A Fast-Neutron Coincidence Collar Using Liquid Scintillators for Fresh Fuel Verification

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AGENDA

- Background
- FNCL hardware and software
- Monte Carlo modelling
- Functionality testing
- Performance evaluation
- Summary

Background: Safeguards

INFCIRC/153: Comprehensive Safeguards Agreements give the right and obliges the IAEA to verify the correctness and completeness of State's declaration of nuclear materials (U, Pu, Th).

IAEA conducts safeguards inspection activities that address:

- Timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities
- Deterrence of such diversion by the risk of early detection

SGTS develop and maintain instruments for the purposes of measuring nuclear material items (e.g. nuclear fuel) to ascertain if sampled items have defects:

Bias defect: Refers to an item or a batch that has been slightly falsified so that only a small fraction of the declared material is missing

Partial defect: Refers to an item or a batch that has been falsified to such an extent that some fraction of the declared material is actually present

Background: NCC

Neutron Coincidence Counting (NCC) used to measure mass of nuclear materials

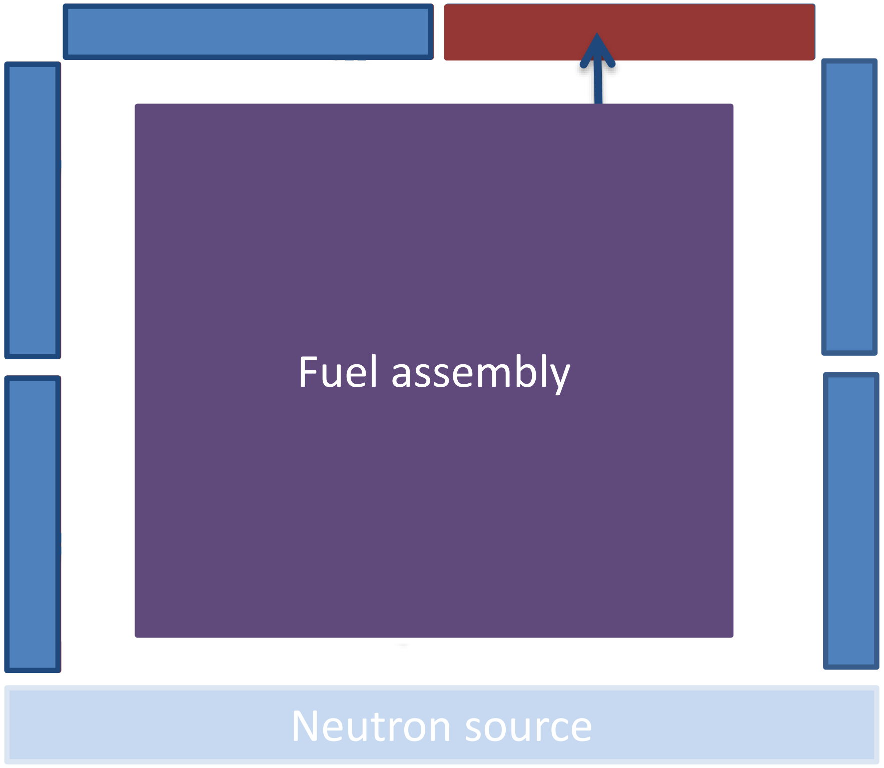
Active NCC applied to U-235 measurement

Applied to fuel assemblies through a collar geometry

NCC used to discern fission events from other neutron events e.g. (α,n) by detecting ≥ 2 neutrons in very short time window, typically μs

Major source of error (historically) are accidentals, e.g. when 2 or more (α,n) reactions happen within a few μs

Active NCC in fuel measurement:



Detected coincident neutrons ⟶ Fission events ⟶ Fissile material
Rate of fission used to determine mass of U-235

Background: Needs

Cd liner

UNCL in fast mode

Currently perform fresh fuel verification with UNCL; a He-3 based Instrument, a very good instrument for measuring fresh fuel (without BPs)

Burnable neutron poisons (BPs) e.g. Gd added to fuel matrix to increase fuel economy: neutrons are absorbed, affects measurement.

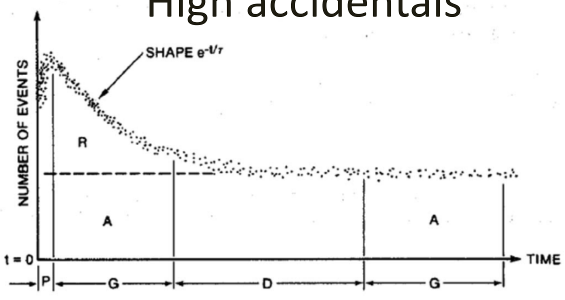
1) Correct for effect (rely on truthful declaration of Gd) → Diversion risk
2) Use Cd liners to remove thermal neutrons → Measurement takes hours

System	Time for 1%RSD on net doubles rate (min)	Drop in doubles due to maximum Gd
UNCL (thermal mode)	~40	~40%
UNCL (Cd mode)	~180	~9%

