction, power, and keff, for fast blanket driven with 30 MW proton beam on Pb









The Purnima neutron generator

Accelerating voltage: 400 KeV

Target: Titanium deutride /tritide on copper substrate

Neutron production with tritium target:

Originally ~ 1.0e9 /s

Upgraded ~ 1.0e10 /s

Purnima Sub-critical assembly

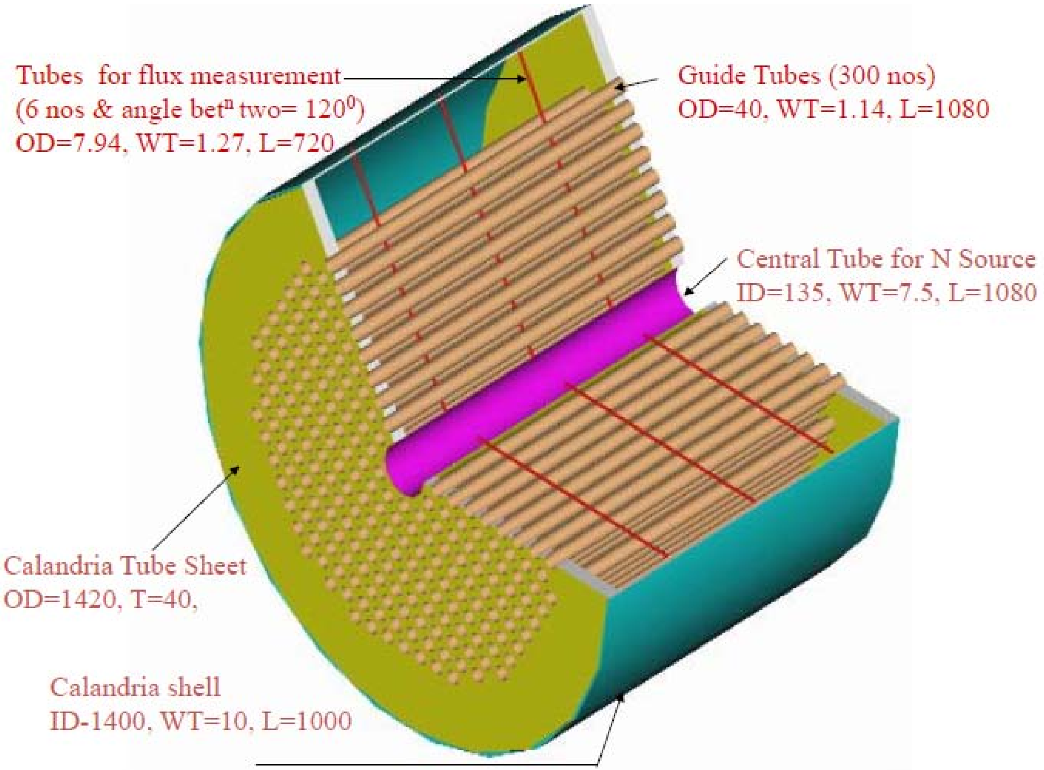
Nat. U H_2O moderated system

K ~ 0.87

Physics experiments for code validation

Flux distribution, spectrum, sub-critical multiplication, fission power measurements

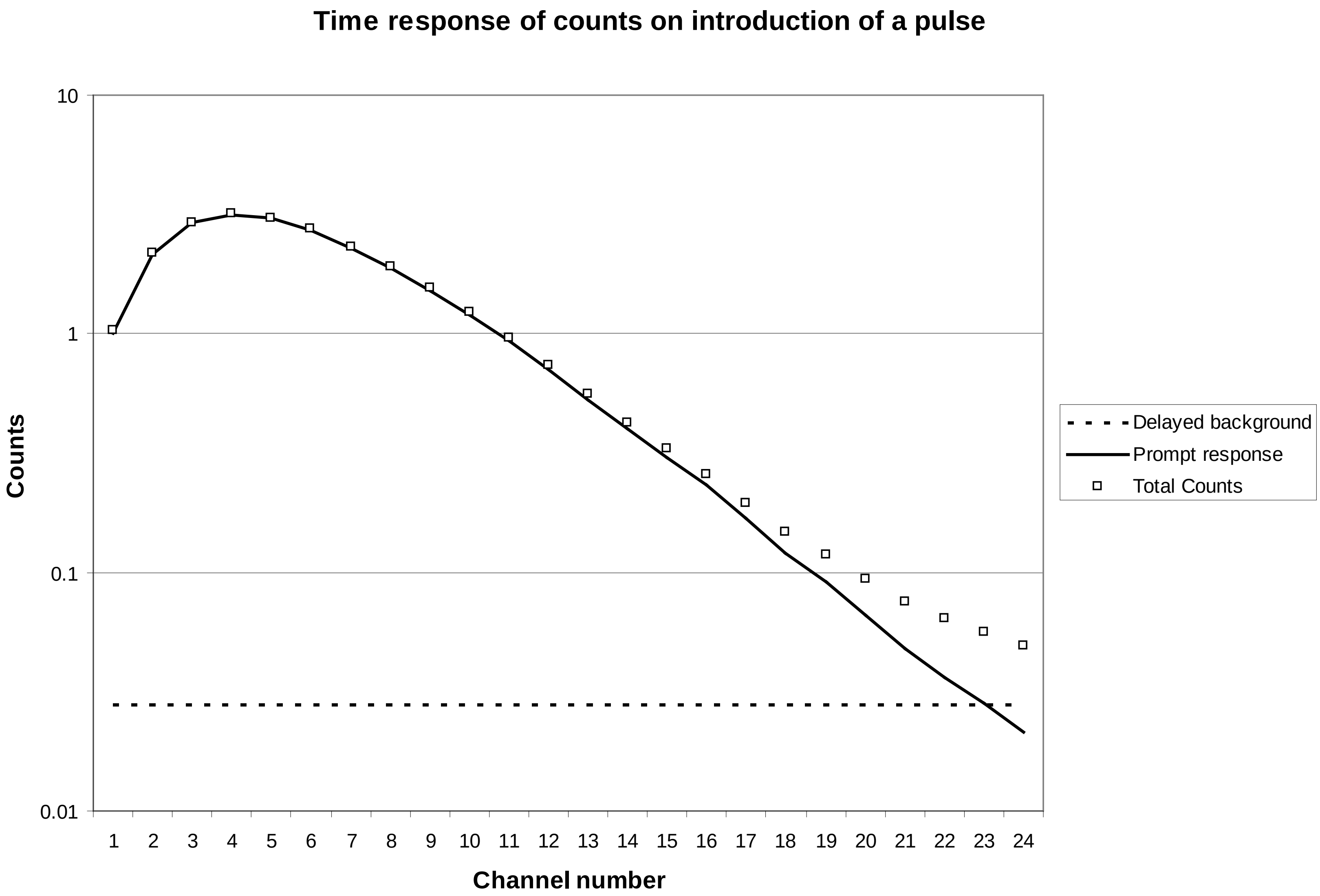
To study various sub-criticality measurement methods



