European ADS Programs - I
(MUSE, TRADE, SAD)

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Outline

- MUSE Program
- TRADE Program
- SAD Program

Background on MUSE

- MUSE->MUltiplication avec une Source Externe (ADS)
- Part of 15 year program to investigate innovative waste treatment methods
- Partially supported by 5th Framework (Euratom)

Background (2)

- 5th Framework partners
  - UK, ES, BE, NL, DE, SE, IT
- Cadarache presence
  - UK (BNFL), US (ANL), ES (CIEMAT), JP (JAERI), CH (PSI) + transient teams
- CNRS-Grenoble (Centers for Scientific Research)

CEA/Cadarache

- CEA->Atomic Energy Commission
- Cadarache is a `Research Center'
  - Technicatom (military)
  - Cogema (Pu processing)
  - ISPN (CABRI, etc)
  - TorSupra (tokamak)
- About 4000 people on Cadarache site

CEA/Cadarache (2)

- Critical facilities
  - – EOLE (thermal, studying 100% MOX)
  - – MINERVE (mix, studying b.u. credit)
  - – MASURCA (fast)
    - MUSE (ADS)
    - Next program-> FGR

Objectives of MUSE Program

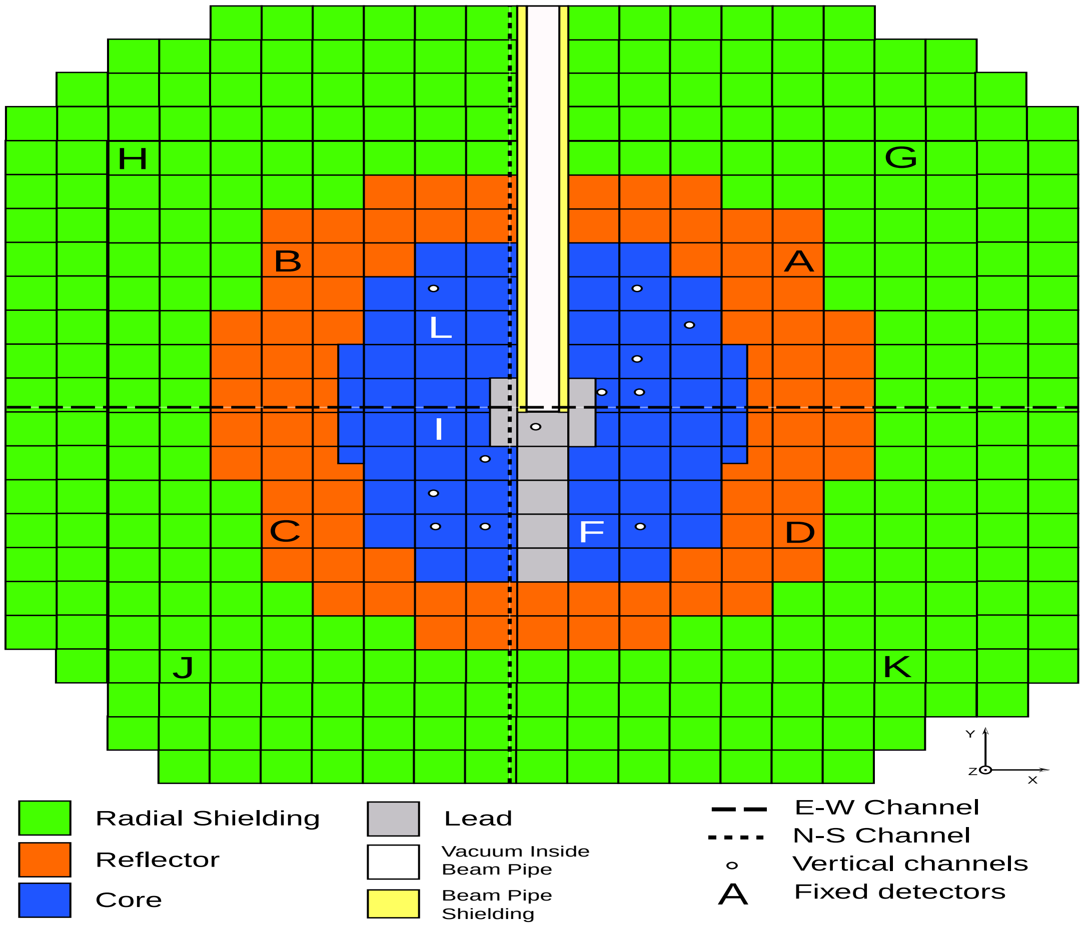
- Measurement of sub-criticality, and development of techniques for “on-line” monitoring (PNS, correlation techniques, source multiplication)
- Reaction rates of minor actinides
- General core characterization (β/Λ, spectrum, source importance)

