The TRADE Experiments

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on behalf of all of the
MUSE and TRADE Experimental Teams)

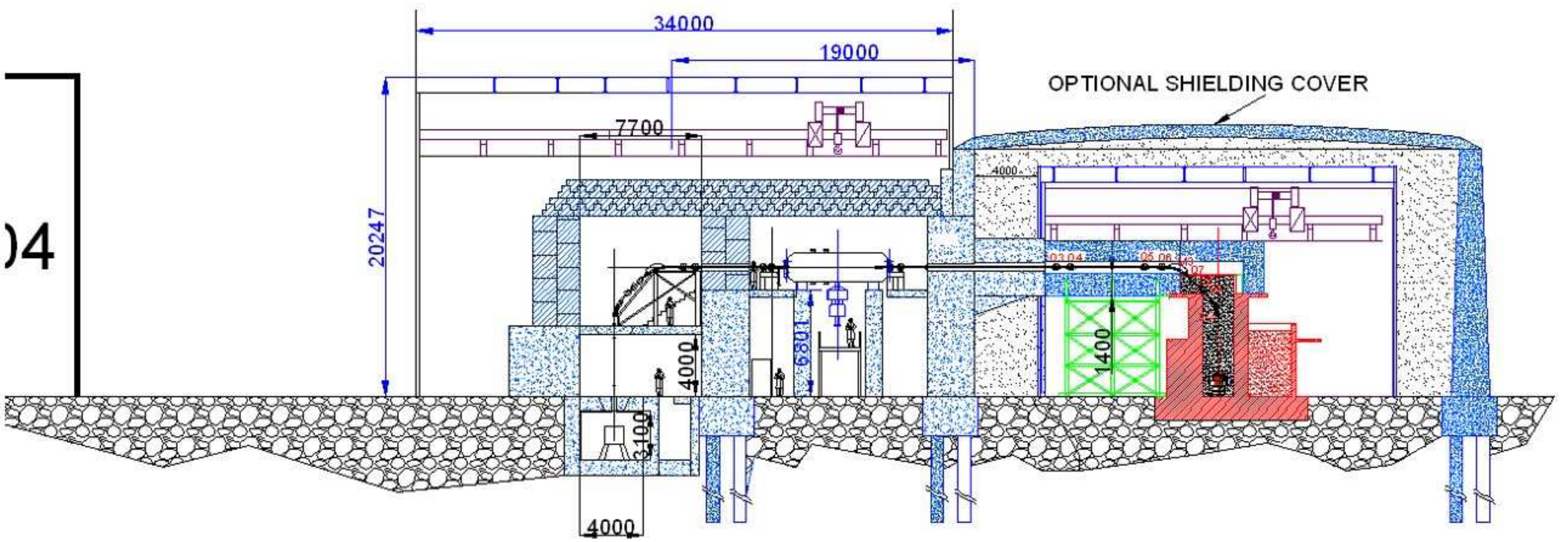
Outline

- General discussion of relevant techniques
- Selected MUSE results (cannot talk about TRADE without MUSE)
- What TRADE experiments before cyclotron?
- TRADE MSM program—finding the reference core(s)
- Planned TRADE experiments (Phase I, II, and III)
- Relevance to ADS

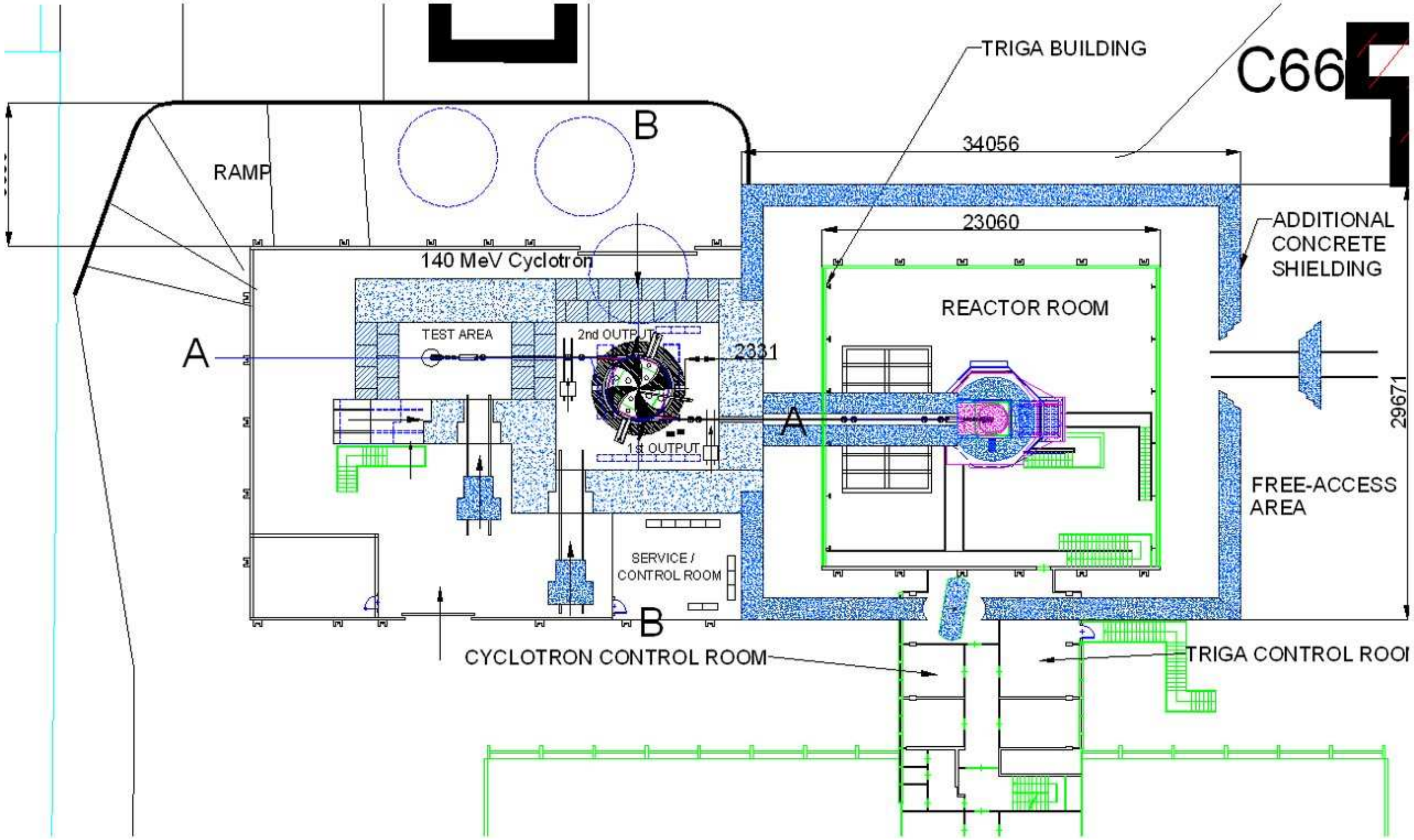
Background

- **TR**iga **A**ccelerator **D**riven **E**xperiment
- Carlo Rubbia and ENEA (Italy)
- Couple a TRIGA reactor with a real spallation source
- 140 Mev cyclotron, probably tantalum target
- Sequence of validation to a real ADS
- Understated value of ADS experiments---preservation of expertise!

Proposed Layout



Plan View with Target Test Area



Sequence to 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

Main Efforts in 2002-2003

- 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
  - MSM factors, source multiplication

Preface to Techniques

- One of the major objectives of the MUSE program was to test various methods of determining the sub-critical reactivity level
- Because of time and source intensity constraints, we perhaps did not perform all of the experimentation desired
- We intend to continue the testing in TRADE, also yielding a kind of “generic validation”

General Discussion on Techniques

- Static techniques
  - MSM
- Dynamic techniques (driven)
  - PNS
  - Source jerk, oscillation
  - Correlation (Rossi, Feynman, transfer function)

General Discussion (2)

- Noise techniques (static on a macroscopic scale but dynamic on a microscopic scale)
  - Rossi, Feynman
  - CPSD/transfer function
- We'll give examples of data on these methods after very brief discussion on theories

General Discussion (3)

- A key is how we move from MUSE to TRADE and on to an ADS
- In this regard, TRADE experiments with Cf, DD, and DT sources are crucial parts of the bridge
- We have developed techniques (of analysis) in MUSE that we need to further qualify on TRADE (different spectrum)

MSM (1)

– Between two states, ρ_1 and ρ_2 , we can write the ratio of count rates at a detector

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

MSM (2)

- MSM -> 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
- Comprehensive measurements already performed in TRADE (many more than MUSE)
- We are finding the TRIGA to be very sensitive to detector and source positions

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)

- Point kinetics---flux is separable in (**x**,t)
- We are looking for α, the prompt neutron decay
- MUSE-4 we are seeing complicated time behavior (detector efficiency changes and pulse propagation)

Pulsed Source (3)

- Also have the area method
- One integrates the “prompt area” and the “delayed area”
- Method seems forgiving

$$\rho_{\$} = -\frac{A_p}{A_d}$$

Source Jerk

- Source jerk with intrinsic source background can yield reactivity in dollars directly

$$\rho_{\$} = \frac{C(0) - C(T)}{\int_0^T C(t)dt + TC(T)} \left(\frac{\Lambda}{\beta} + \sum_j \frac{\alpha_j}{\lambda_j} \right)$$

Source Jerk (2)

