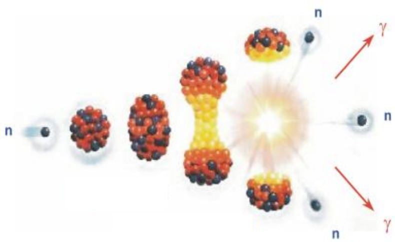


VERDI – a double fission-fragment time-of-flight spectrometer

R. Borcea, S. Oberstedt

IRMM - Institute for Reference Materials and Measurements

Geel - Belgium

http://irmm.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

- **Motivation**
- **VERDI – concept and design**
- **EFNUDAT experiment @ IKI: first results**
- **More about diamonds…**
- **Conclusion & Outlook**

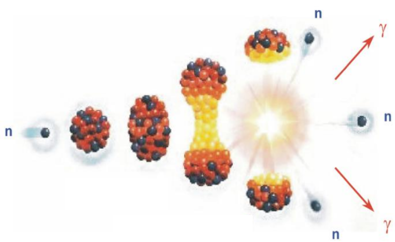
Motivation

✓ **Reliable predictions on fission product yields relevant in modern nuclear applications (GEN-IV, ADS…)**

- Radio-toxicity of the nuclear waste
- γ-ray heating
- Decay heat calculations
- Delayed neutron yields relevant during reactor operation

- **Prediction of fission-fragment mass and kinetic energy distributions of minor actinides (^{237}Np, ^{241,243}Am, $^{242\text{-}248}$Cm)**
- **Emission spectrum and multiplicity (as a function of fragment mass) of prompt γ-rays and neutrons**
- **Delayed neutron emission pre-cursor yields**

Motivation



- **Fission fragment (FF) yield $\underline{Y(A, E_{kin}; TKE)}$**
- **Prompt neutron multiplicity $\underline{\nu(A, TKE)}$**
- **Prompt fission neutron spectrum; $\underline{\varepsilon(A)}$**
- **Prompt fission γ-ray spectrum and multiplicity;**

✓ Double-energy (2E) technique

- ➢ (Twin Frisch-grid) Ionization chamber (large angular acceptance)
- ➢ Silicon detectors
- ⇨ Pre-neutron mass and total kinetic energy distribution (A*, TKE)
- 😐 Input of prompt neutron emission data (multiplicity, TXE dependence), iterative procedure $\rightarrow \Delta A > 4$ u
- ☹ Experimental neutron data only for a few isotopes available

✓ Double-velocity (2v) measurement

- ✓ Double TOF spectrometer
- ⇨ Pre-neutron mass and kinetic energy distribution (A*, E^*_{kin}; TKE)
- ☹ Hitherto mostly limited timing (=mass) resolution, efficiency…

✓ Recoil mass-separator (e. g. LOHENGRIN)

- ⇨ Single post-neutron mass and kinetic energy distribution (A, E_{kin})

VERDI – the concept

✓ **Simultaneous measurement of kinetic energy and velocity of both fission fragments, 2(v, E)♥**

- 2v $\rightarrow$ pre-neutron masses, A_i* (i = l, h), TKE
- v, E $\rightarrow$ post-neutron masses, A_i, $E_{k,i}$ (i = l, h)

➢ **$\nu_i(A_i^*)$ from the difference $A_i^* - A_i \rightarrow$ TXE(A_i)**

➢ **prompt and delayed decay modes of FF**

♥ **Cosi Fan Tutte (ILL)**

Goals:

- **spectrometer efficiency $\varepsilon \approx 0.005 - 0.01$♥**

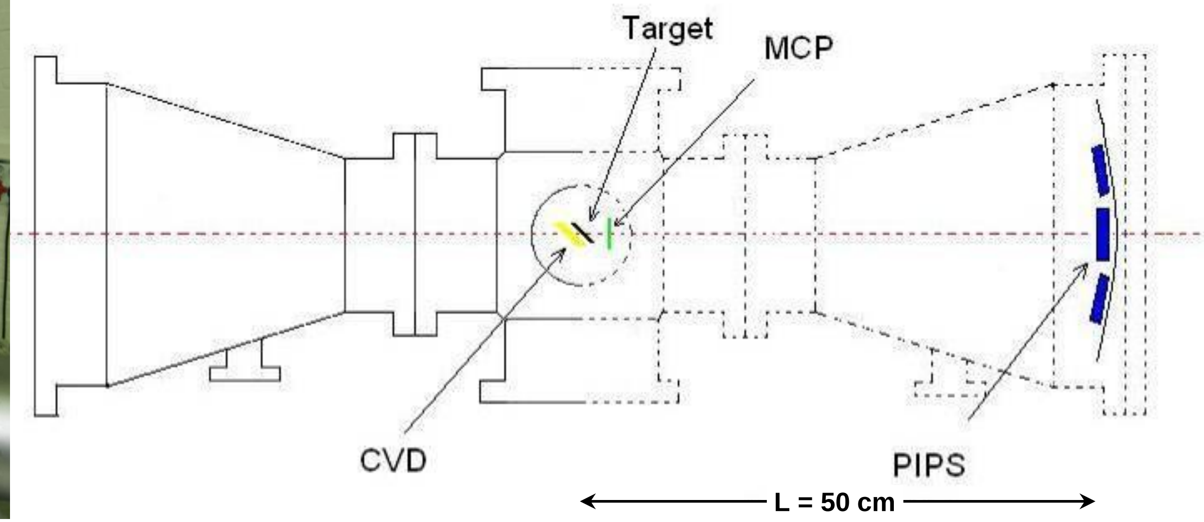
- **high resolution energy detector ($\Delta E/E = 0.006$)**
- **high precision (transmission) time pick-up with $\tau < 200$ ps @ L = 50cm**

- **for a mass resolution of $\Delta A < 2$**

- **radiation hardness of the fission time pick-up**

♥ **Cosi Fan Tutte ($\varepsilon \approx 5\times10^{-5}$)**

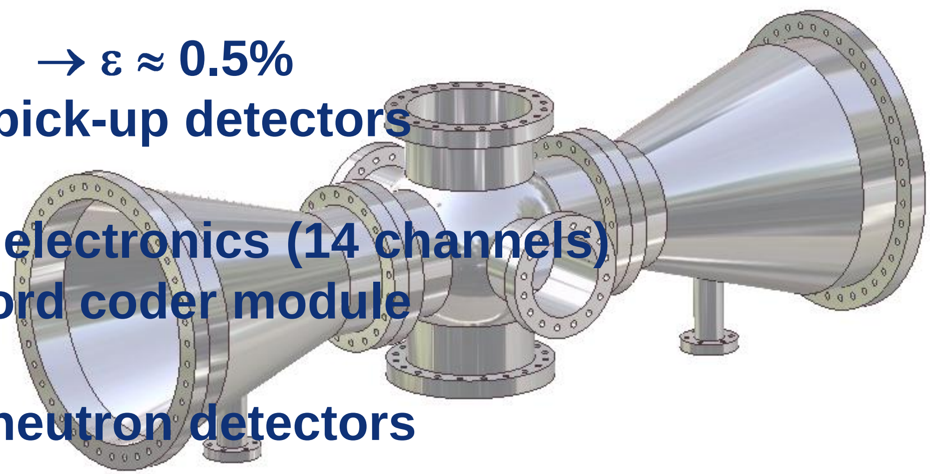
VERDI - the design



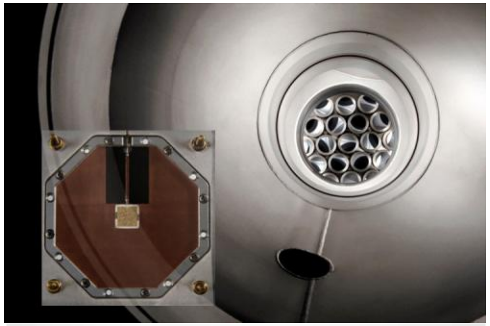
- ✓ **2 x 19 PIPS detectors (450 mm²) $\rightarrow \varepsilon \approx 0.5\%$**
- ✓ **pCVDD (or MCP) ultra-fast time pick-up detectors**

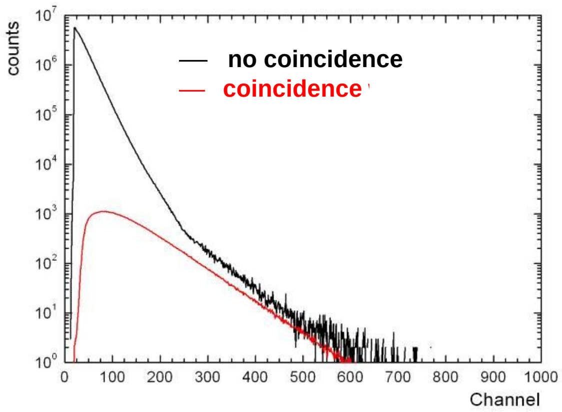
- ✓ **Set-up can be handled with NIM electronics (14 channels)**
- ✓ **development of an ASR + tag-word coder module**