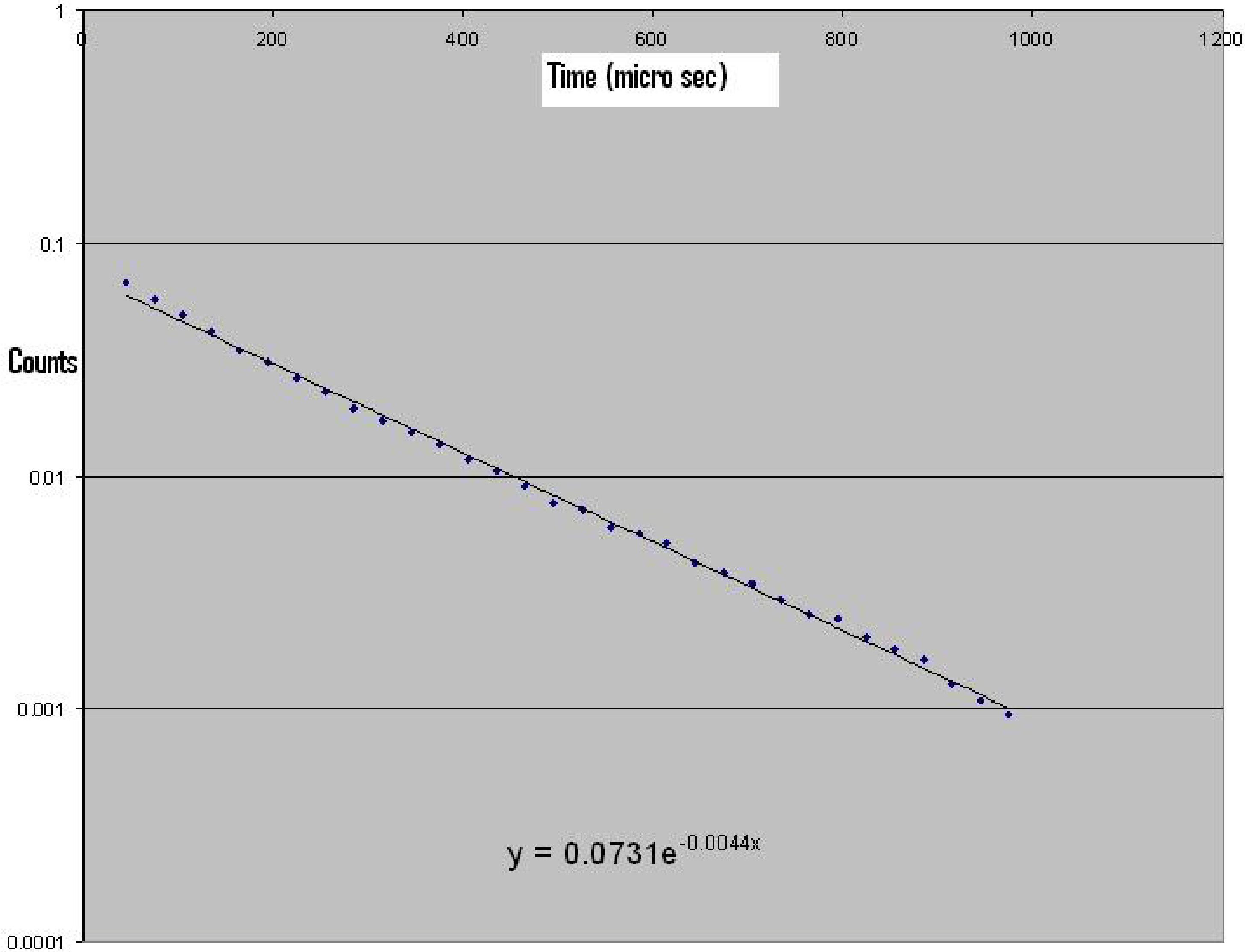
Deterministic methods for sub-criticality measurements

- Pulsed Neutron Experiment
  - Neutron pulse introduced periodically
  - Decay of counts recorded in short time bins
    - For detremining ‘α’
    - and ρ/β
  - Results of simulations
- Source jerk method
  - Source switched off after steady state operation
  - Decay of flux observed as a function of time
  - Does not require pulsing
  - Experiment may have to be repeated several times