MUSE

- MUSE 1 and 2 Cf source driven
- MUSE 3 commercial 14Mev generator
  - many problems!
- MUSE 4 GENEPI (from CNRS)
  - DT and DD
  - 3 x 10^6 n/pulse
  - 50-5000 Hz (reactor break frequency about 1500 Hz)

MUSE-4 Reference 1112 cells

Top View at half height



Sub-critical Reactivity Measurements

- MSM and pulsed source are the most promising
- Others include variations of correlation measures (Rossi-α, Feynman-α and transfer function)
- We are looking for methods that can be used in a commercial size ADS

MSM (1)

- Simplified MSM theory
  - A reactor is first and foremost a neutron multiplier
  - At sub-critical levels, a reactor will multiply source neutrons

$$\frac{S}{1-k}$$

MSM (2)

– A detector will detect C counts/second where ε is the detector efficiency

$$C = \frac{\varepsilon S}{1-k}$$

MSM (3)

– Between two states, k_1 and k_2, we can write the ratio of count rates as seen by a detector

$$\frac{C_1}{C_2} = \frac{\varepsilon_1 S_1}{\varepsilon_2 S_2} \frac{\rho_2}{\rho_1}$$

MSM (4)

- MSM corrects for the fact that the ratios of the detector efficiencies and the effective source strengths are not precisely unity with a change in state
- Establish a reference reactivity near critical by rod drop

MUSE-3 Experience

- SC3 configuration
- ∈εS = 1.04 (from reference)
- MSA reactivity -1636 pcm
- MSM reactivity -1579
- 57 pcm due to correction, about 3%

MUSE-3 Experience (2)

- Pb central buffer zone (large perturbation)
- ∈εS = 0.8
- MSA reactivity -4539
- MSM reactivity -5687
- 1100 pcm due to correction, about 20%

Pulsed Source (1)

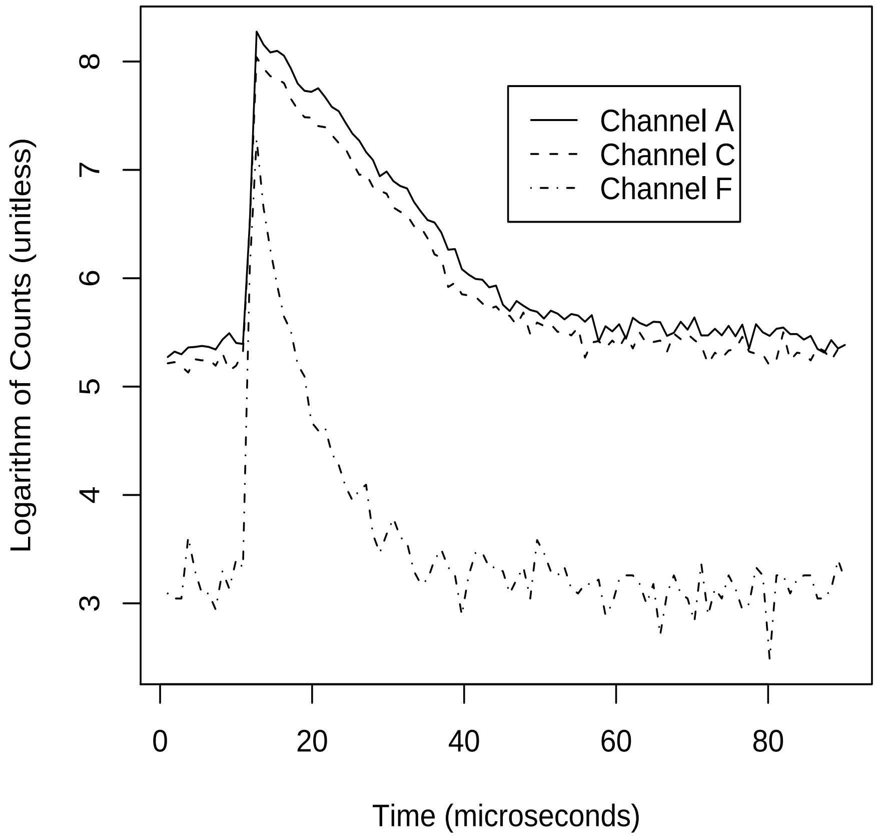
- Point kinetics predicts the prompt decay rate after a pulse to be