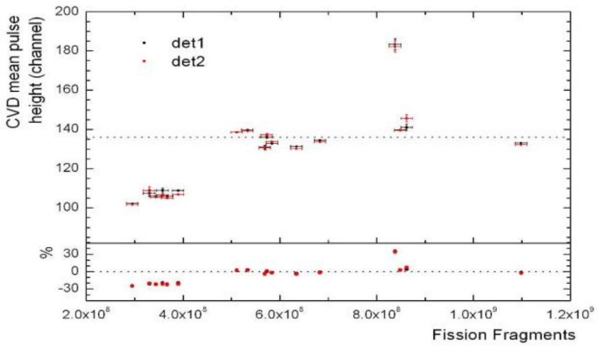
☺ **Coupling of an array of photon/neutron detectors**



pCVDDD as fission trigger



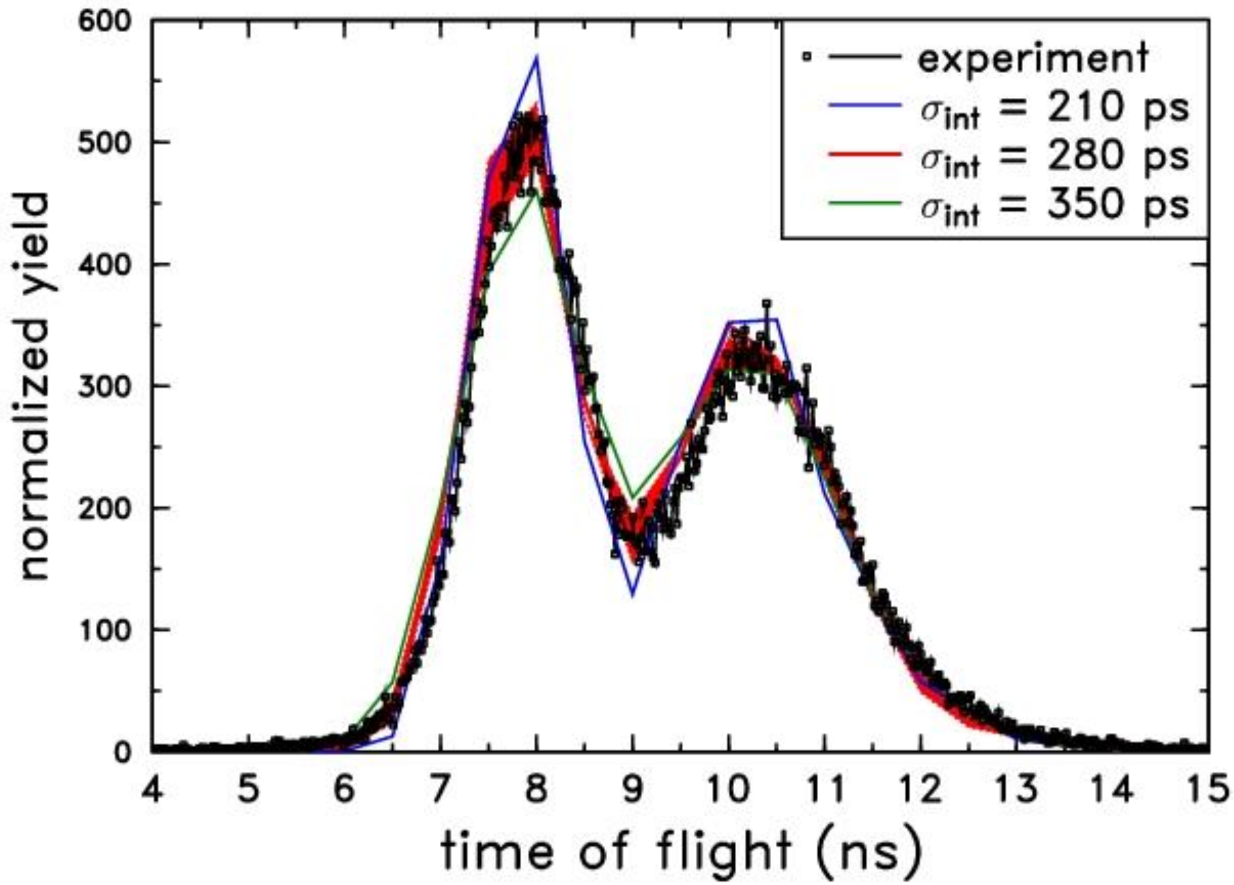




- ✓ **Detector size: 1×1 cm^2**
- ✓ **thickness: 100 μm**
- ✓ **Charge collection efficiency (CCE): 0.3**