- We can also use the prompt approximation (not integrated)
- Problem of where to pick the "prompt drop"

$$\rho_{\$} = 1 - \frac{C_0}{C(T)}$$

Source Oscillation

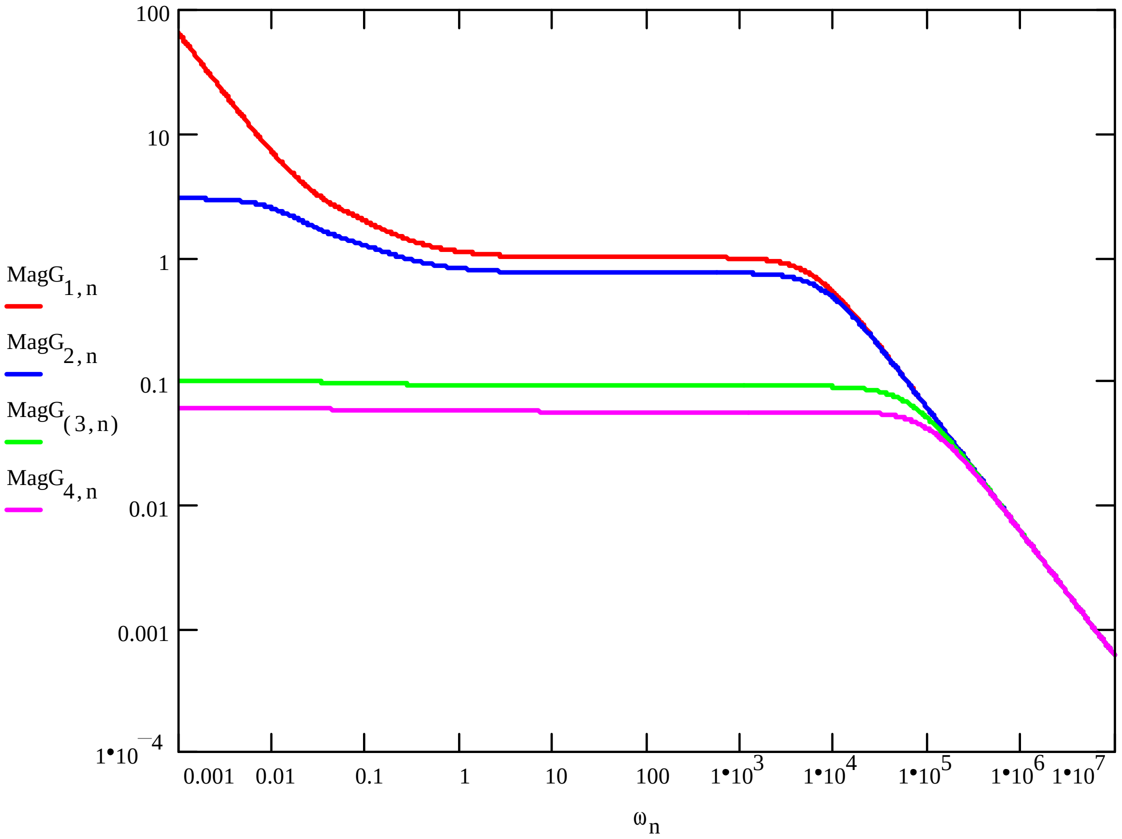
$$\frac{n'}{n} = \frac{\delta q}{q}\frac{\rho_{\$}}{\rho_{\$} - 1}$$

Transfer Function

- It is the reactor's response to a perturbation
- This is general for fast or thermal reactors---only the time constants change

$$G(s) = \frac{n'(s)}{\rho'(s)} = \frac{n_0}{\Lambda s + \beta - \rho_0 - \sum_i \frac{\lambda_i \beta_i}{s + \lambda_i}}$$

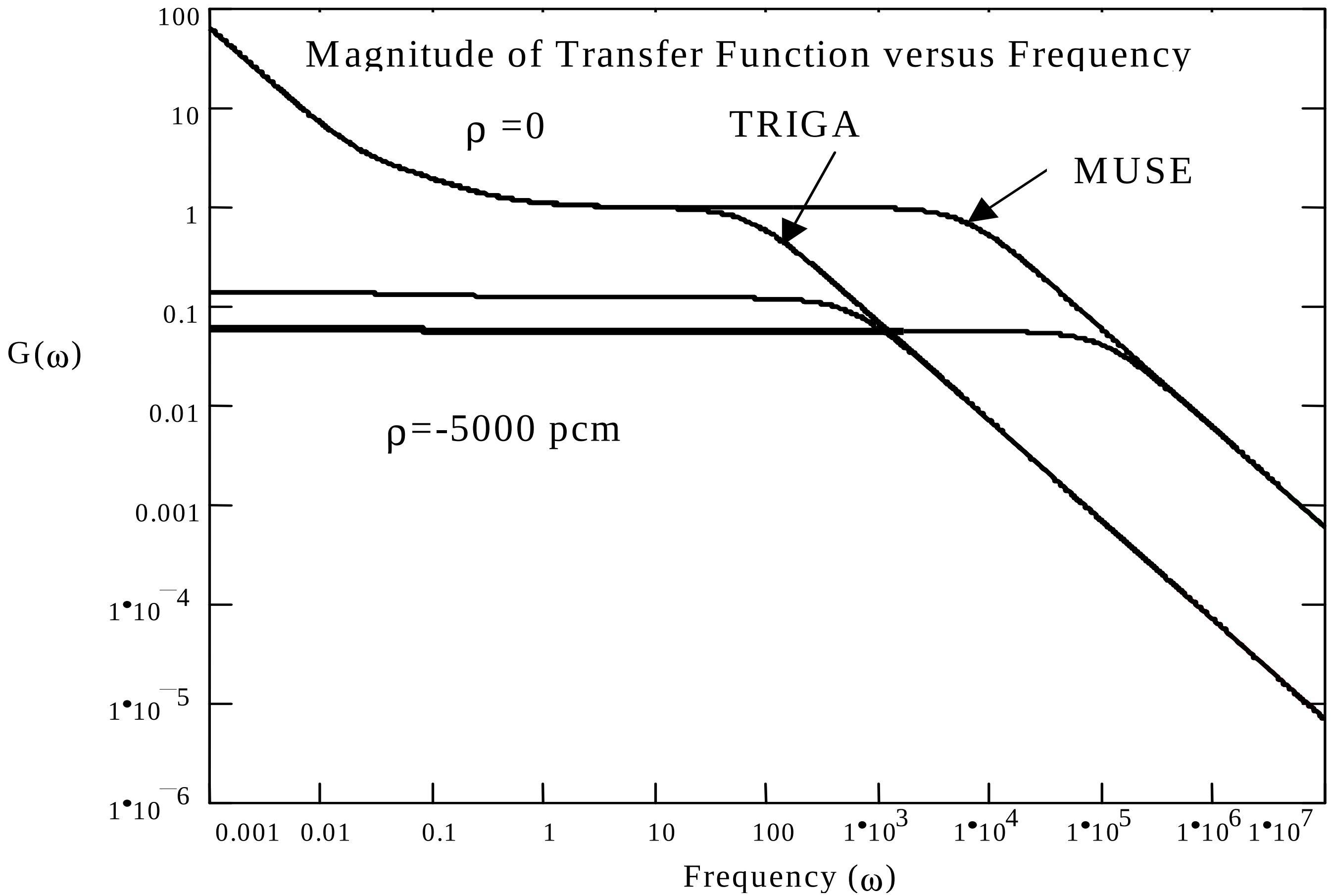
Transfer Function (MUSE)



Transfer Function Limits

- Low frequency $$G(s) = \frac{n_0}{\rho}$$
- Intermediate $$G(s) = \frac{n_0}{\beta - \rho}$$
- Breakpoint at $$\frac{\beta - \rho}{\Lambda}$$

Transfer Function (MUSE vs TRADE)



Feynman and Rossi α

- 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

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 (fission power)

Feynman α

- Deviation of the variance to the mean

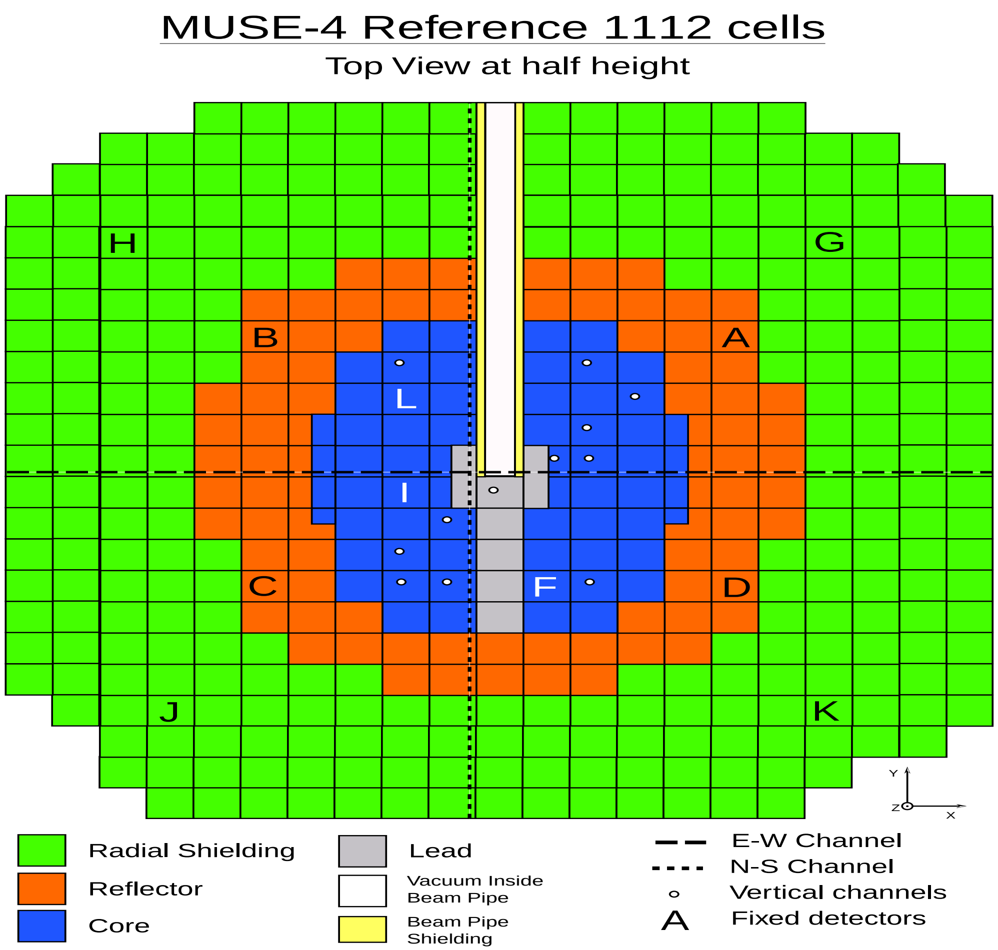
$$y = \frac{\varepsilon D}{\alpha^2 \Lambda^2}\left(1 - \frac{1 - e^{-\alpha\tau}}{\alpha\tau}\right)$$

- Note fission power not explicit, but now ε (detector efficiency)