Use of LS to directly detect fast neutrons (>500 MeV) allows huge improvement in measurement statistic

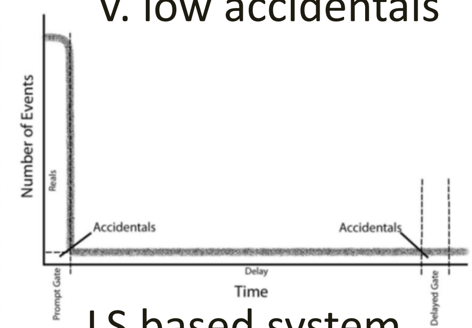
Fast neutrons also have lower cross-section with Gd hence lower drop in doubles

High accidentals



He-3 based system

V. low accidentals



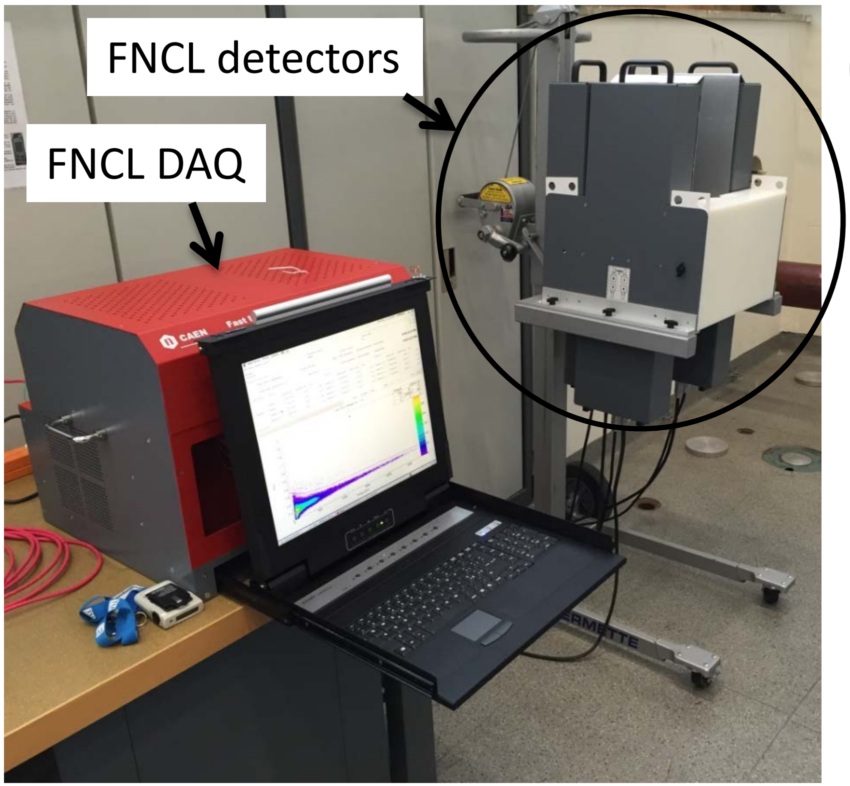
LS based system

FNCL hardware: Detectors

Detectors mounted on moveable crane with adjustable height

Modular detector panels and simplified cabling for ease of assembly in 10 minutes