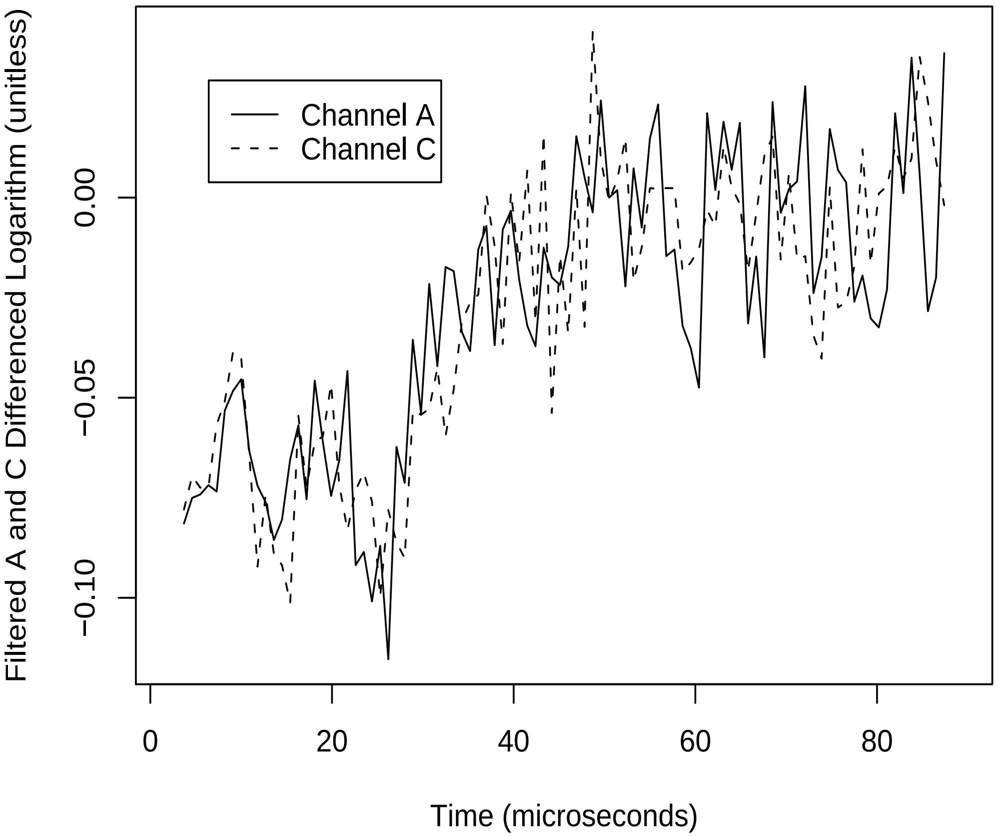
$$\frac{1}{\beta-\rho}\left(\beta e^{-\lambda' t}-\rho e^{-\alpha t}\right)$$

$$\alpha=\frac{\rho-\beta}{\Lambda}$$

Pulsed Source (2)

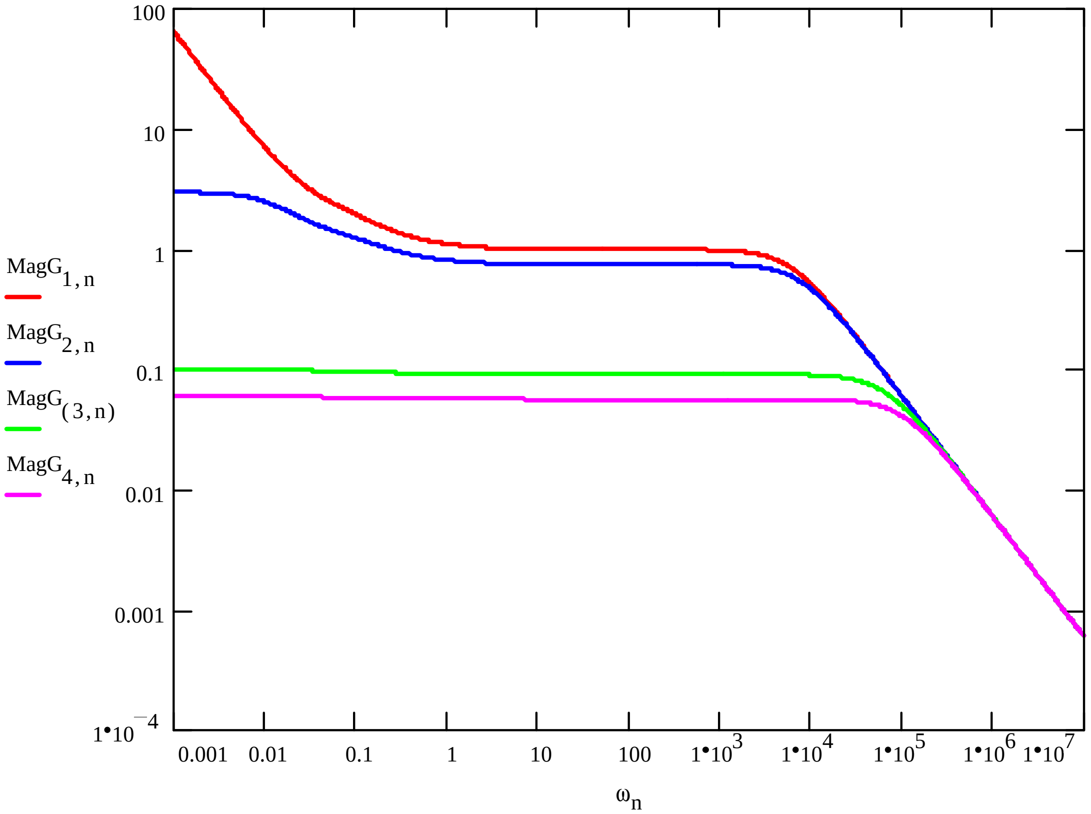
- The presence of a reflector increases the effective lifetime
- MUSE-4 is 3 regions, as lead buffer zone leads to extra dynamics (n,2n reactions, internal reflector behavior)
- MUSE-4 we are seeing complicated time behavior (detector efficiency changes)