Pulsed neutron experiments
Detector located in reflector



Pulsed neutron experiments: Detector located at zeros of modes



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

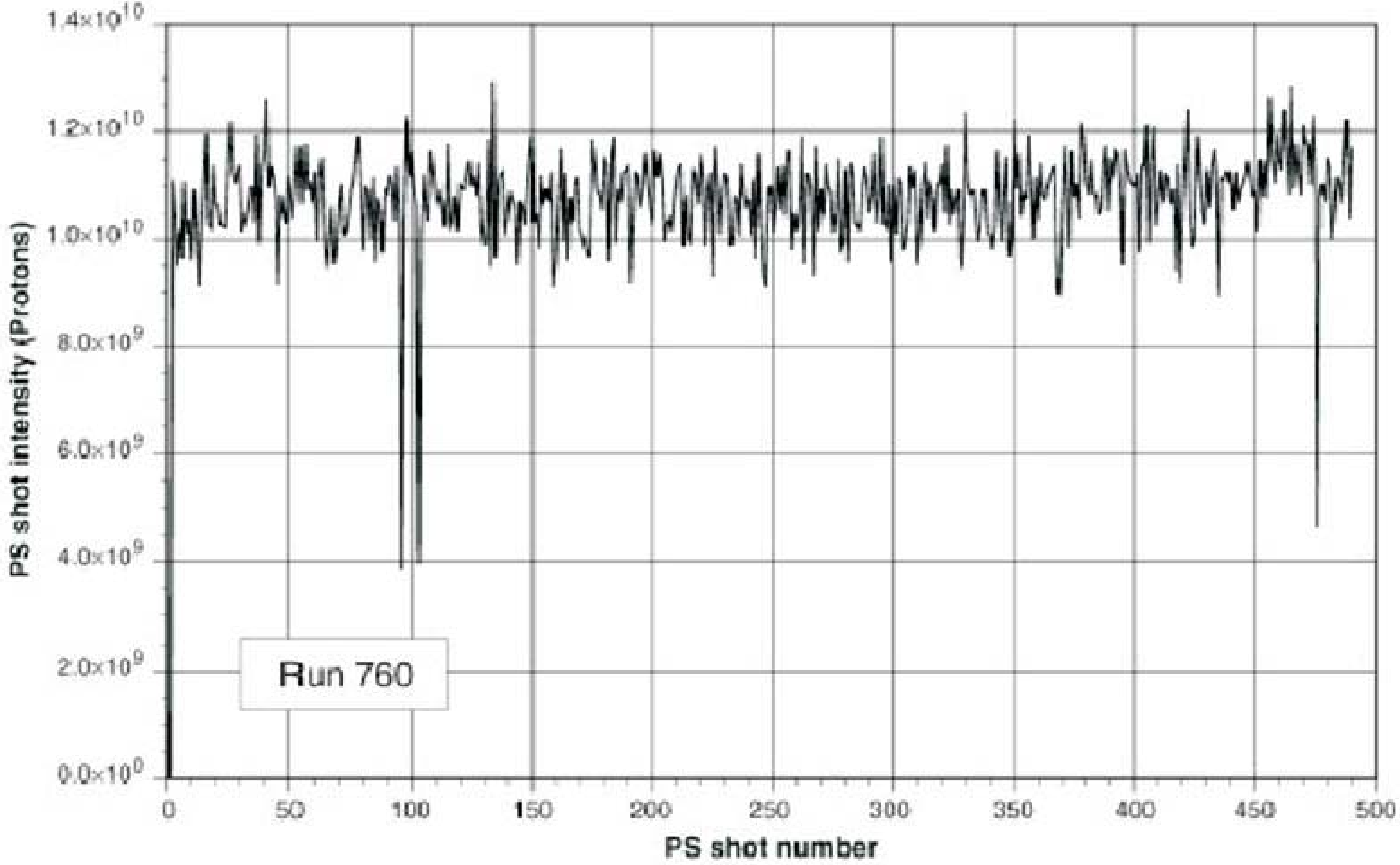
- **Radioactive sources are Poisson sources due to**
  - Large number of radioactive atoms
  - Relatively small number decay independently
- **Accelerator sources are different**
  - Pulsing
  - Cw accelerators
  - Fluctuations in intensity
    - Typically a few per cent
    - For Poisson source of 1e8 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**

Reactor Noise in ADS: New Theory

- **Such a theory has been worked out in BARC**
  - All statistical descriptors commonly used for analysis
    - v/m, Rossi alpha, acf, psd,cpsd
  - Spatial effects
  - Finite pulse widths
  - Delayed neutrons
  - Probability generating function approach
  - Langevin approach
- **Some confirmatory experimental evidence**
- Measurement of statistics of source is required
  - Non-Poisson character
  - Preliminary measurements indicate non-Poisson nature

Reactor Noise in ADS:

Example of measured proton beam current (A. Abanades et al.: TARC experiment, Nucl. Instr. Methods, A478, 577(2002)