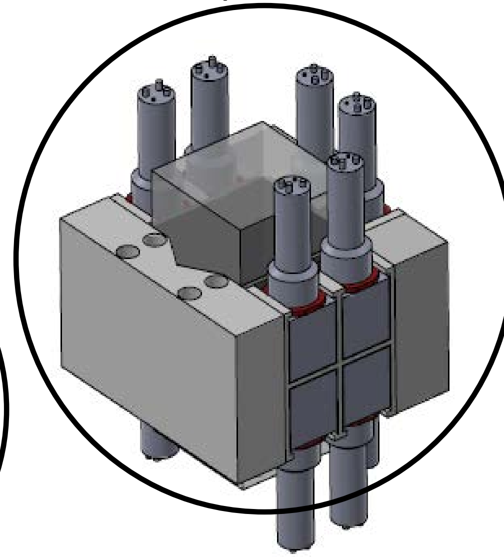
Integrated Cd liner – always fast mode



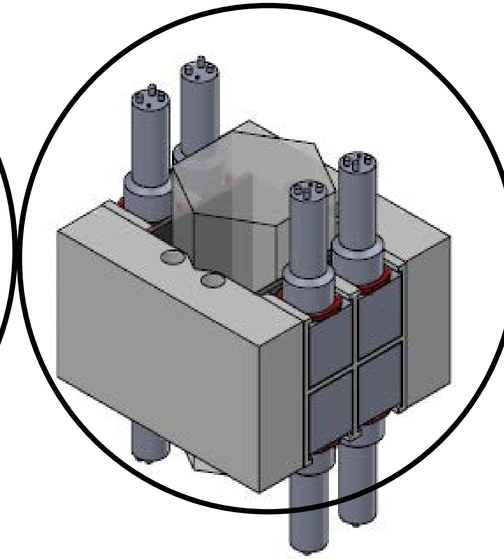
FNCL system

Both options fit PWR and WWER fuel types

Option 1



Option 2



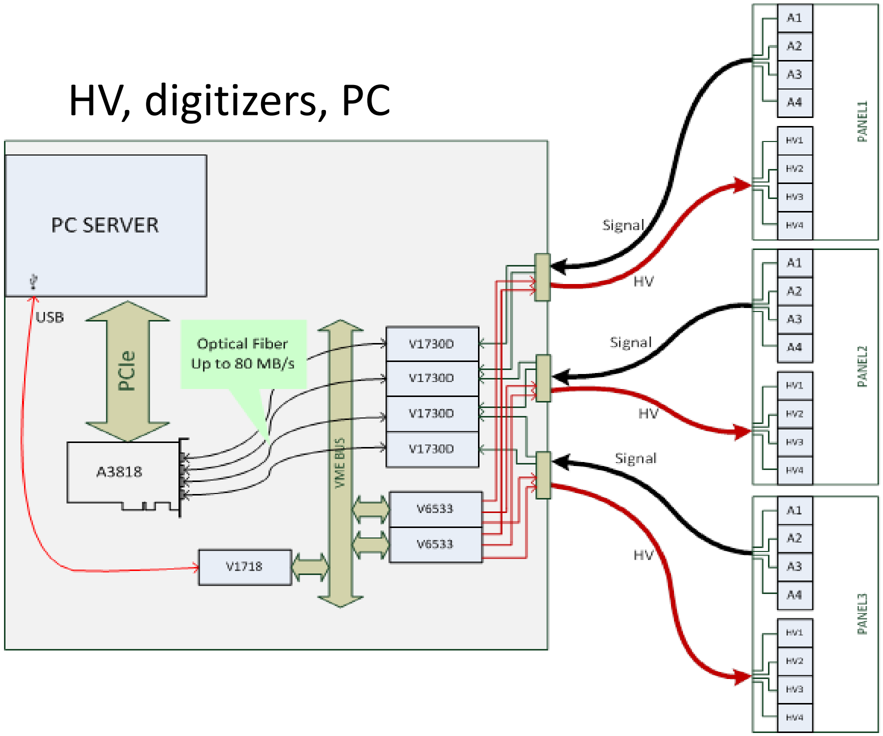
Option 1	Option 2
12 detectors	8 detectors
Higher efficiency	Lower efficiency
2 x AmLi sources	4 x AmLi sources
More components	Fewer components

The following sealed sources are required for operation and calibration of the FNCL:

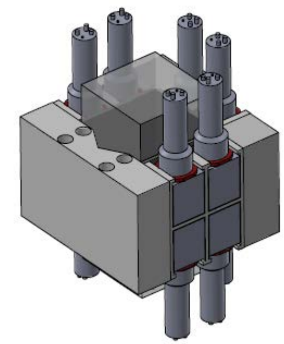
- Up to 4 x ^{241}AmLi (N,C series; emission ≥ 5e4 ns^{-1})
- 1 x ^{137}Cs (Activity ≥ 100 kBq)

FNCL hardware: DAQ

HV, digitizers, PC



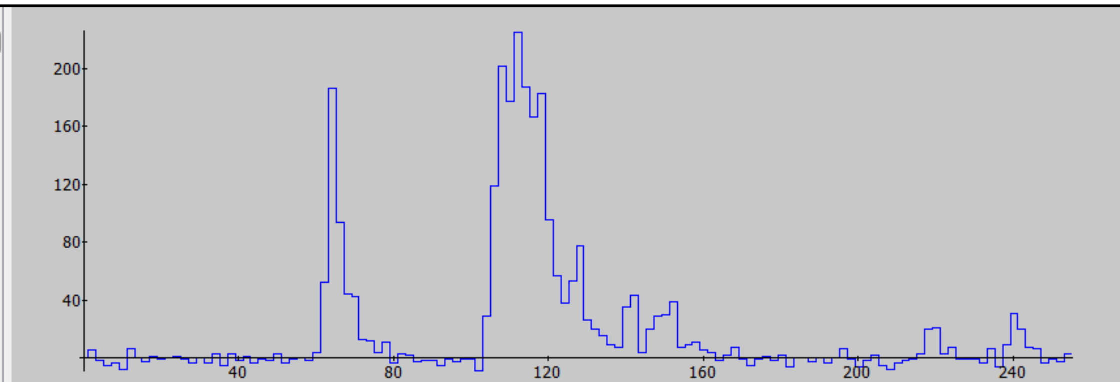
data



Digitize up to 1M events per second with:

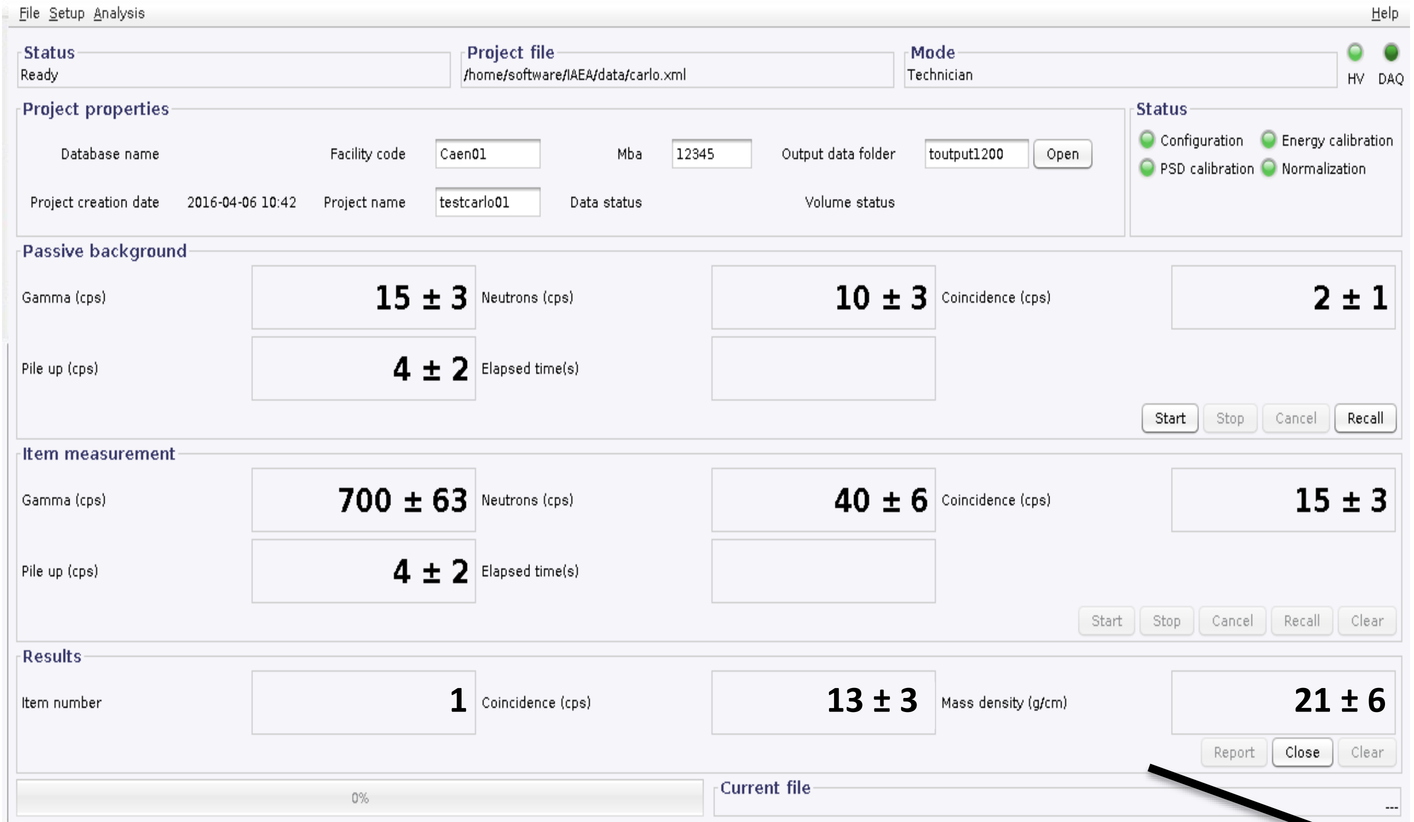
- Detector number (1-12)
- Time stamp (±1 ns)
- Digital sampling of its waveform at 500 MHz 14 bit depth in a time window of 256 ns
- Record pulse train for data re-evaluation

##	Address	Time stamp, ns
1971	6	858129456
1972	9	858134380
1973	10	858141102
1974	7	858141708
1975	2	858141836
1976	1	858147328
1977	3	858148546
1978	1	858150108
1979	6	858151184
1980	2	858151884
1981	1	858152140
1982	2	858152666