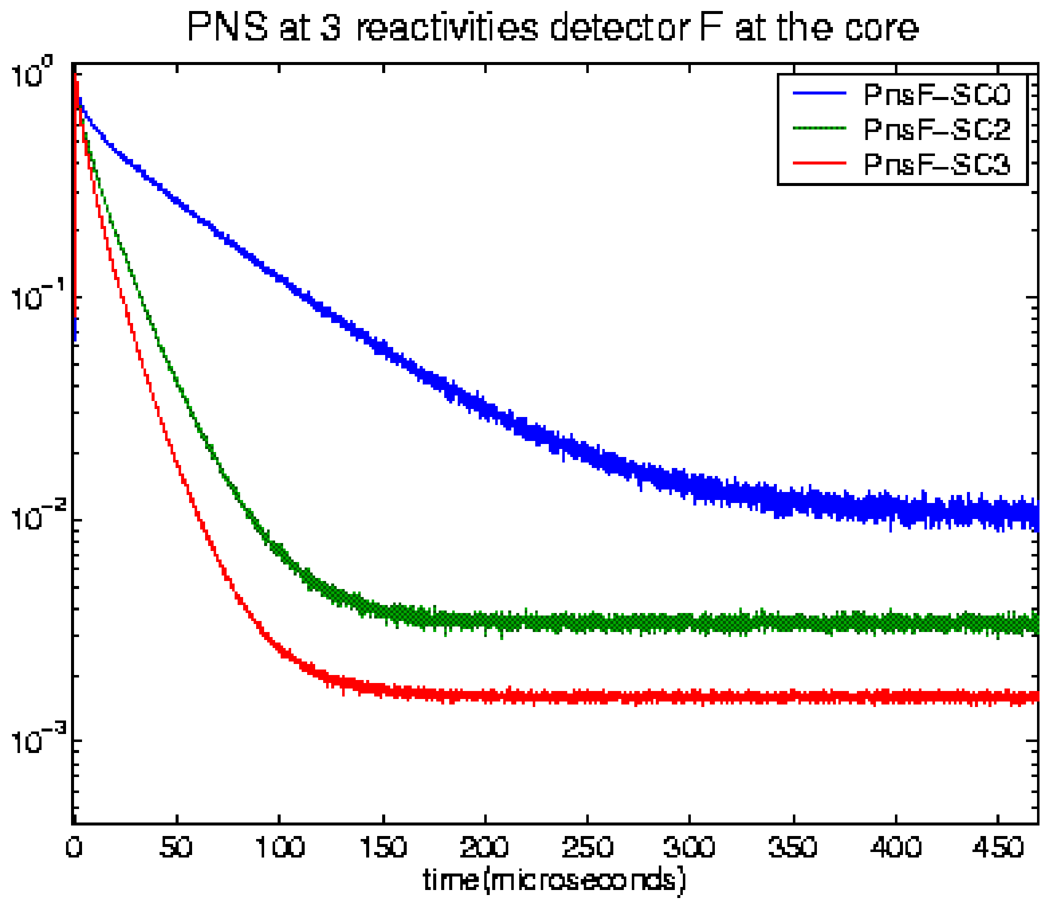
Instrumentation

- Traditional
  - CF, MCS, PHA
- New
  - Time marking
  - Each detector event is time stamped and recorded
  - In principle have a complete record of the experiment for later analysis