Logarithm of Counts (unitless)
Time (microseconds)
Channel A
Channel C
Channel F
3
4
5
6
7
8
0
20
40
60
80


Channel A
Channel C
Filtered A and C Differenced Logarithm (unitless)
0.00
−0.05
−0.10
0
20
40
60
80
Time (microseconds)

Feynman, Rossi α, Transfer Function (2)

- By measuring correlations from individual neutron events, one can determine the decay of individual fission chains (Rossi) or by measuring deviations of the fluctuations from Poisson (Feynman), one can obtain β/Λ
- Transfer function also can give same information


100
10
1
0.1
0.01
0.001
1•10−4
0.001
0.01
0.1
1
10
100
1•10³
1•10⁴
1•10⁵
1•10⁶
1•10⁷
ωn
MagG1, n
MagG2, n
MagG(3, n)
MagG4, n

Feynman, Rossi α, Transfer Function

- Low frequency $$G(s) = \frac{1}{\rho}$$
- Intermediate $$G(s) = \frac{1}{\beta - \rho}$$
- Breakpoint at $$\frac{\beta - \rho}{\Lambda}$$

NIKO

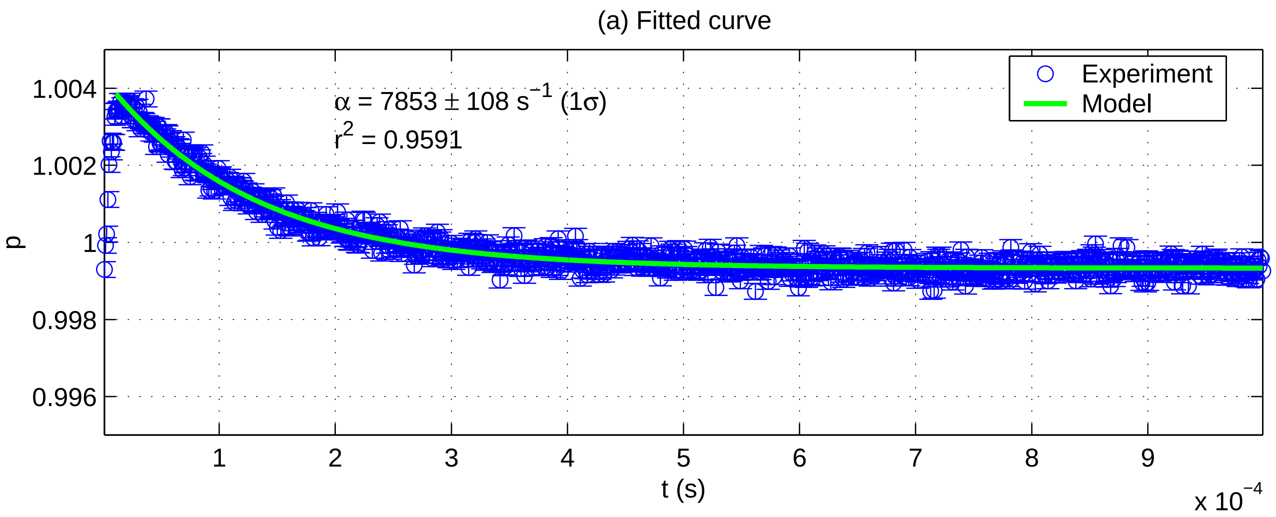
- New measurement technique at MASURCA
- Based on Feynman technique of 1944!
- Time mark each neutron detector event and record
- After the fact, can perform any dynamic analysis technique desired