FNCL software: GUI

User software for technician setup and field use by inspector



Configuration

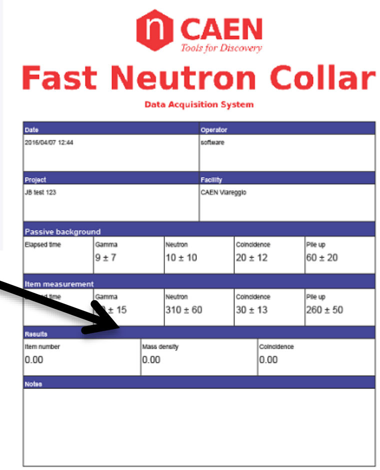
Energy calibration

PSD calibration

Normalization

Measurement

Report

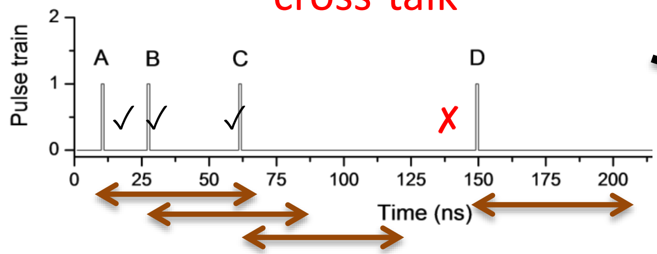


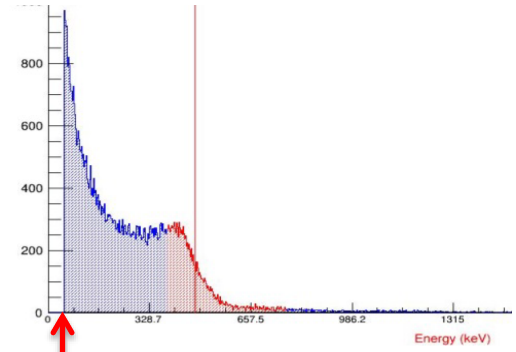
Measurement results and uranium mass compiled into PDF report

FNCL software: Data processing

Data in

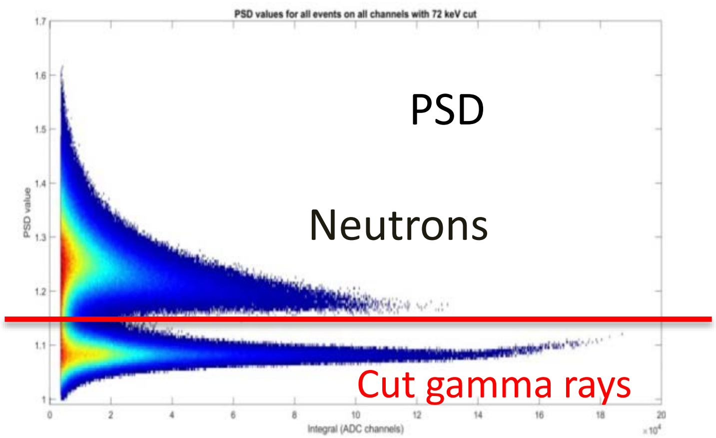
Cut non-correlated events and cross-talk





Energy thresh cut

Neutron doubles rate calculated on-the-fly

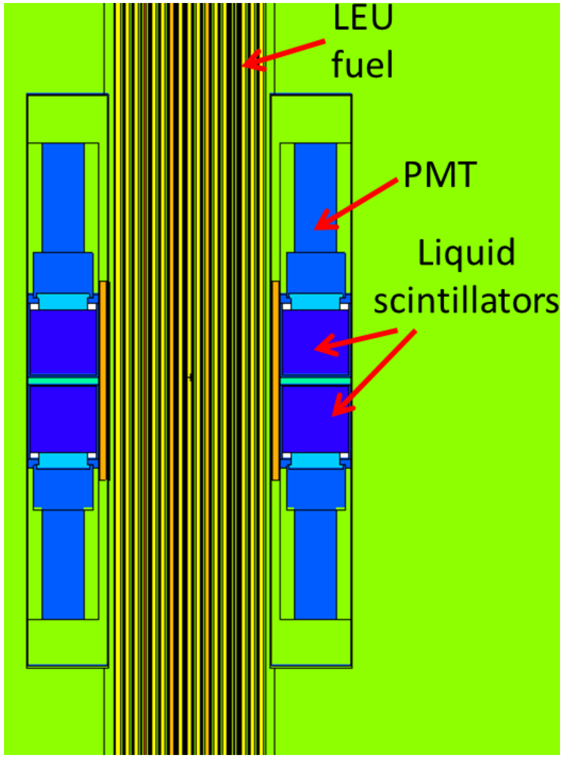


Cut pile-up events

Monte Carlo modelling

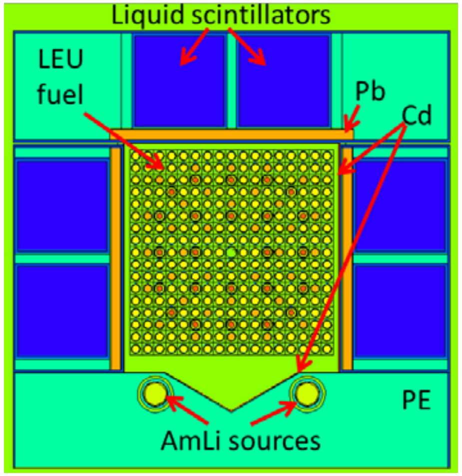
1. MCNPX-Polimi
   - Input geometry and sources
   - Induced fission
   - Radiation detection (Cell, E, t, n/γ, generation…)

2. SimPLiS-NCC
   - Light generation
   - Electronic filters: Coinc, Cross-talk, Energy, PSD, Pileup
   - NCC counting



Model benchmarked against laboratory sources and reference fuel assembly

System	Source	Measurement	Experiment (cps)	σ (cps)	MCNP-SimPlis (cps)	σ (cps)
3 panel	^{252}Cf	Neutron doubles	610.95	1.01	644.29	1.07
	^{137}Cs	Gamma singles	12035	4.5	12367.2	1.9
2 panel	^{252}Cf	Neutron doubles	221.83	0.61	227.26	0.62
	^{137}Cs	Gamma singles	8567.3	3.2	8722.0	3.6