- ✓ **"Weak" energy resolution: σ = 0.2 – 0.4**

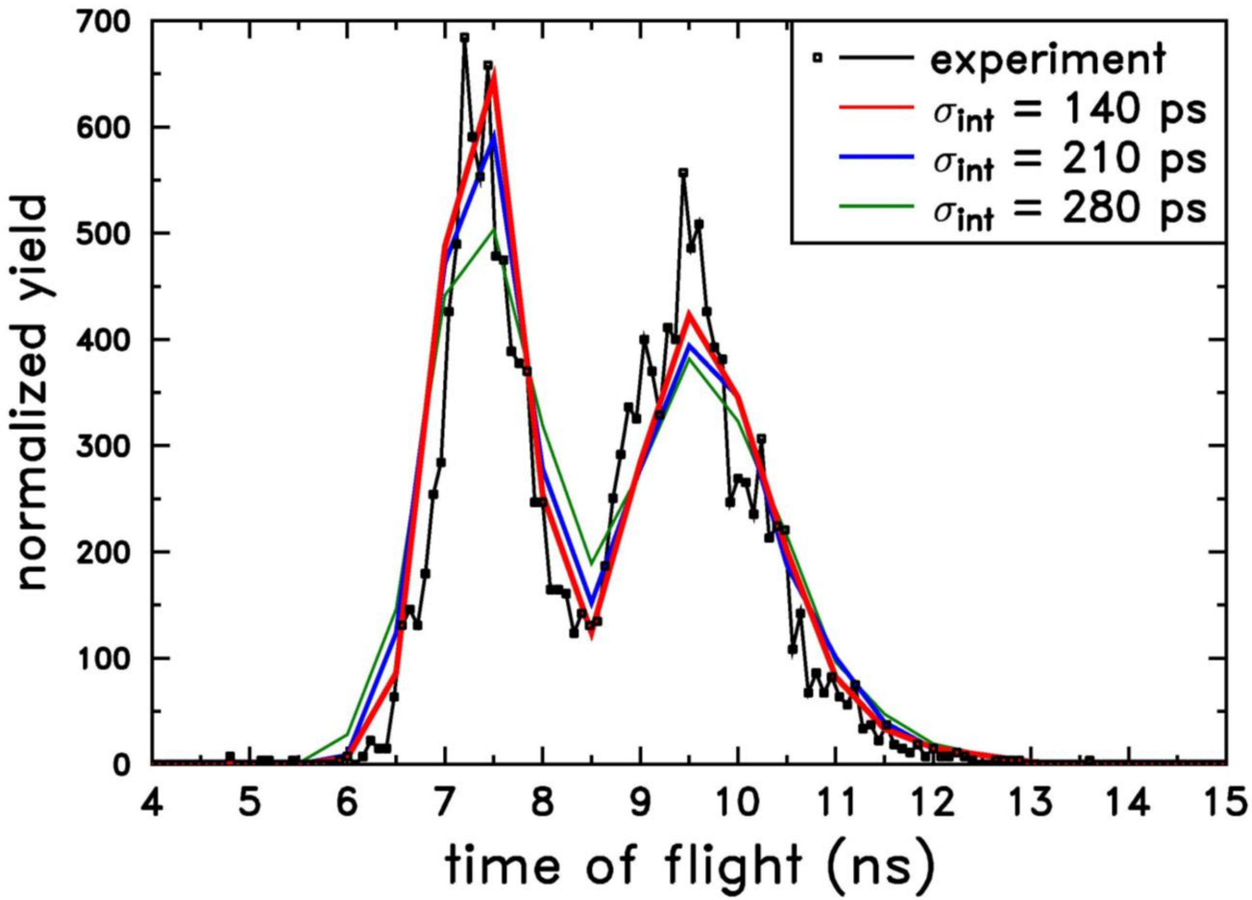
- ✓ **Pulse height stability against radiation damage up to a fission-fragment dose of at least 1.2×10^9**
- ✓ **Including an α-particle dose of 4×10^{10} and a fast neutron dose of about 5×10^9**