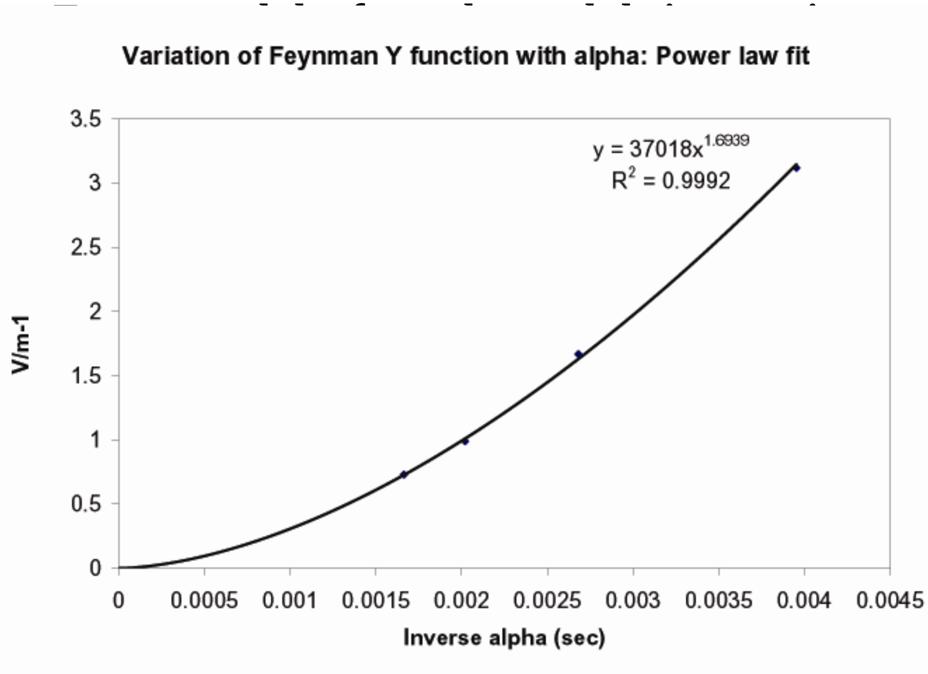


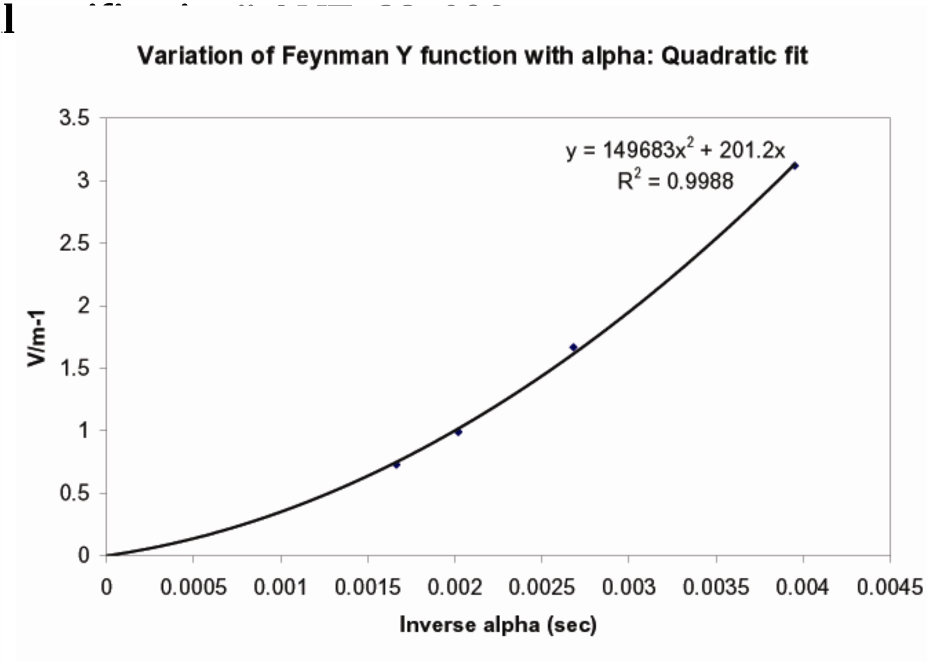
Another Example *[Y.S.Rana, S.B.Degweker, Nucl. Sci. Eng. 162, 117 (2009)]*