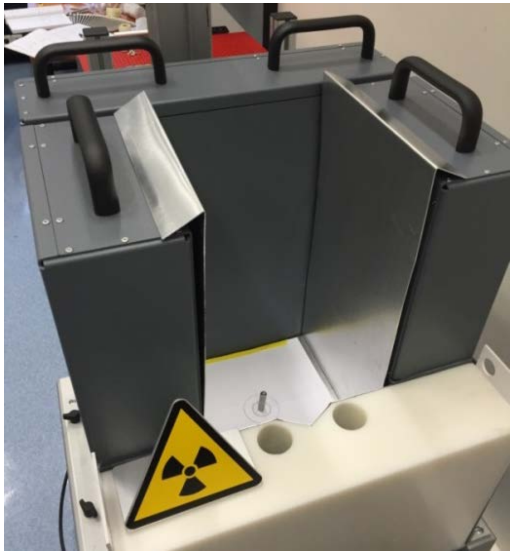


Functionality testing

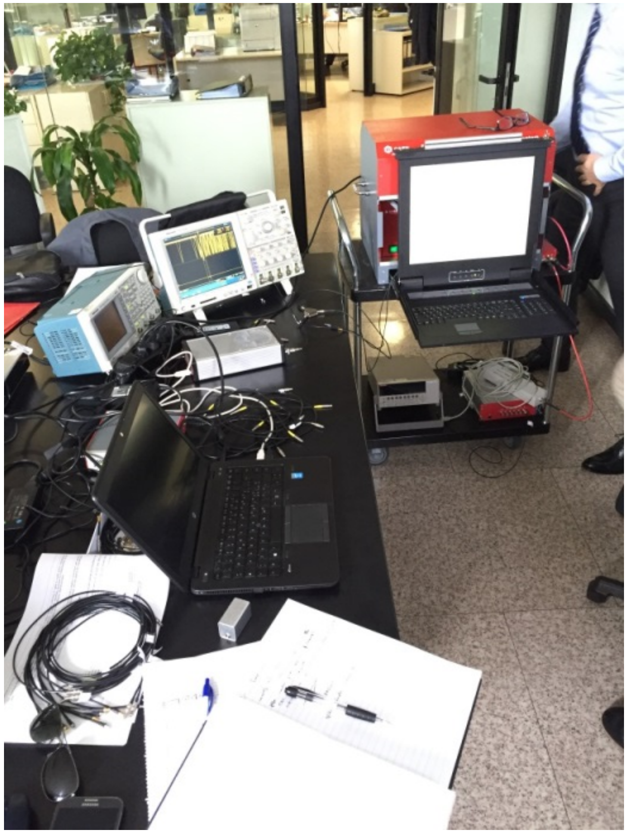
27 tests performed with electronic instrumentation, synthesized data, calibration radiation sources, WWER440 fuel assembly to comprehensively test functionality of hardware and software against requirements.

- Time stamping
- High event rates
- Data transfer
- Coincidence counting

Calibration sources



Electronic testing



WWER440 fuel

Performance Evaluation: Fuel Assembly

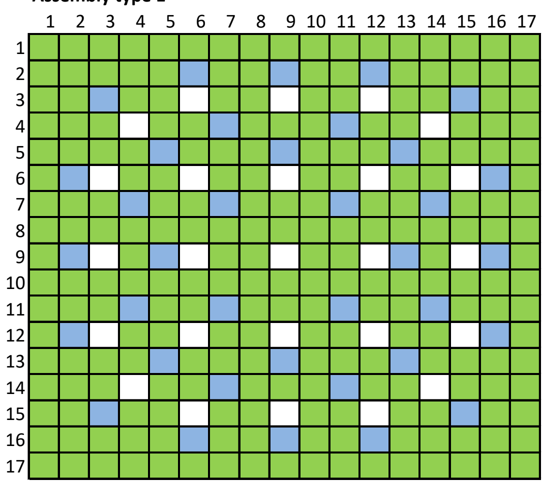
JRC Institut für Transurane (ITU), Karlsruhe, Germany