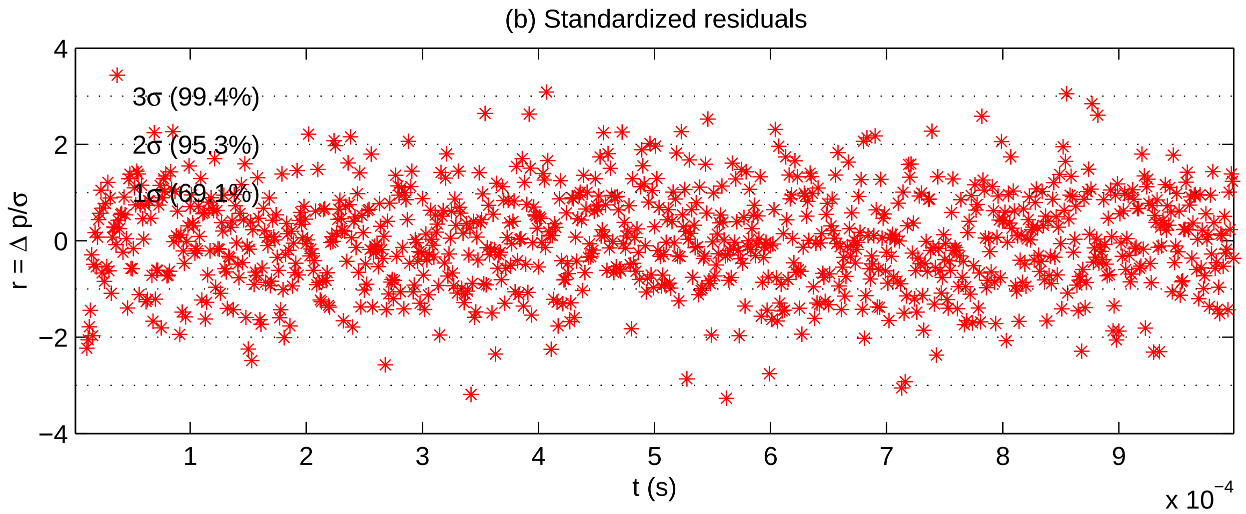
Rossi α

- Probability of correlated counts related to fission power and kinetic parameters

$$p(\tau)dt_g dt_c = \varepsilon_g \varepsilon_c F_0 dt_g dt_c \left(F_0 + \frac{D}{2\alpha\Lambda^2} e^{-\alpha\tau} \right)$$

- Note that F_0 is un-correlated background


(a) Fitted curve
Experiment
Model
α = 7853 ± 108 s^-1 (1σ)
r^2 = 0.9591
p
1.004
1.002
1
0.998
0.996
1 2 3 4 5 6 7 8 9
t (s)
x 10^-4