pcCVDDD - intrinsic timing resolution



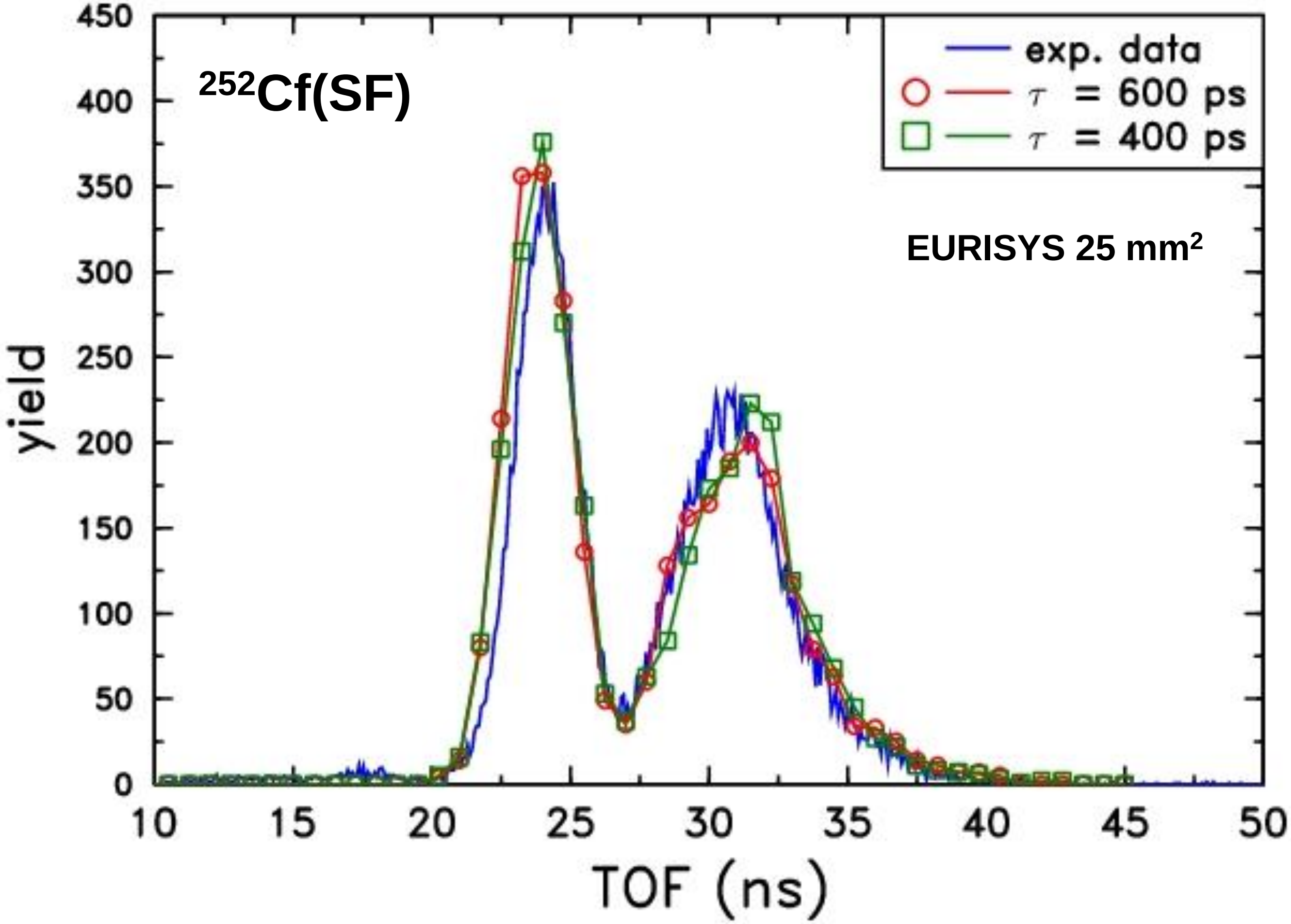
- **Simulation by means of Monte-Carlo simulation from known fission-fragment data**
- **TUD pre-amplifier (QS) + TFA Ortec 474: rise-time 6 ns**
- **Timing resolution very good but worse than expected from HI experiments**