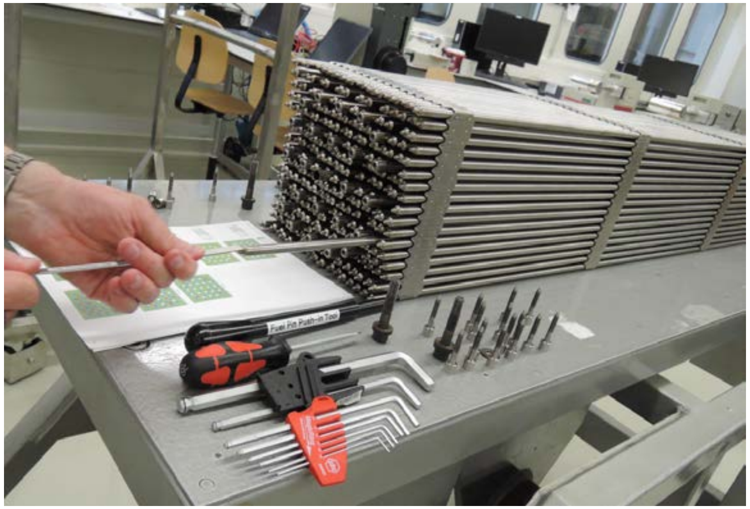
17 x 17 PWR fuel assembly on moveable crane

Uranium rods at 3 enrichments

Assembly Type	1% Enr. # of rods	3% Enr. # of rods	5% Enr. # of rods	Average Enr.	U-235 LD (g/cm)
1	36	228	0	2.82%	36.59
2	0	264	0	3.11%	40.38
3	0	228	36	3.36%	43.71

Assembly type 1



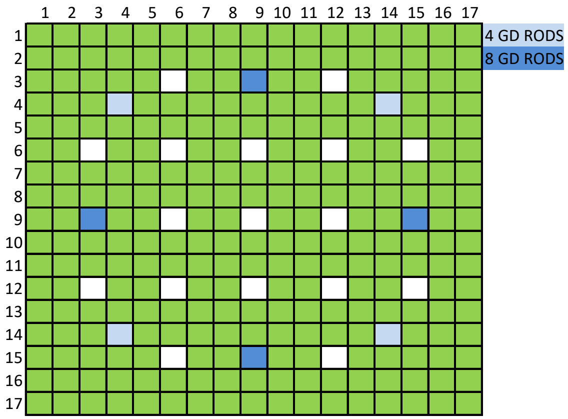


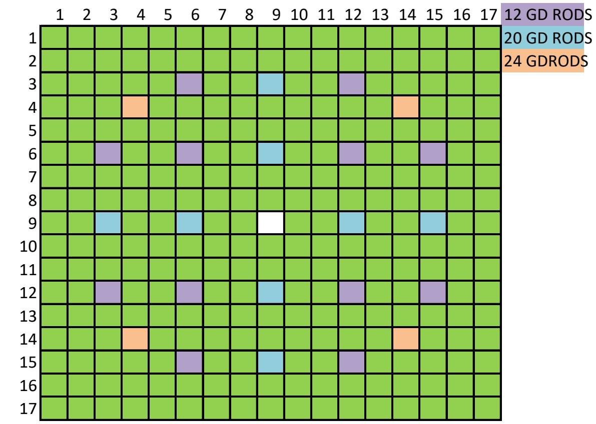
Performance Evaluation: Gd rods

24 steel rods manufactured at IAEA and filled with Gd_2O_3 powder at HQ

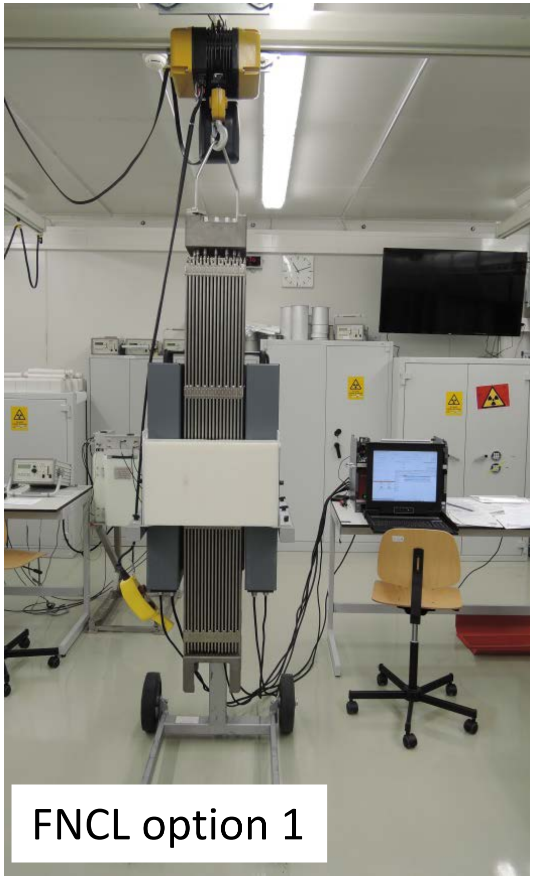
Measurements of 3.36% enr. assembly with 0, 4, 8, 12, 20, 24 Gd rods inserted into guide tubes. Matching mass ratio range in commercial fuel

		UO_2 loading	Gd_2O_3 loading	Mass ratio
# Rods	wt% Gd_2O_3	(g/cm)	(g/cm)	Gd_2O_3:(Gd_2O_3+UO_2)
4	~10	1420.3	1.9600	0.1378%
8	~10	1420.3	3.9200	0.2752%
12	~10	1420.3	5.8800	0.4123%
20	~10	1420.3	9.8000	0.6853%
24	~10	1420.3	11.7600	0.8212%