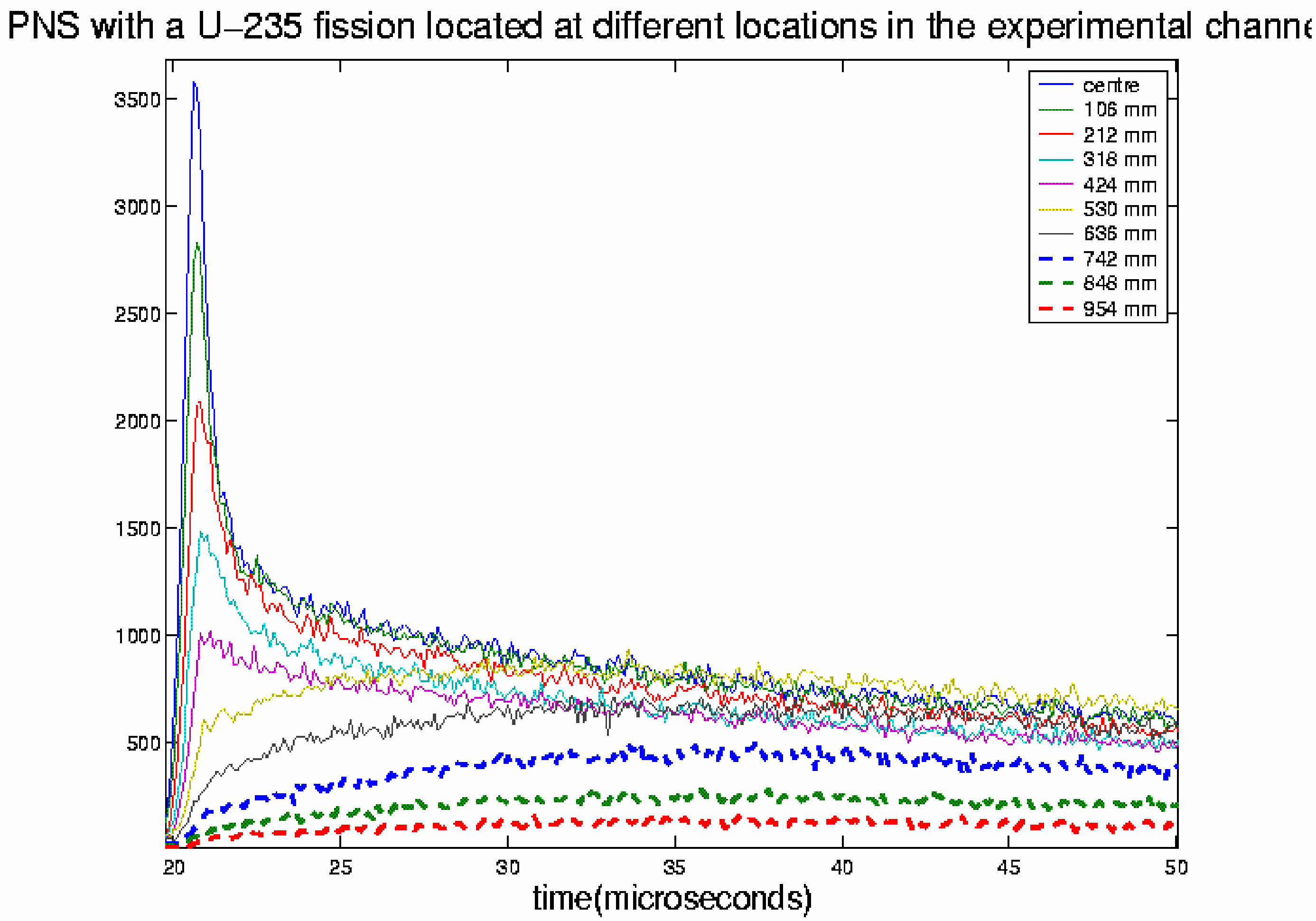
MUSE 4 Configuration



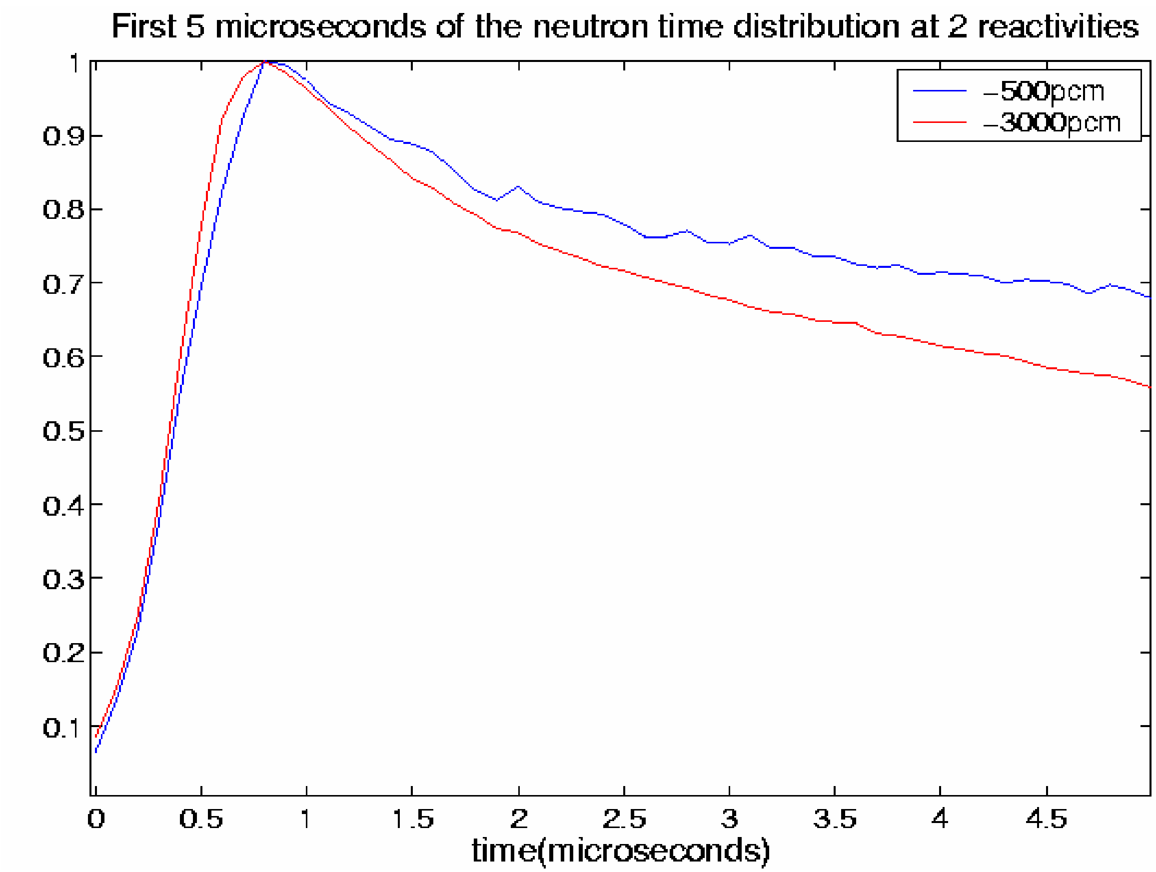
MUSE PNS Example in Core



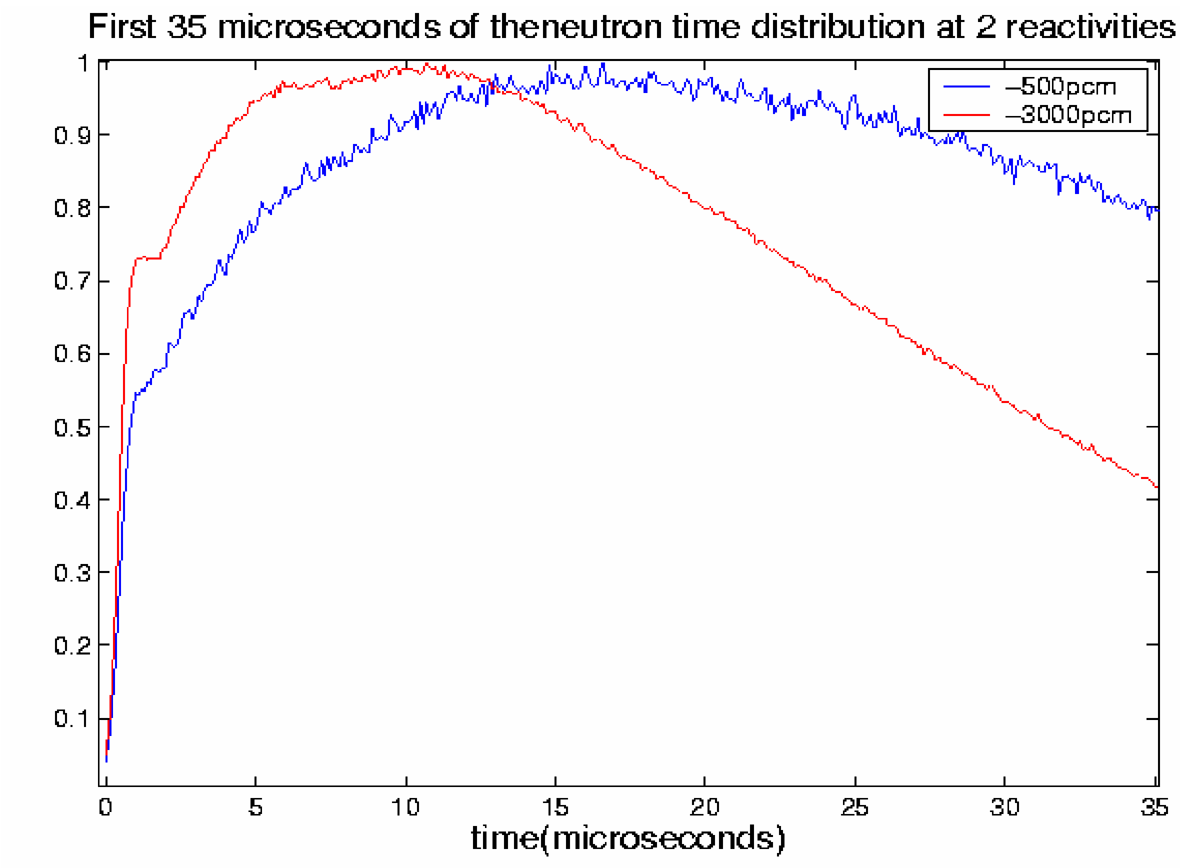
PNS vs Detector Location



Very Early Time PNS in Core



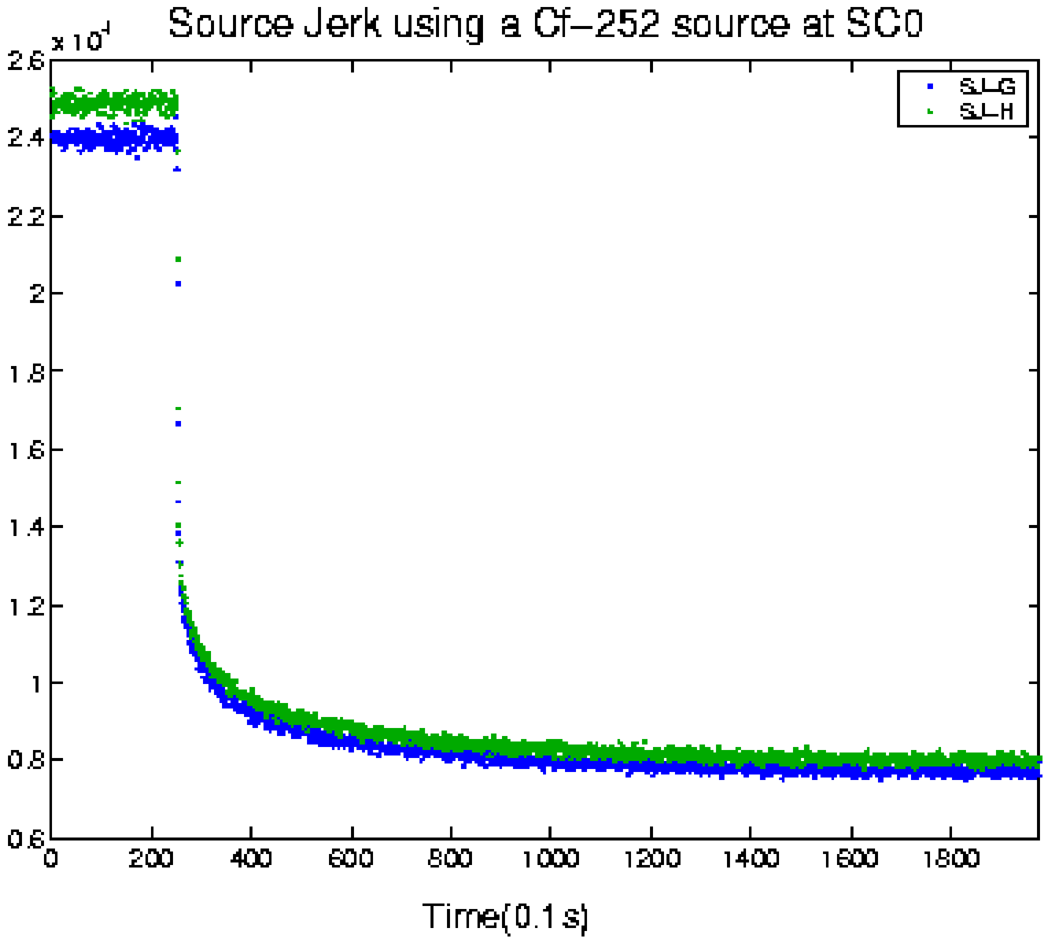
Early Time PNS in Reflector



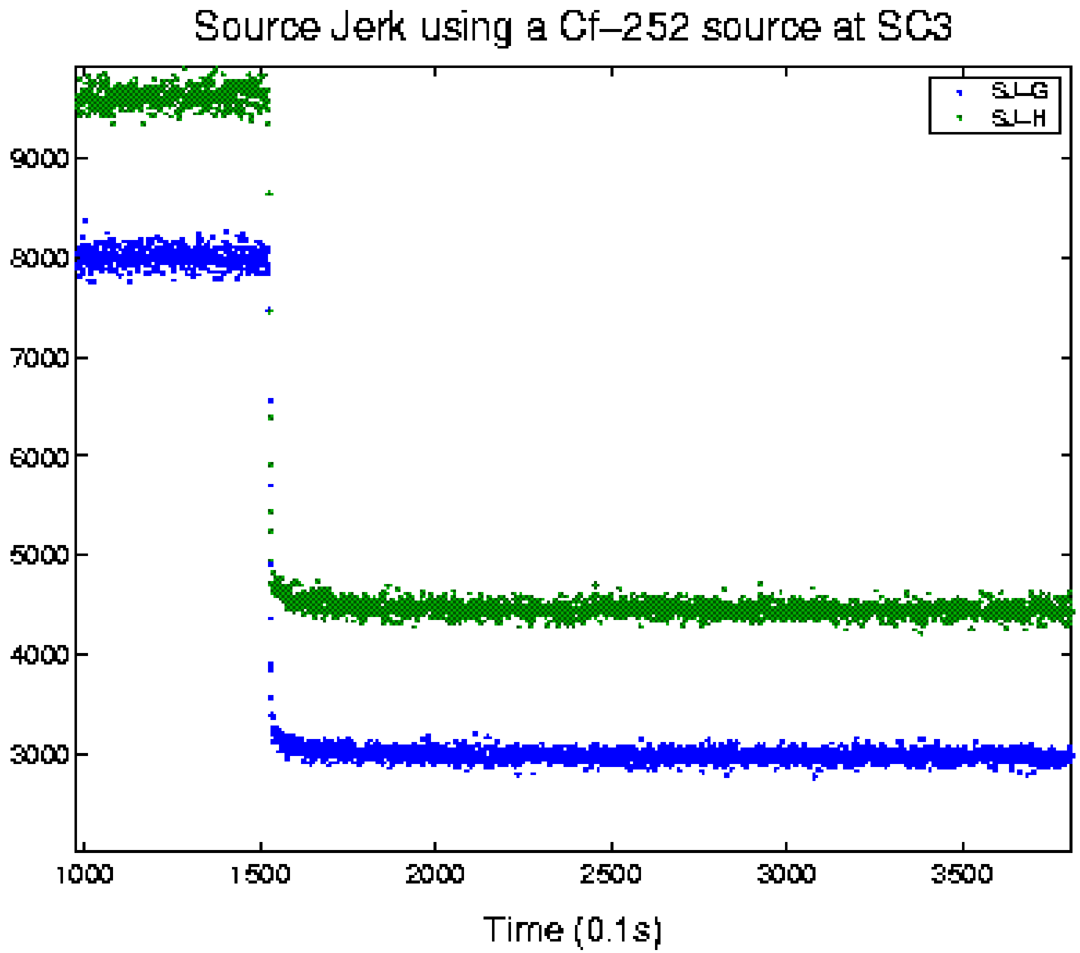
Key Points on PNS

- Slopes depend on reactivity (good!) but there is not a single slope (bad!)
  - Worsens for deeper subcritical
  - Two (+) schools of thought
    - Fit to multiple slopes because of different time regimes (e.g., source, equilibrium, reflector)
    - Don’t assume the generation time is constant

Source Jerk (-500 pcm)