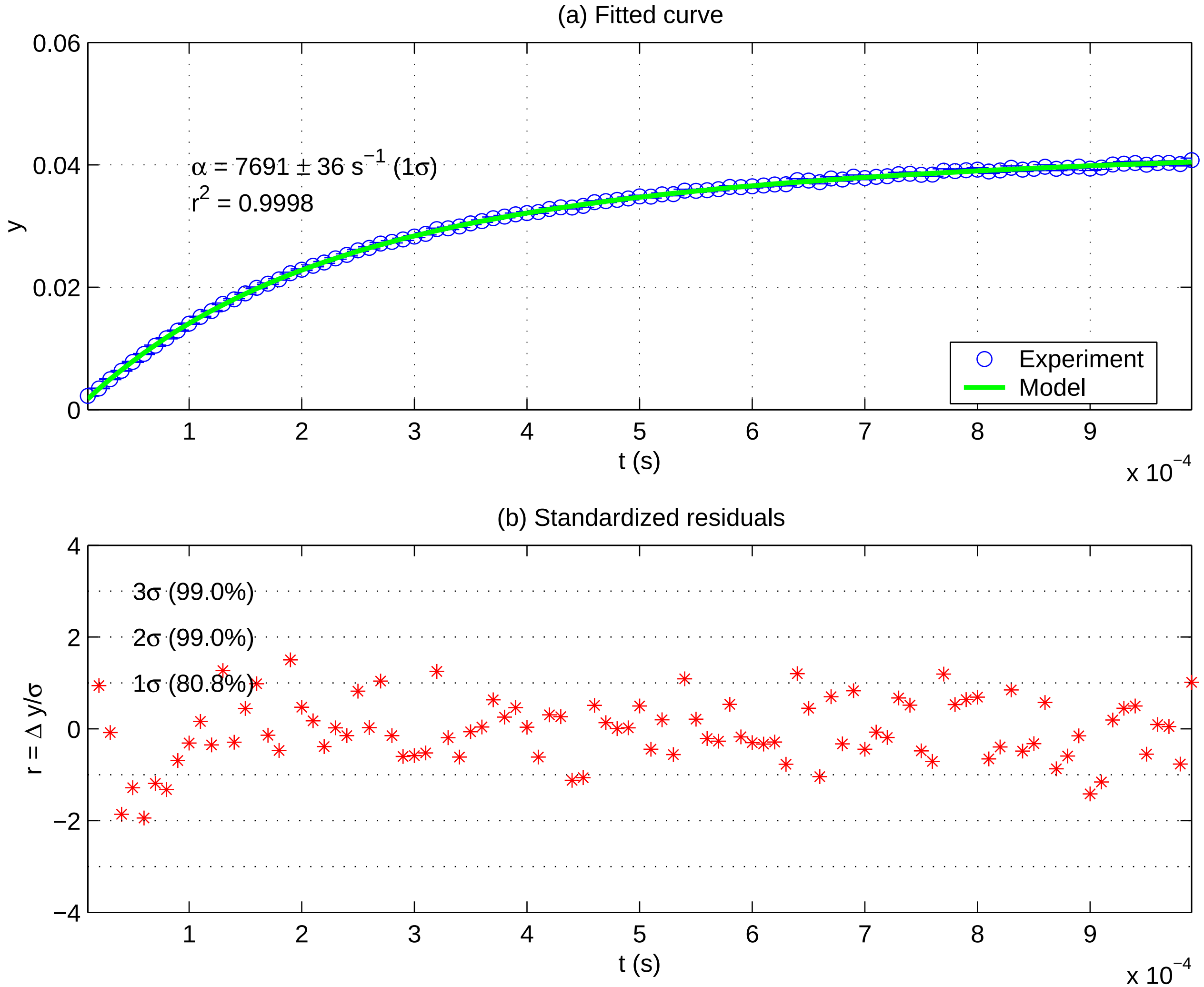

(b) Standardized residuals
3σ (99.4%)
2σ (95.3%)
1σ (69.1%)
r = Δ p/σ
4
2
0
−2
−4
1 2 3 4 5 6 7 8 9
t (s)
x 10^-4

Feynman α

- Deviation of the variance to the mean

$$y = \frac{\varepsilon D}{\alpha^2 \Lambda^2}\left(1 - \frac{1 - e^{-\alpha\tau}}{\alpha\tau}\right)$$

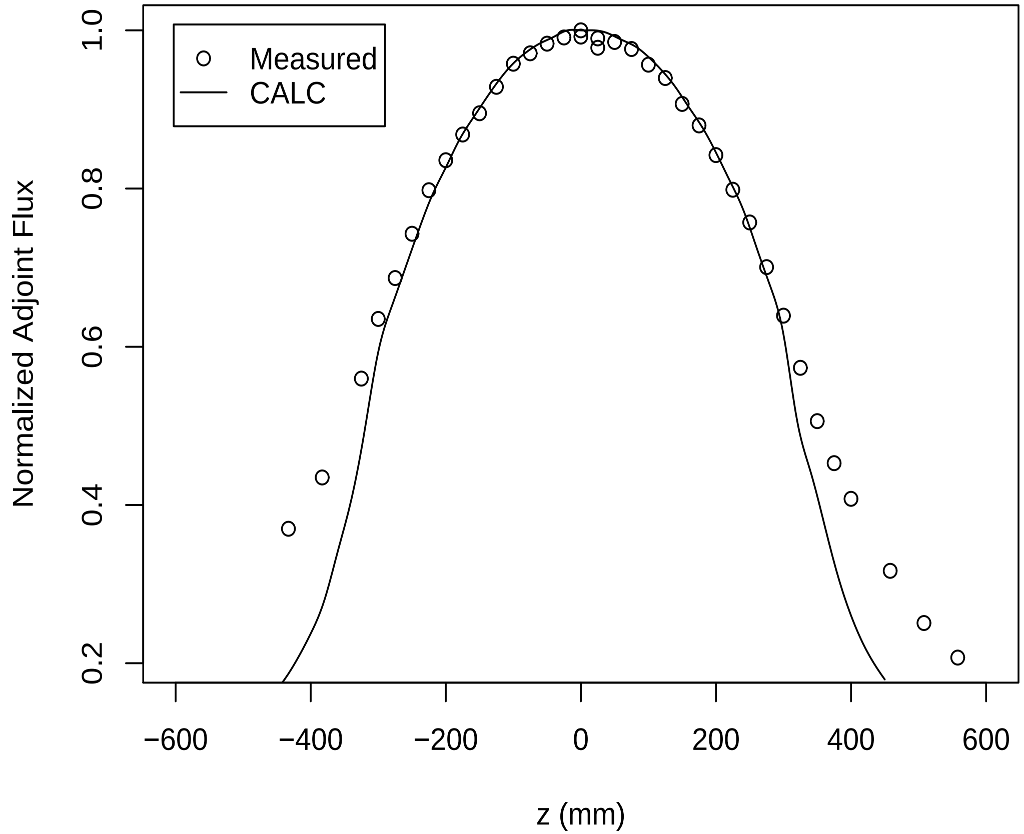
- Note fission power not explicit, but now ε