Variation of v/m with inverse of the decay constant

points are based on the experimental results presented in-

Pazsit I., Y. Kitamura, J. Wright, T. Misawa (2005) "Calculation of the pulsed



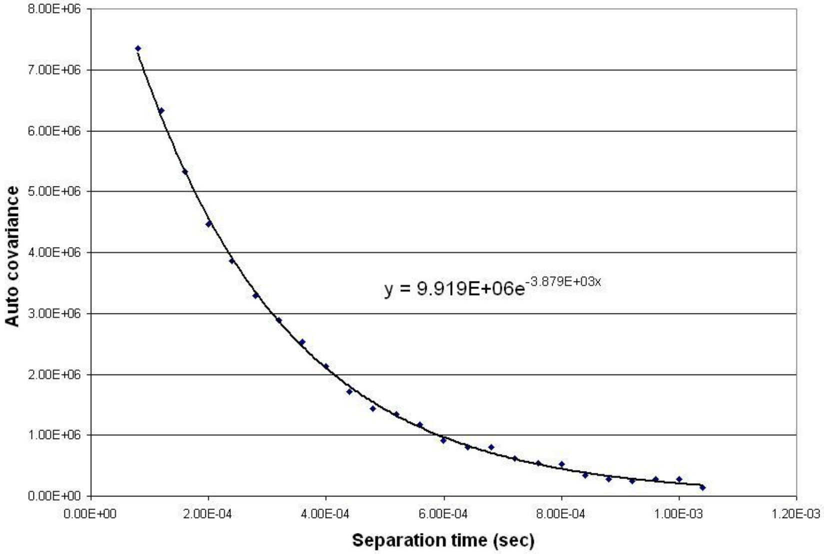


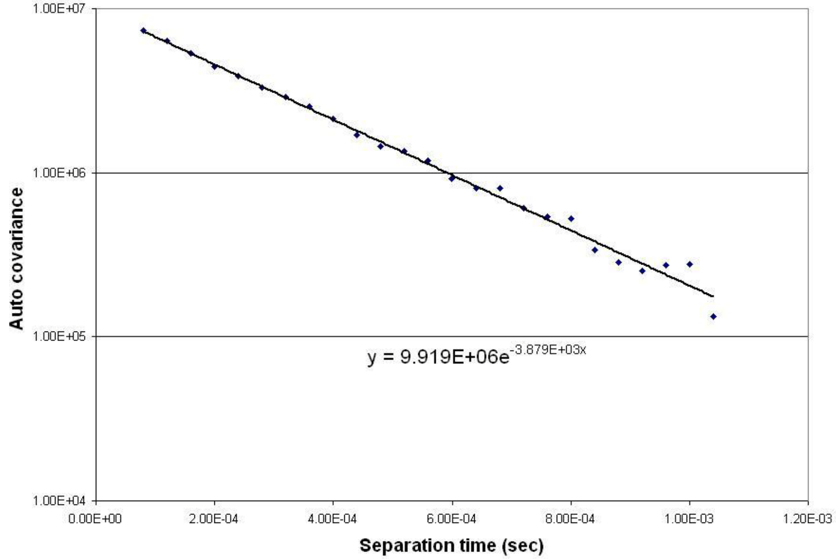
- **While both fits are equally good, the power obtained is not 2 as is expected on the assumption of a Poisson source**
- **The quadratic fit passes through the origin and the linear term indicates a non Poisson source contribution**

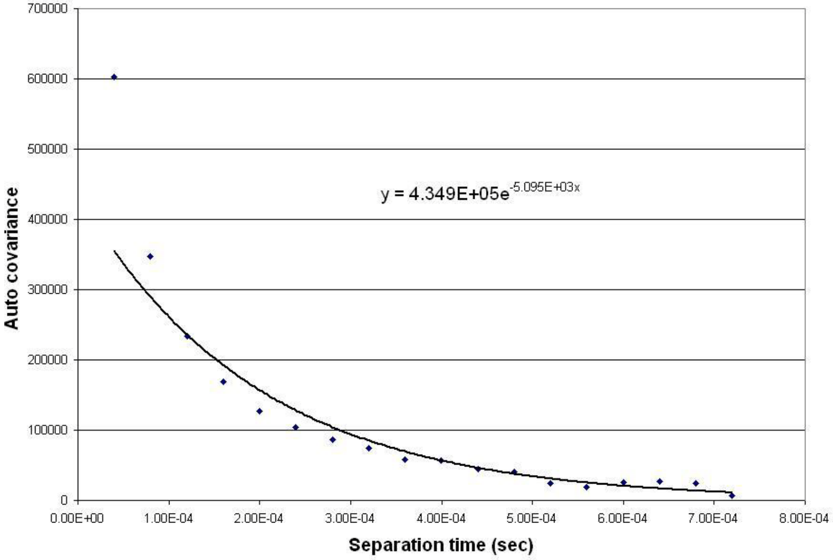
Noise simulator

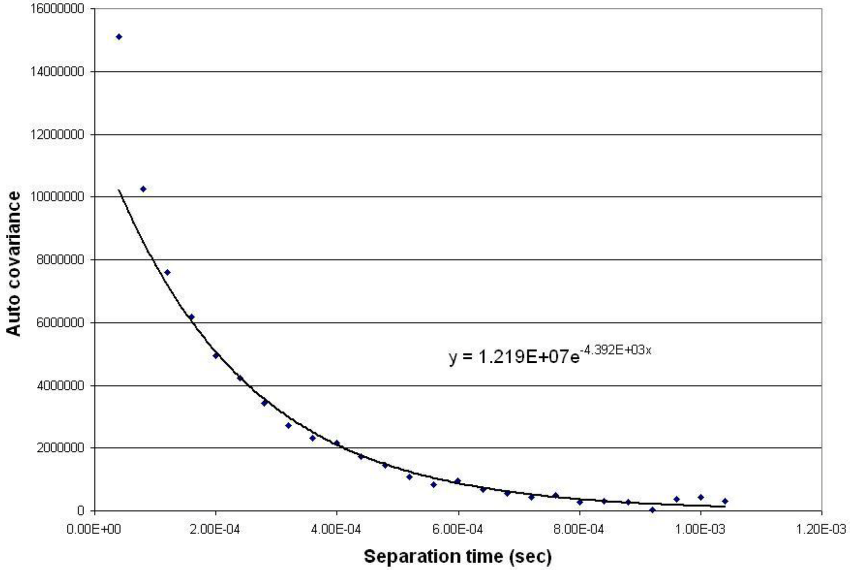
- To study various factors affecting measurements
  - space dependent effects; modal contamination
  - Statistical errors
  - Dead time errors
  - Delayed neutron effects
- Conventional Monte Carlo codes
  - Non-analogue features built in
  - Analogue simulation is time consuming
- Analogue ‘diffusion theory’ Monte Carlo simulator
  - Derivation of few group diffusion kernels
    - Analytical kernels for finite rectangular geometries
    - Finite difference kernels for more general geometries