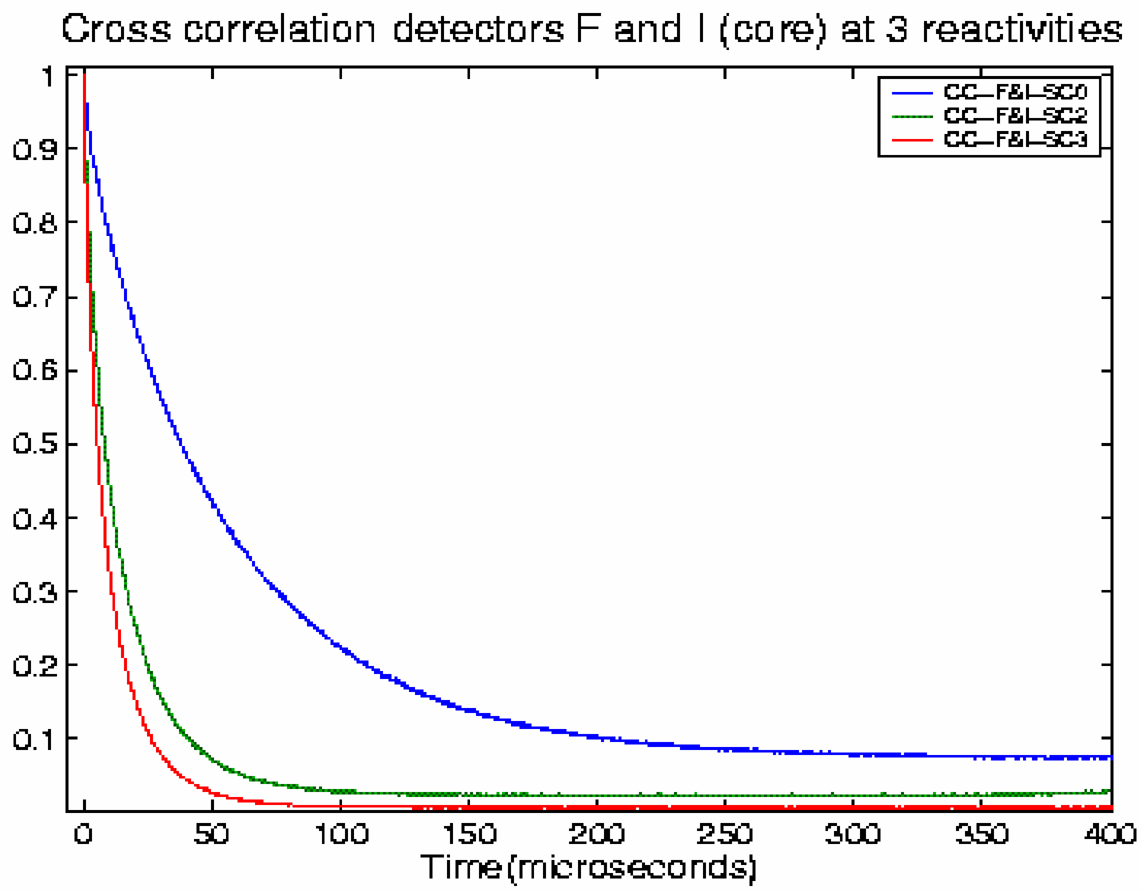
Source Jerk (-5000 pcm)



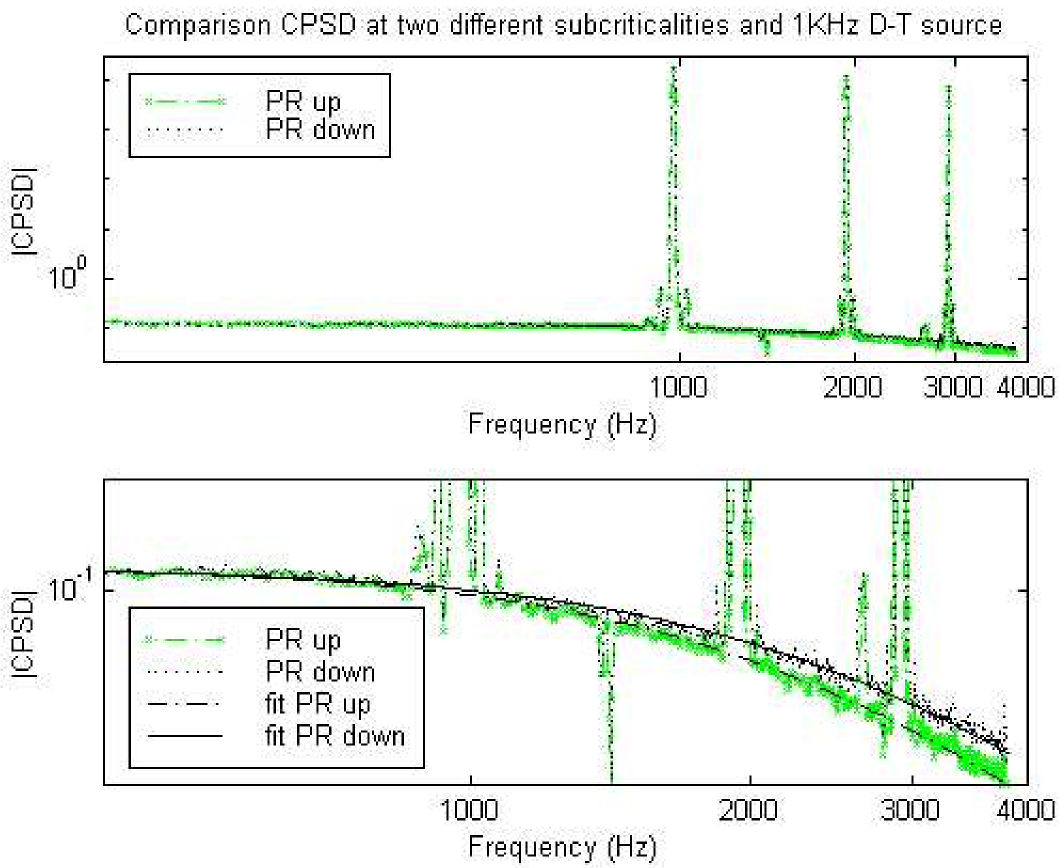
Key Points on Source Jerk

- Note that you cannot use prompt drop with no inherent source assumption
- Often a problem with statistics at lower reactivities

Cross Correlation



CPSD with PNS



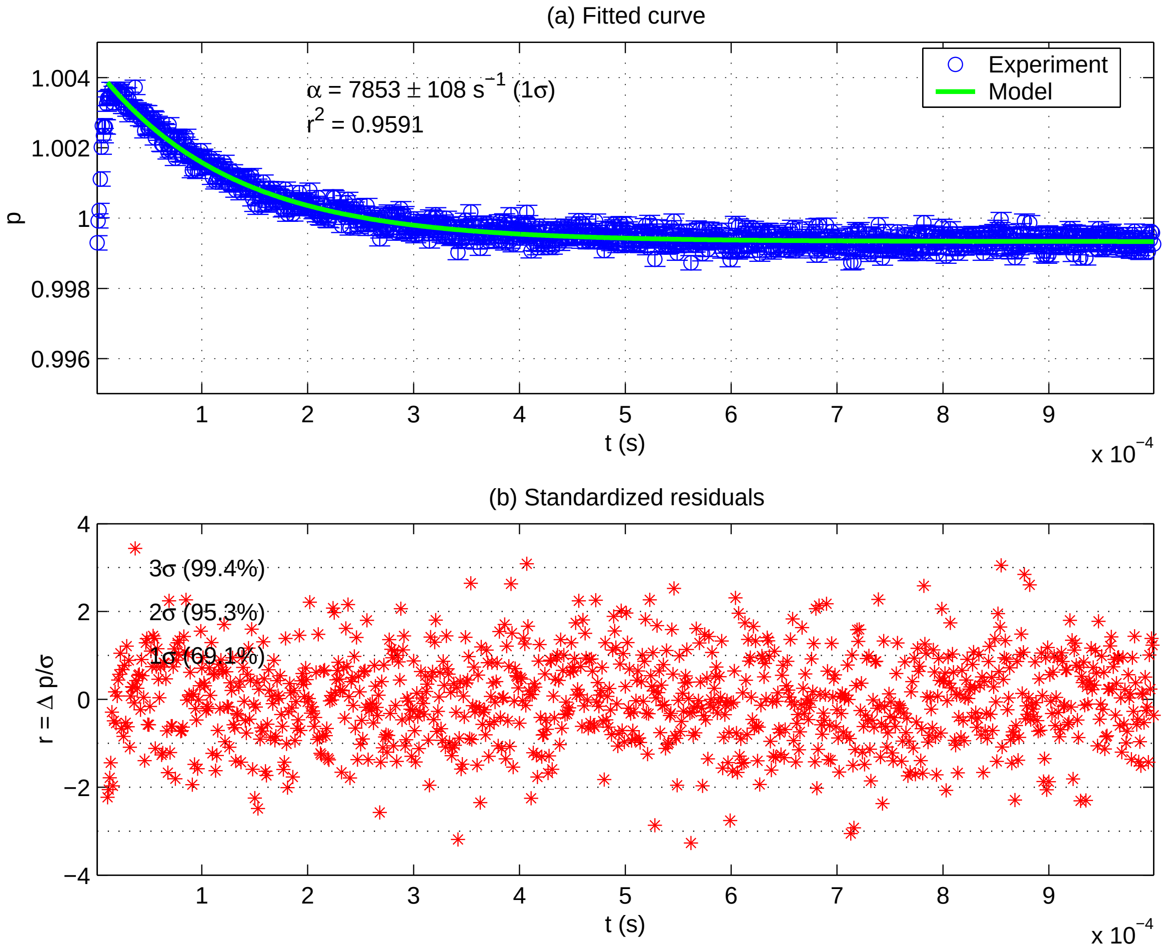
Key Points on CPSD

- Method works when not too deeply sub-critical
- Measurements in MUSE are more difficult because of the strong intrinsic source---leads to more background ("accidental correlations")