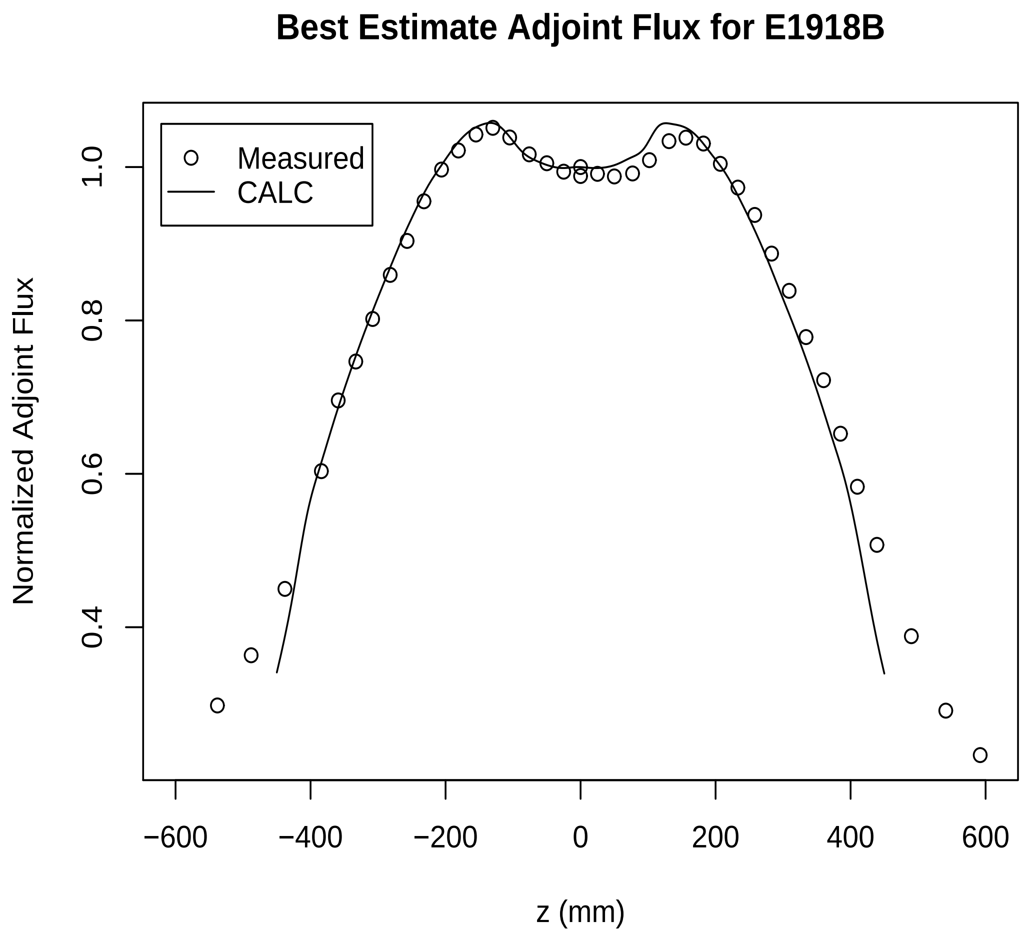

(a) Fitted curve
α = 7691 ± 36 s−1 (1σ)
r2 = 0.9998
Experiment
Model
y
t (s)
x 10−4
0.06
0.04
0.02
0
1 2 3 4 5 6 7 8 9
(b) Standardized residuals
3σ (99.0%)
2σ (99.0%)
1σ (80.8%)
r = Δ y/σ
t (s)
x 10−4
4
2
0
−2
−4
1 2 3 4 5 6 7 8 9

Reaction Rate Profiles and Spectral Indices

- Use 4 or 8 mm diameter fission chambers
- U235, U238, U233, Pu(238-242), Np237, Am(241-243), Cm(243-247), Th232
- Spectral Indices are ratios of reaction rates eg, U5/P9
- Source importance (adjoint) profiles

Best Estimate Adjoint Flux for E1615B





Best Estimate Adjoint Flux for E1918B
Measured
CALC
Normalized Adjoint Flux
0.4
0.6
0.8
1.0
−600
−400
−200
0
200
400
600
z (mm)

Other measures

- β/Λ by noise technique (actually transfer function, but uses random noise as the driving function)
- Reaction rate profiles (axial and radial)
- Spectrum by foil activation and unfolding (SANDII) and spectral indices
- Spectrum by He-3 detector

MUSE Program

- MUSE 4 first went critical in January 2001
- GENEPI with deep subcritical June 2001
- GENEPI near critical November 2001
- Reference core measurements through September 2002
- Fall 2002-Fall 2003
  - k=0.995, 0.97, 0.95

MUSE Program (2)

- At present, we are preparing for last level of reactivity (k=0.95)
- A short program with lead coolant (vs sodium) is planned for early 2004
- MASURCA will then be embarking on a FGR critical program

MUSE Program (3)

- Data available for
  - critical reference configuration (profiles)
  - k=0.995, DD and DT
  - k=0.97, DD and DT
  - k=0.95 DT
- PNS, source jerk, CPSD, Rossi- and Feynman- α as well as fission and californium traverses

MUSE Program (4)

- This would have been an ideal program to involve US universities, students and faculty
- Opportunity to train young researchers in the lost arts of experimental techniques
- Too late now for MUSE---but TRADE is coming!