ACF Results from noise simulator

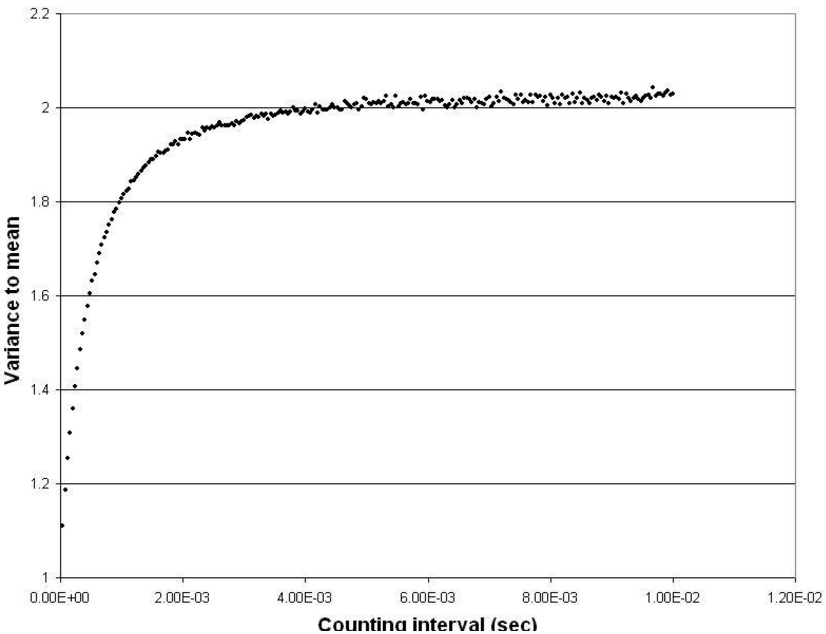


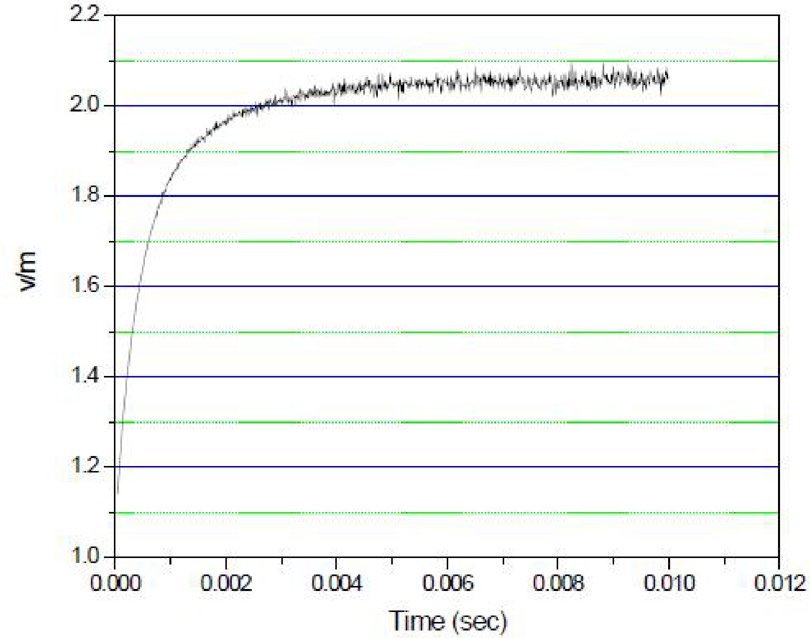


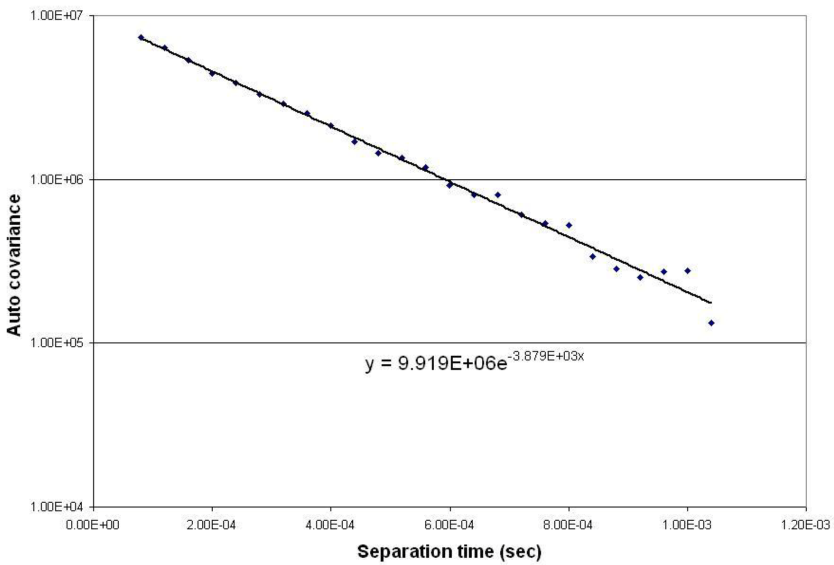


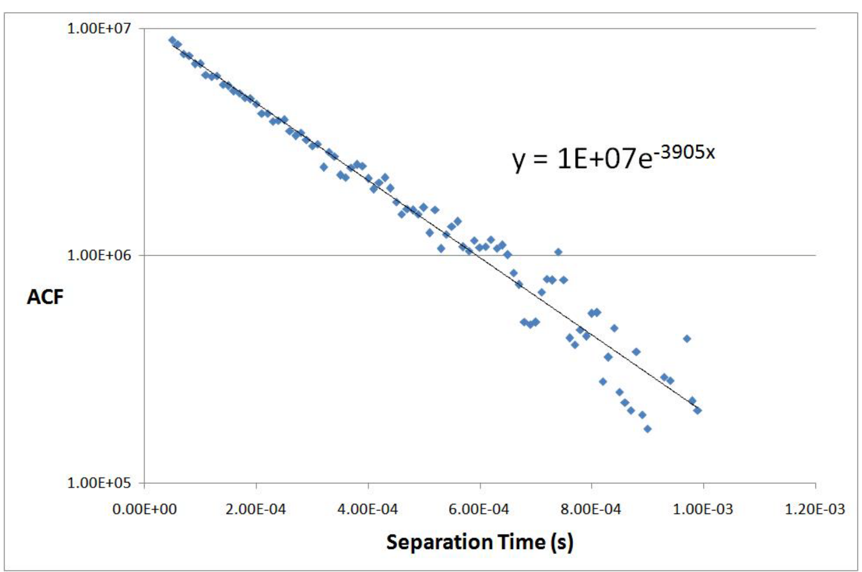


V/m and ACF: Analytical vs finite difference





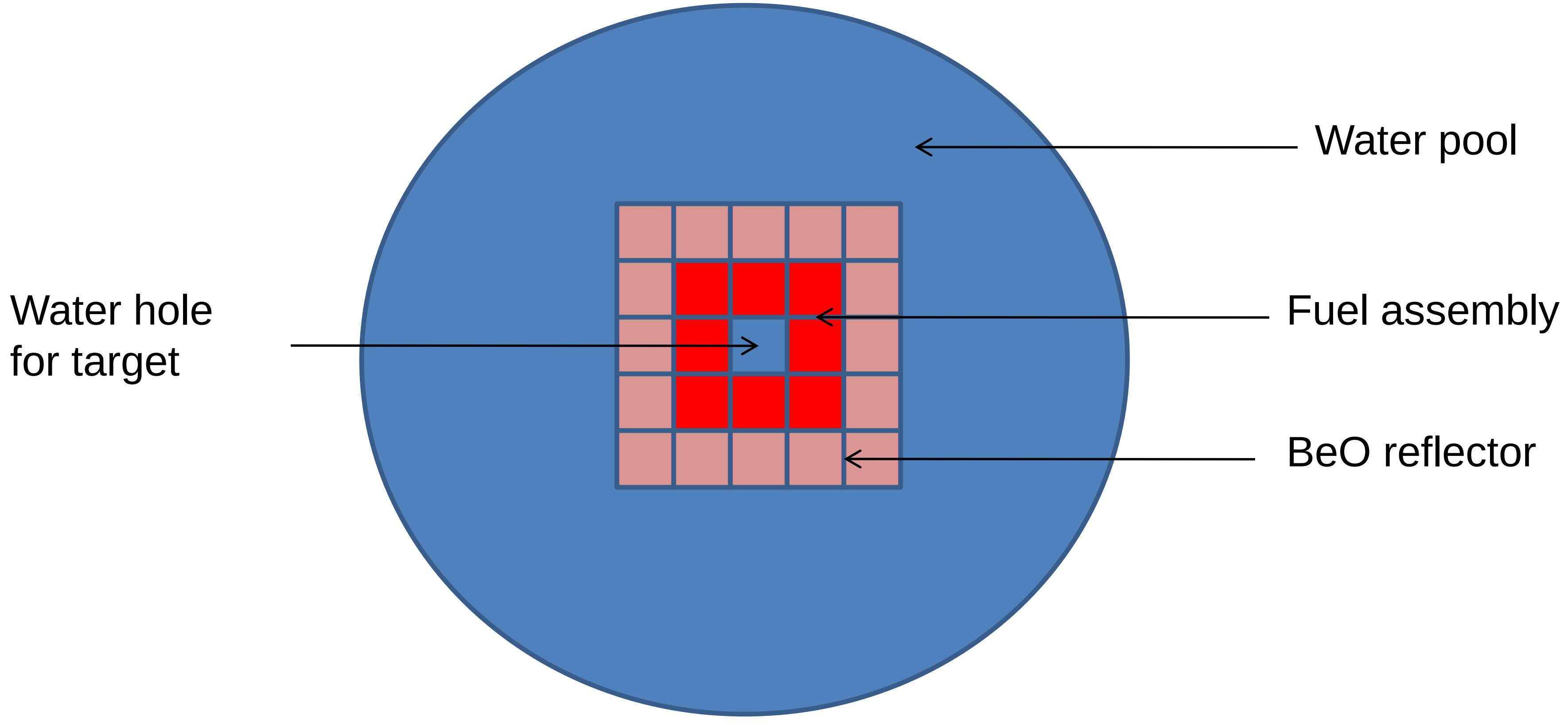




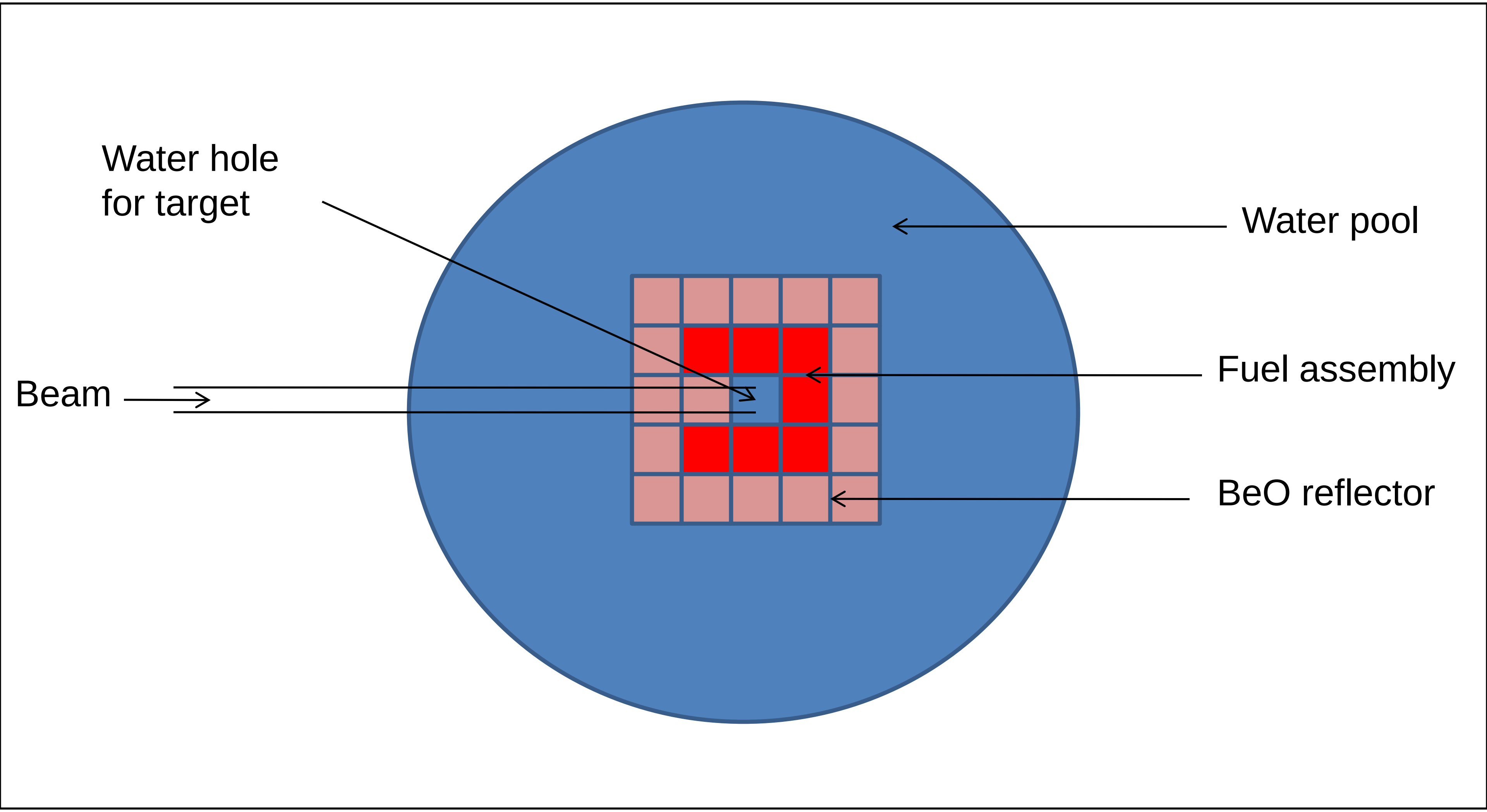
Electron ADS

- Accelerator
  - Electron Linac
    - 100 MeV electron beam (average current - 1 mA)