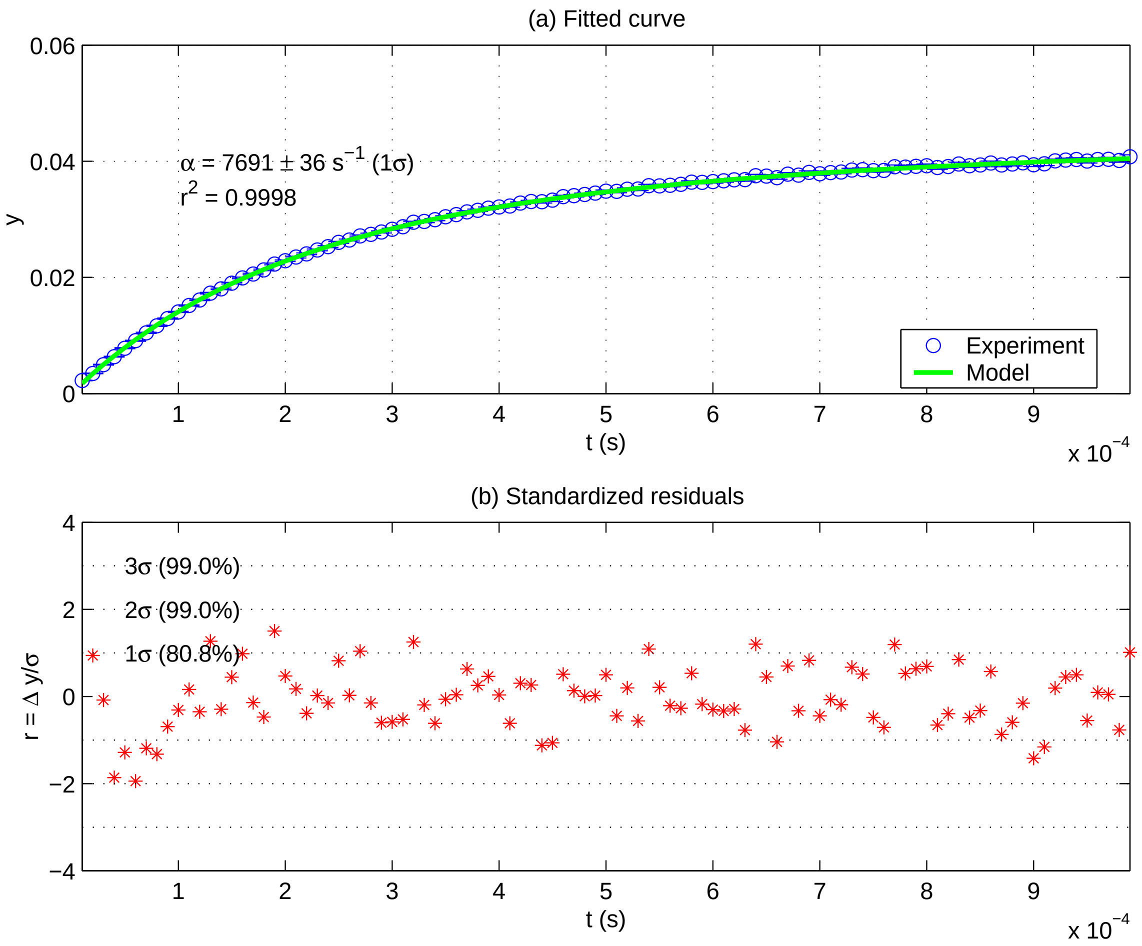
Summary Predictions of α

Configuration	Detector location	PNS	Cross-Correlation	Source-Jerk	CPSD
SC0	core	16639$\pm$23	16674$\pm$11	15899$\pm$794	-----
	reflector	15911$\pm$30	15824$\pm$12	15633$\pm$654	16023$\pm$228
	shielding	15642$\pm$45	15708$\pm$33	15314$\pm$794	-----
SC2	all	-----	-----	-----	-----
SC3	reflector	-----	-----	81889$\pm$4504	-----

Rossi-α


(a) Fitted curve
α = 7853 ± 108 s⁻¹ (1σ)
r² = 0.9591
Experiment
Model
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


(a) Fitted curve
α = 7691 ± 36 s^−1 (1σ)
r^2 = 0.9998
Experiment
Model
y
t (s)
x 10^−4
(b) Standardized residuals
3σ (99.0%)
2σ (99.0%)
1σ (80.8%)
r = Δ y/σ
t (s)
x 10^−4

Key Points on Rossi- and Feynman-α

- “Low” detector efficiency makes Feynman measurement difficult
- Intrinsic source makes Rossi measurement difficult
- Note both are only a few percent above background

Summary Discussion on MUSE Results

- Two schools of thought on PNS
  - Multiple slopes, where to start?
  - Changing generation time
  - Problem is trying to fit a point kinetics model to a non point kinetics world
- Feynman and Rossi alpha problems
- CPSD problems
- Source jerk

Why Experiments Before Cyclotron ?

- Uncertainties in all the measures
- However---MUSE will produce a report with suggested methods of measurement
- Part of TRADE's objective is to test those methods developed in MUSE
- Generic validation ?
- Blind testing of methods for final validation

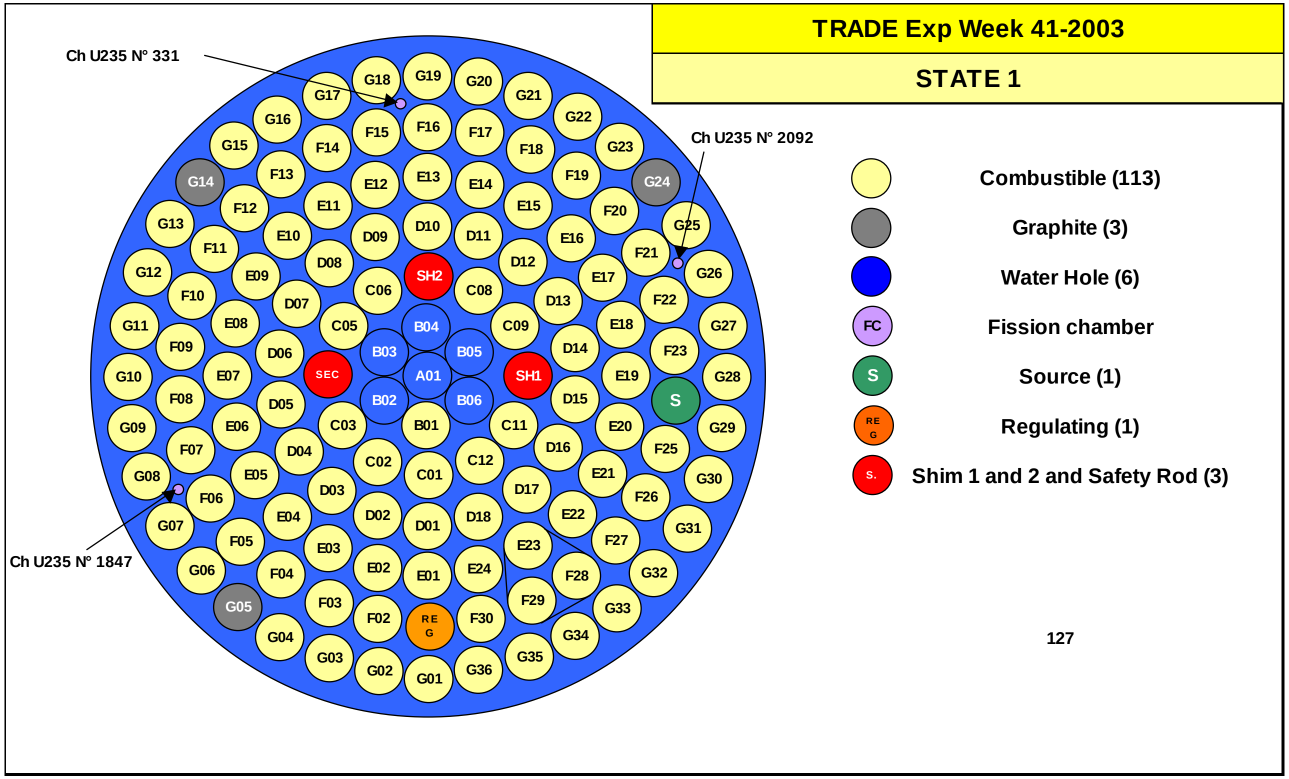
Sequence of Validation

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

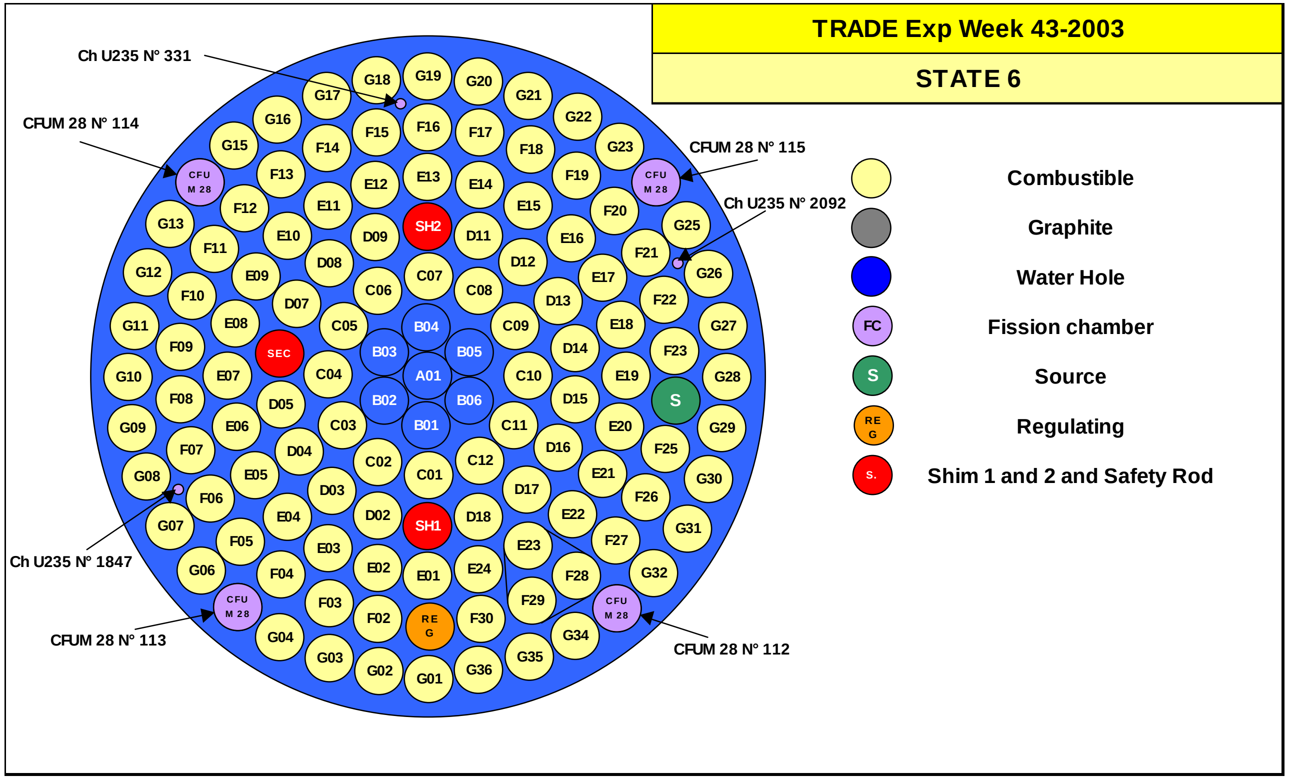
2003-2004

- MSM
  - Find the “TRADE core” w/o cyclotron
- Measures with Am-Be, Cf, DD, and DT sources
  - Source importance, source jerk
  - For direct comparison to MUSE
- Noise techniques (Feynman, Rossi and CPSD)
- Have approached “TRADE core” with MSM