Performance Evaluation: Measurement



FNCL option 1

FNCL option 2

Calibration measurements:

- Background – once
- Active background (with AmLi sources) – once
- Cs (Energy calibration) – once daily
- Cf (PSD calibration) – once

Measurements:

- 10 min passive
- 10 min active (2/4 AmLi)

Calculation:

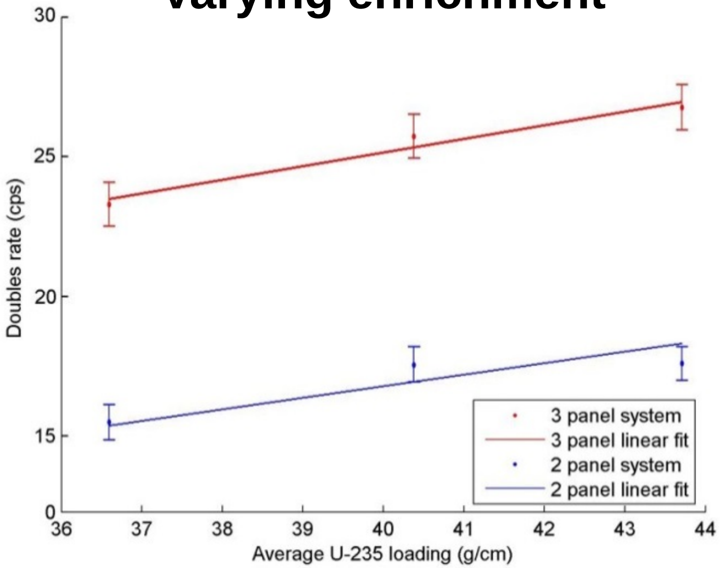
Net doubles = active - passive

Impact of enrichment and Gd loading investigated for FNCL options 1 and 2:

Enrichment (%)	0 Gd	4 Gd	8 Gd	20 Gd	24 Gd
2.82	✓				
3.11	✓				
3.36	✓	✓	✓	✓	✓

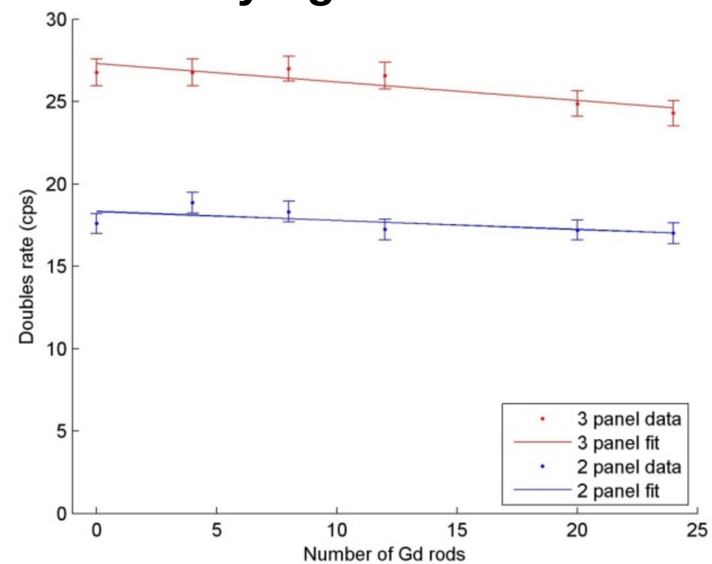
Performance Evaluation: Results

Varying enrichment



Average σ on doubles 1.03% for 3 panel system and 1.19% for 2 panel

Varying Gd content



Drop in doubles rate due to Gd <u>SS</u> rods agreed within 1 σ with Monte Carlo. SS contributed to drop in doubles

Extrapolation to commercial Gd geometry (Zr cladding):

Detector type	Time for 1% RSD doubles	Max Gd drop
UNCL (fast mode)	3 h	~9%
HE UNCL (fast mode)	2 h 45	~7%
FNCL 2 panel	18 min	3%
FNCL 3 panel	14 min	3%

Fast measurement ✓
Low Gd dependence ✓

Summary

- Functional hardware and software for fresh LEU fuel verification
- Benchmarked Monte Carlo model with PWR fuel
- Field-deployable: modular assembly in 10 minutes
- PWR and WWER 1000 fuels assayed to 1%RSD faster than alternatives (factor of 6)
- Almost immune to burnable poisons (~3% max drop compared with 7%)
- Approval for inspection use pending field testing on commercial fuel assemblies
- Made possible with LS and fast neutron detection

System	Time for 1%RSD on net doubles rate (min)	Drop in doubles due to Gd
UNCL (thermal mode)	~40	~40%
UNCL (fast mode)	~180	~9%
HE-UNCL (fast mode)	~145	~7%
FNCL (fast mode)	20-25	~3%

Large Gd dependence ✗

Large measurement time ✗

Large measurement time ✗

Good performance ✓