TRADE Background

- ENEA (Italy) and Carlos Rubbia
- Couple a TRIGA reactor with a spallation source
- Originally to be115 Mev cyclotron/tungsten target, then 140 Mev
- Now maybe 300 Mev (!)/tantalum target
- TRIGA has temperature feedback >1Kw
- Sequence of validation to a real ADS

MUSE and TRADE---Progressive Steps

- MUSE can
  - Investigate source importance effects to 14 MeV
  - Investigate aspects of flux distributions in a fast spectrum
  - Validate dynamic methods of zero-power reactivity monitoring (a major objective)

MUSE and TRADE---(2)

- MUSE cannot
  - Investigate source importance above 14 MeV
  - Investigate power/current/importance relations
  - Study dynamic effects with power feedback
  - Study operational procedures (startup/shutdown, reactivity swings)

MUSE and TRADE---(3)

- TRADE can
  - Study dynamic effects at power at different subcriticality levels (feedback vs. source effects)
  - Study startup/shutdown scenarios
  - Study current vs control rods for reactivity compensation
  - Validation of beam control/shutdown approach

MUSE and TRADE---(4)

- TRADE can
  - In general, study all relevant aspects of current/power/importance/control rod relations
  - Be used to test dynamic methods developed in MUSE in a thermal system (“generic validation”)
  - Study the effects of different buffers

MUSE vs TRADE

- A multi-step process to validate methods
  - MUSE provides the validation of reactivity measurements at zero power
  - TRADE provides the bridge to more protypical source and feedback effects, full scale validation of ADS concept in terms of coupling of realistic components
  - Reactor spectrum is not an issue with these objectives

Sequence of Validation

CONFIG	SOURCE	KINETICS	FDB
MUSE	DD/DT	FAST	NO
TRADE	DD/DT	THERMAL	NO
TRADE	SPALL	THERMAL	NO
TRADE	SPALL	THERMAL	YES
ADS	SPALL	FAST	YES

TRADE Working Group

- Initiated in early 2001 with meetings in Rome
- Purpose was to generate a feasibility report
- Initial members from ENEA, CEA, CERN, and Ansaldo (Italian manufacturing company)
- Final feasibility report was presented in Rome in June, 2002
- Invitations extended to DOE and FZK
- www.enea.it for more information on report (click Attivita)

Main Efforts

- Choice of target
  - tungsten or tantalum or combination
- Thermal hydraulics and safety case
  - although natural convection is probably feasible for less than 20 Kw on target, not enough data are available, so likely will use forced convection on target

Main Efforts (2)

- Physics
  - benchmark (ANL, CEA, ENEA, FZK)
  - shielding
  - burn-up evaluation
  - not much experience with U-ZrH fuel

TRADE Experiments

- Pre-TRADE characterizations Fall 2002 to Summer 2003
- TRADE Reference Core Fall 2003
- TRADE SC with DT source Summer 2004
- TRADE SC with cyclotron Summer 2006 (7?)

Pre-TRADE core characterizations

- TRADE configuration will require removal of all A and B ring fuel (6 elements actually)
- In Fall, 2002 we performed some initial tests
  - of detectors
  - of reactivity levels with fuel removal
- We found we needed new detectors, and reactivity might be a problem with old fuel

Burn-up evaluations

- Some fuel has been in reactor for over 30 years
- We have a good record of fuel locations and power history
- An effort was made in summer to evaluate burn-up experimentally (gamma scanning and reactivity worth)
- Very sensitive to flux gradients
- This will be fed into the benchmark effort

2003-2004

- Reactivity transients for the safety group
- Transition to TRADE mockup core
  - removal of A and B rings
  - movement of control rods to D ring
  - removal of all other experimental loops
  - installation of mockup target

2003-2004 (2)

- Measures with Am-Be and Cf sources
  - source importance, source jerk, MSM
- Noise techniques (measures of β/Λ)
- Feynman and Rossi also
- Campaign is full through Spring, 2004
- Will then repeat measures with DD and DT sources (direct comparison to MUSE)

TRADE Conclusions

- Experiments will be conducted jointly by ENEA, CEA (and hopefully DOE)
- The project seems to have enough momentum to survive---ENEA is footing the majority of the capital, and other partners are providing manpower or expertise plus some cash
- Another excellent opportunity for US university involvement

SAD

- Sub-critical Assembly Driven by proton acclerator
- Joint Institute of Nuclear Research (JINR) Dubna
- ISTC project, Main collaborators are
  - CEA RIT
  - CIEMAT FZK

Characteristics

- Create an experimental installation coupling a 660 Mev proton beam with MOX sub-critical assembly
- Still in conceptual design stage
  - core thermal power of 15-20 Kw (order of magnitude under TRADE)
  - k ~ 0.95
  - beam power ~ 0.5 Kw

Characteristics (2)

- Will use fuel from BN-600 experiments
- Targets will be Pb, W, Pb-Bi plus ??

Status

- Current work
  - neutronics design
  - target irradiations
  - neutron density distributions in non-fissionable materials
- Several years from spallation source coupled to sub-critical fissionable fuel
- No US presence in SAD project