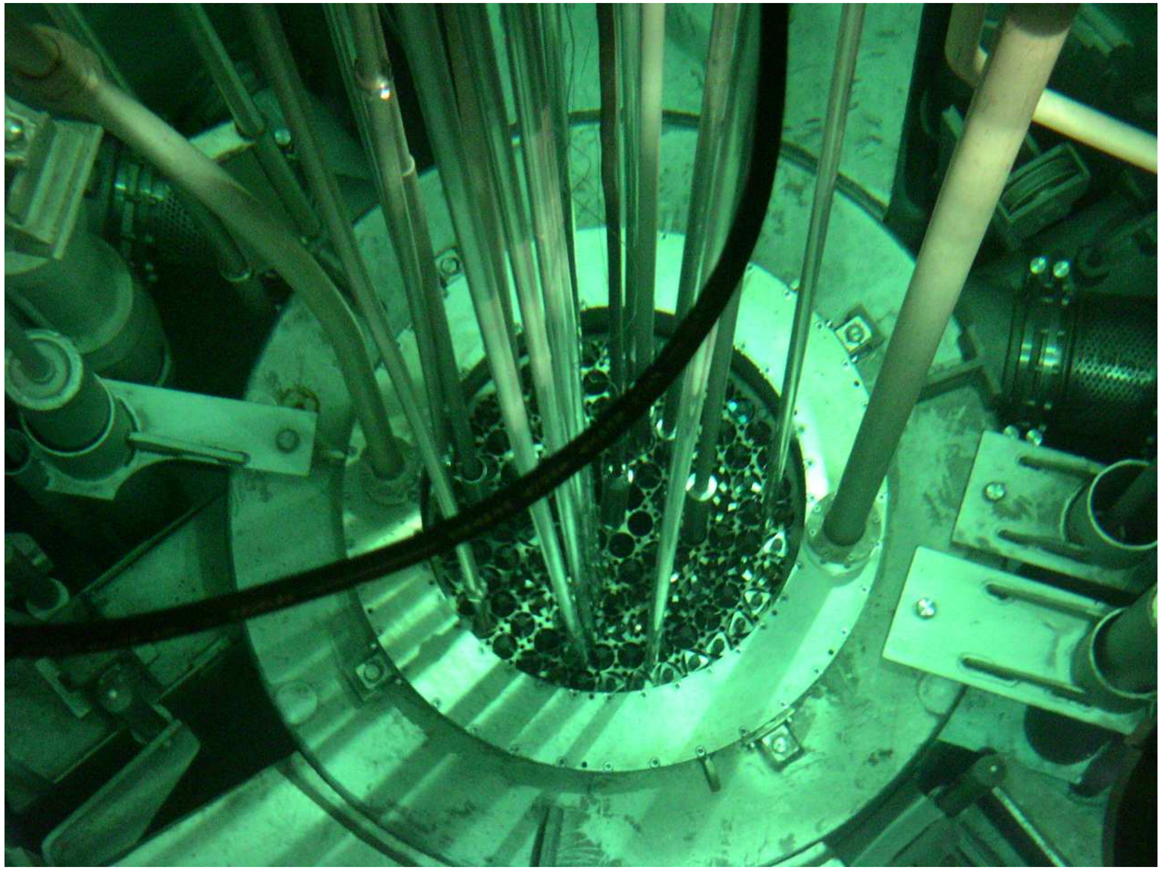
TRADE Reference Core



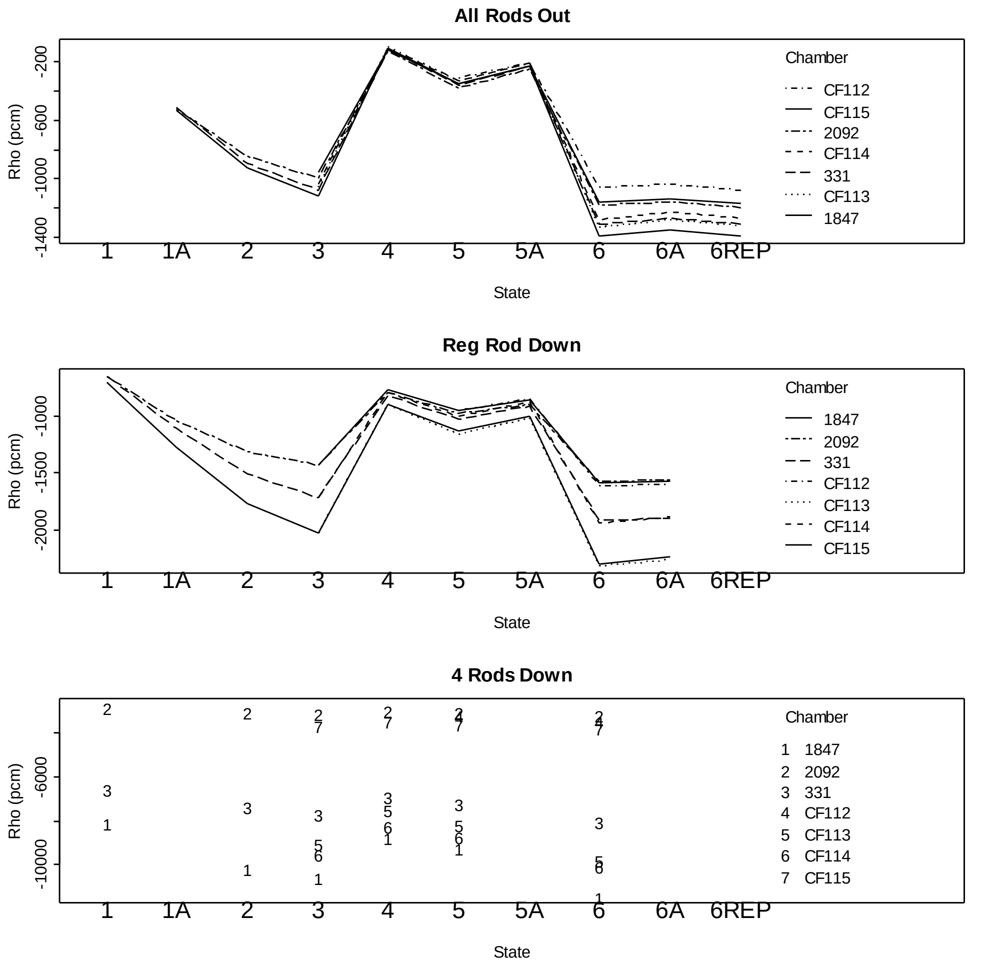
TRADE Mockup Core - 1



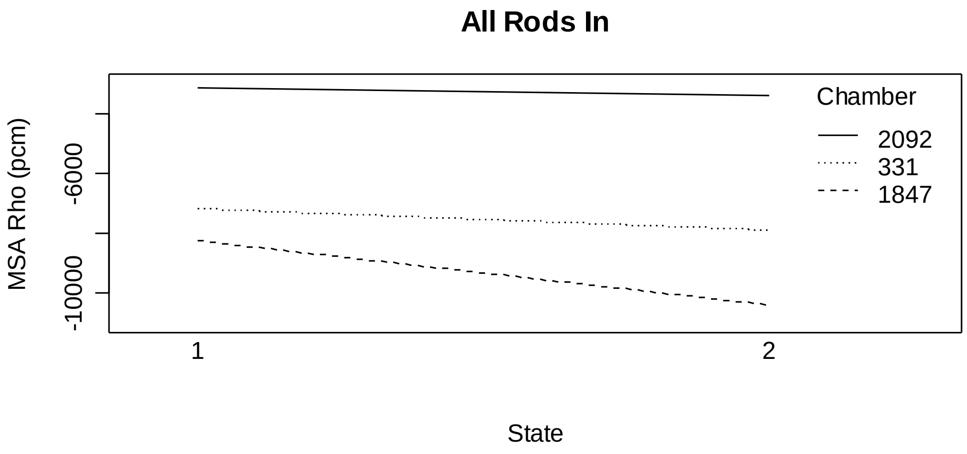
TRIGA w/o B-ring fuel

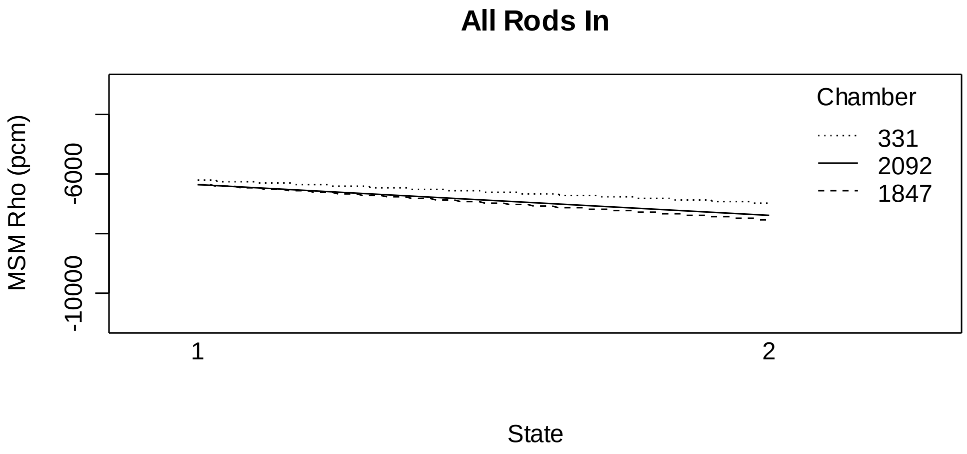


MSA Reactivities

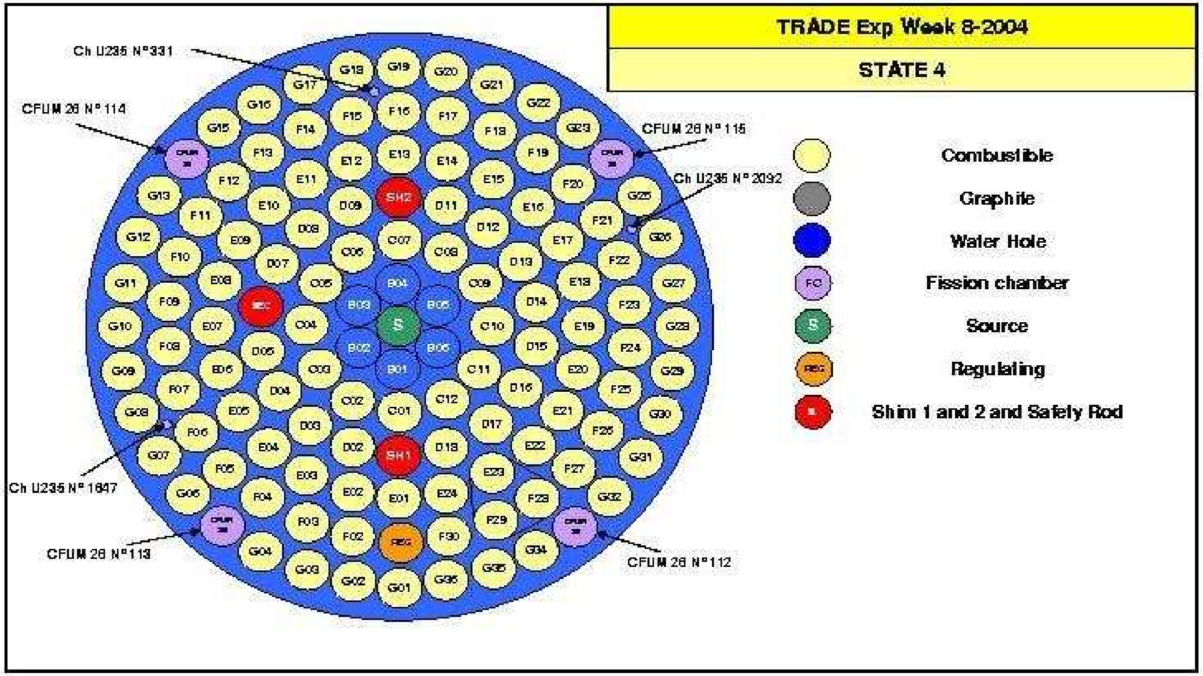


MSM Correction

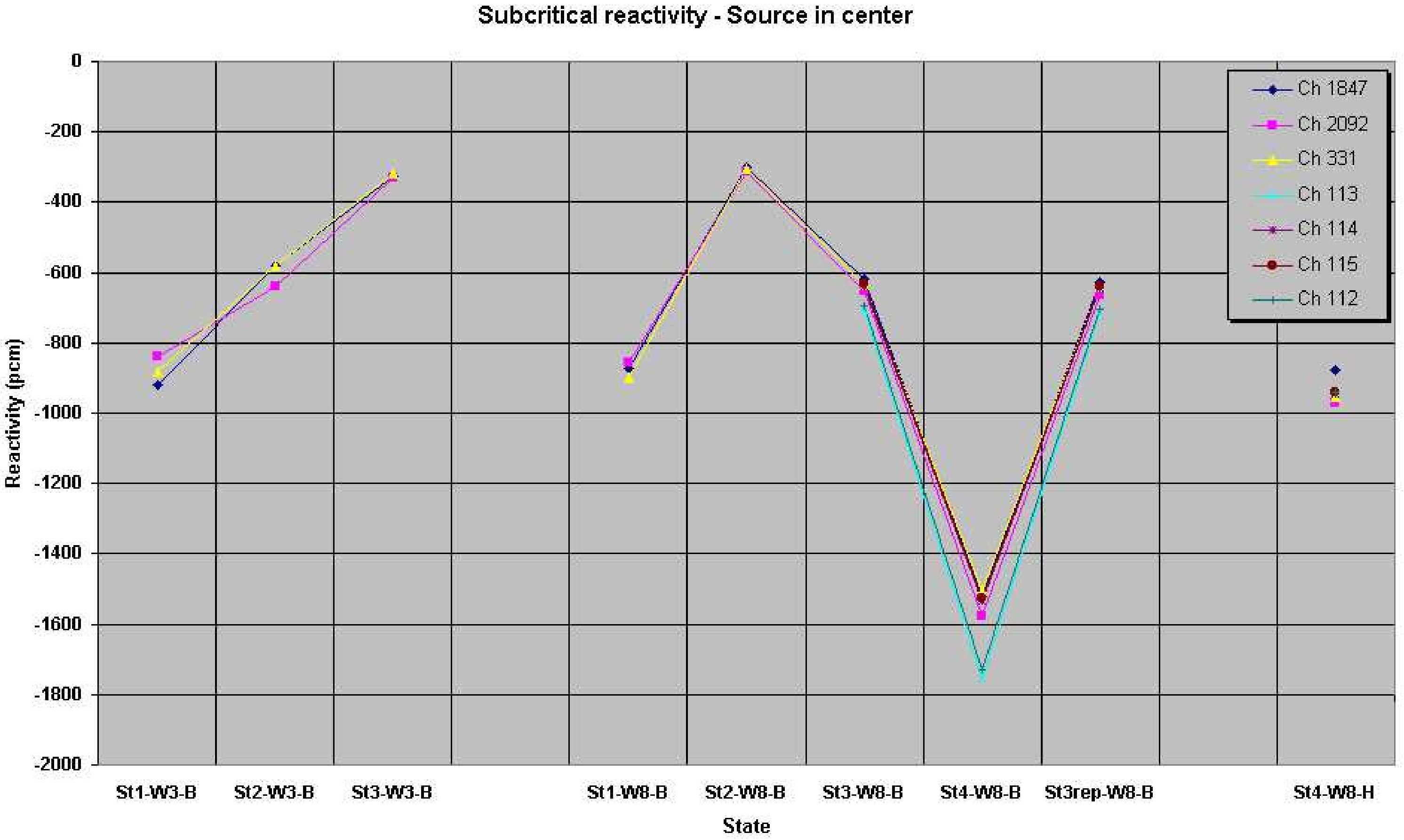




TRADE Mockup Core - 2

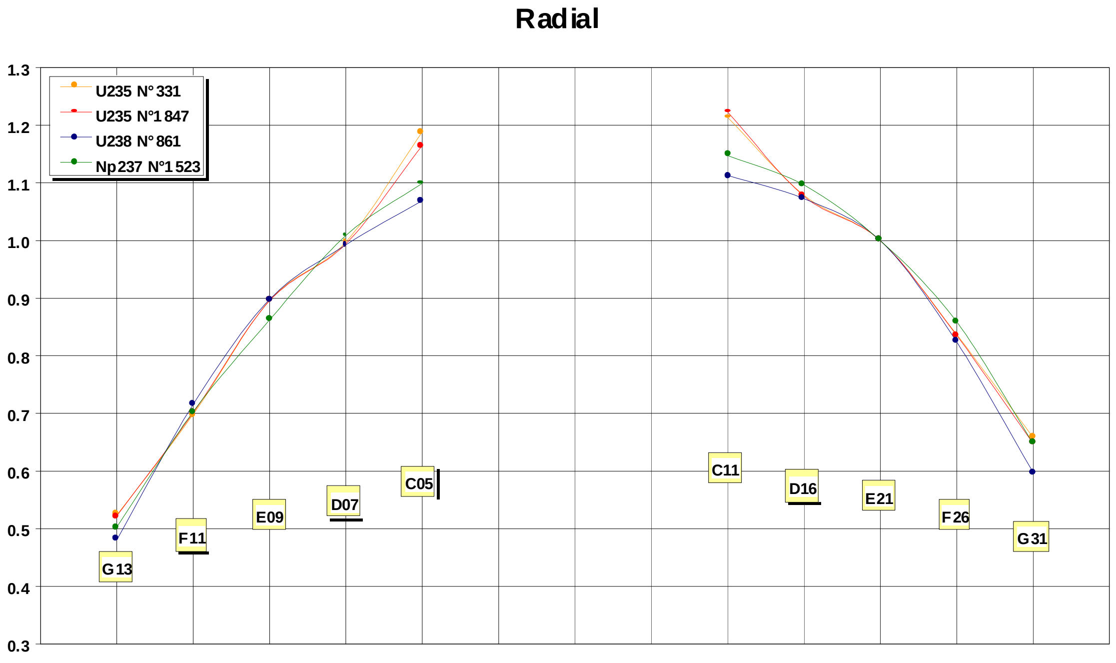


Source in Center



Radial Traverses

DEN / DER / SPEx / LPE



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Phase I, II, and III Experiments

- Phase I is 2003-2004 (before cyclotron)
  - MSM
  - Am-Be and Cf source
    - Jerk
    - Oscillation
    - Importance
  - Repeat with DD and DT

Phase I, II, and III Experiments (2)

- Phase II concerns the startup phase of the cyclotron
- Phase III concerns the full range of TRADE experiments, with the cyclotron

Phase II and III

- In these phases, the accelerator is in place
- We will be performing a number of reactivity determinations, using techniques qualified in Phase I
- With cores well characterized (3000-5000 pcm), we will then move into the full TRADE experimental program of operational testing (power, current, reactivity relations)

Operational Experiments

- Other than preliminary measures to determine the reactivity levels, we will most certainly be operating in current mode

$$i_p \propto P \frac{v}{\phi^* Z \rho}$$

Power/Reactivity Relations

- Can perturb reactivity or current to obtain an "operational" reactivity measure

$$\frac{\delta P}{P} = \frac{\delta S}{S} + \frac{\delta k / k}{1 - k}$$

Moving on to an ADS

- With our MUSE experience, we have found that measurement of sub-critical reactivity is not completely straightforward
- However, we have made much progress---it is not a question of whether you can see effects of reactivity changes, but to what level of uncertainty?
- Through TRADE, we hope to gain a better quantification of this

A Reminder

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

Last Word

- During MUSE program, Western Europe’s entire experimental capability actively participated (and often was in the same room!)
- Extremely productive interchanges
- TRADE has generated much the same interest (we hope)
- Programs such as these are the only way to preserve capabilities until we get serious about the next generation of reactors