- Target: Nat U /Ta
- Sub-critical system
  - Keff ~ 0.97-0.98
  - Pool type with H_2O as moderator and coolant
  - Fuel
    - Plate type uranium (LEU) silicide dispersed in Al
  - Reflector BeO
  - Maximum Thermal Flux 1.5e13 n/sq. cm/sec

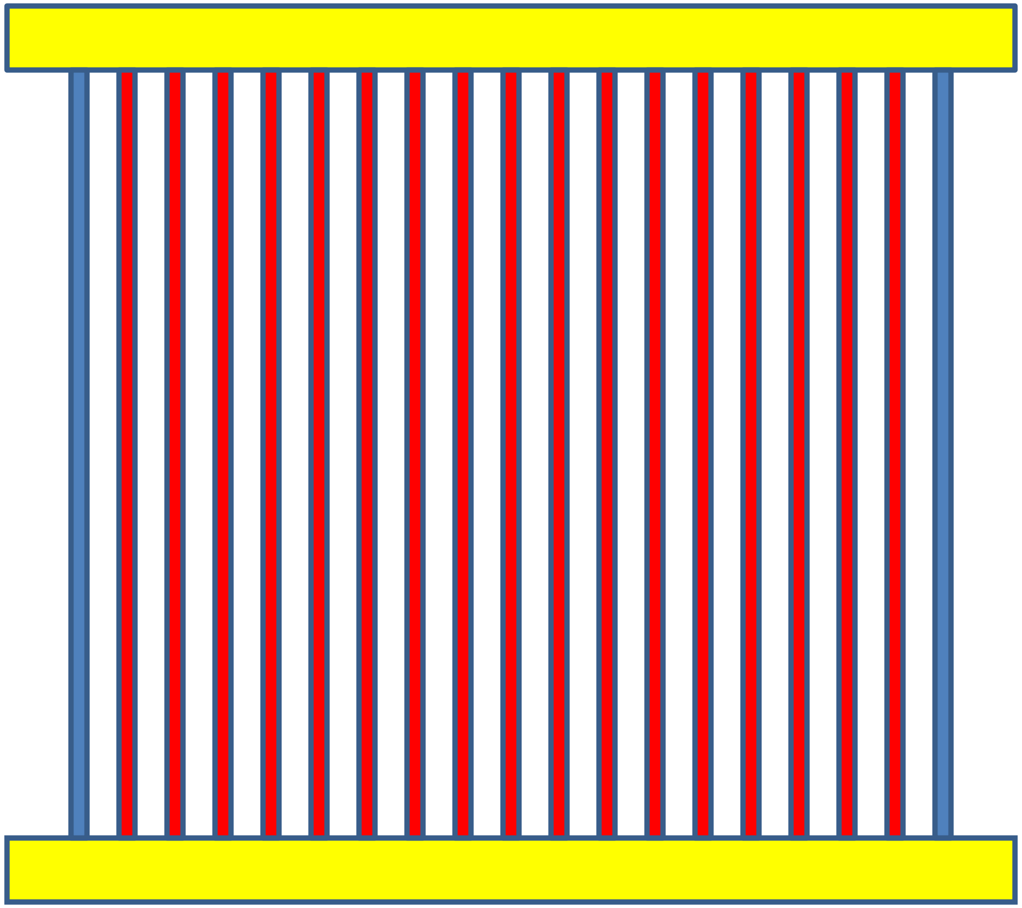
Core layout for proposed electron ADS (vertical beam insertion)



Core layout for proposed electron ADS (sideways beam insertion)



17 plate fuel assembly for electron ADS



Acknowledgements

- ***The authors would like to thank the following for inputs received in preparing this talk***
  - ***R.S.Modak & Anurag Gupta***
  - ***K.P.Singh & Rajeev Kumar***
  - ***Amar Sinha, P.K.Nema & Shirish Navathe***
  - ***Harphool Kumavat***
  - ***P.Sathyamurty, K.C. Mittal & L.M.Ganatayet***
  - ***G.J.Prasad, K.Sasidharan & A.Bhatnagar***

Thank You