pcCVDDD - intrinsic timing resolution



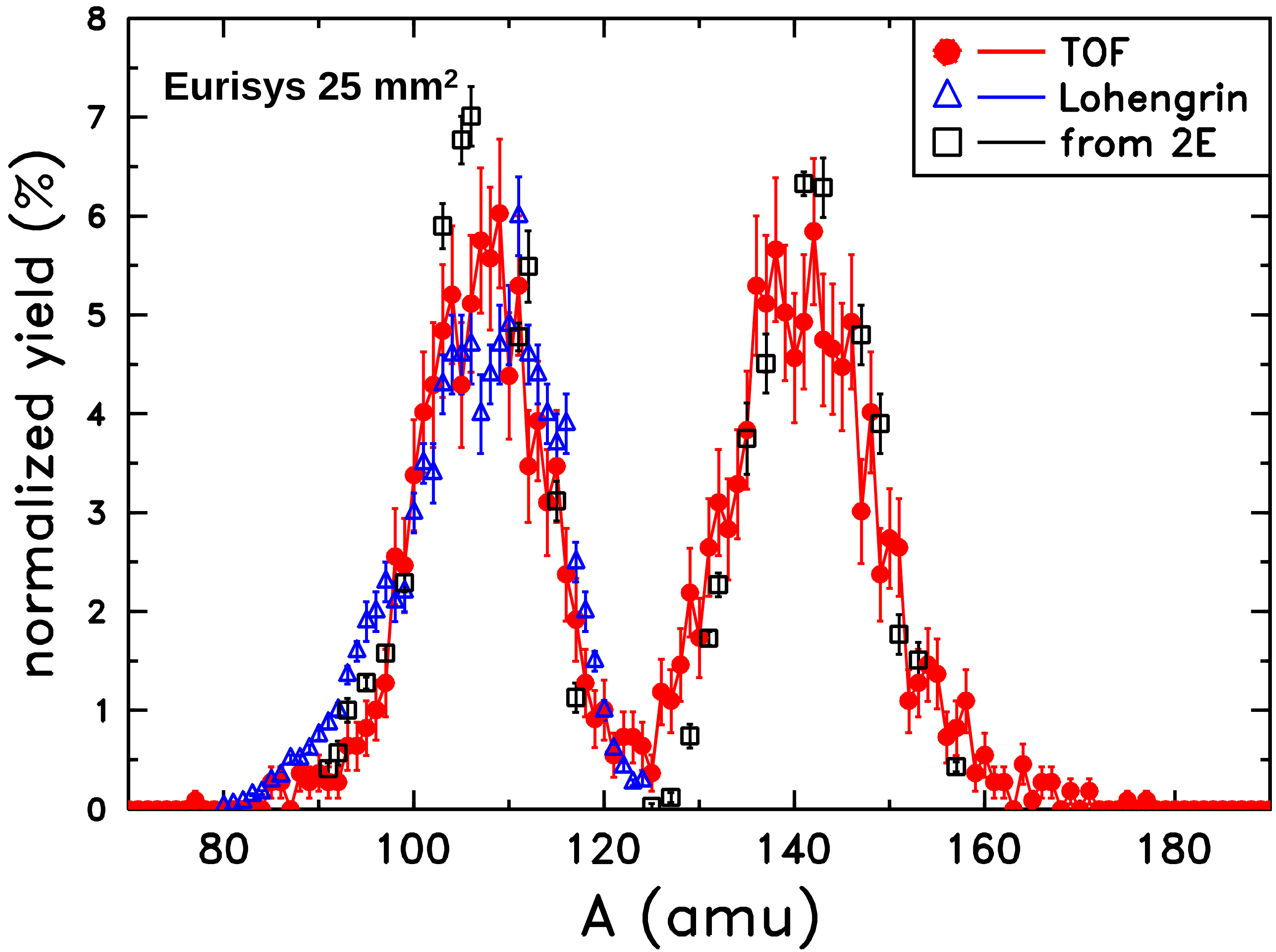
- **TUD pre-amplifier: current sensitive, rise-time < 4 ns**
- **Wave-form digitization (Tektronix: 1GHz, 10 GS/s)**

VERDI - the timing resolution



- **pCVDDD →TUD pre-amplifier (QS) + TFA Ortec 474: rise-time 6 ns**
- **PIPS → MSI 8 (SA, TFA + VT120)**

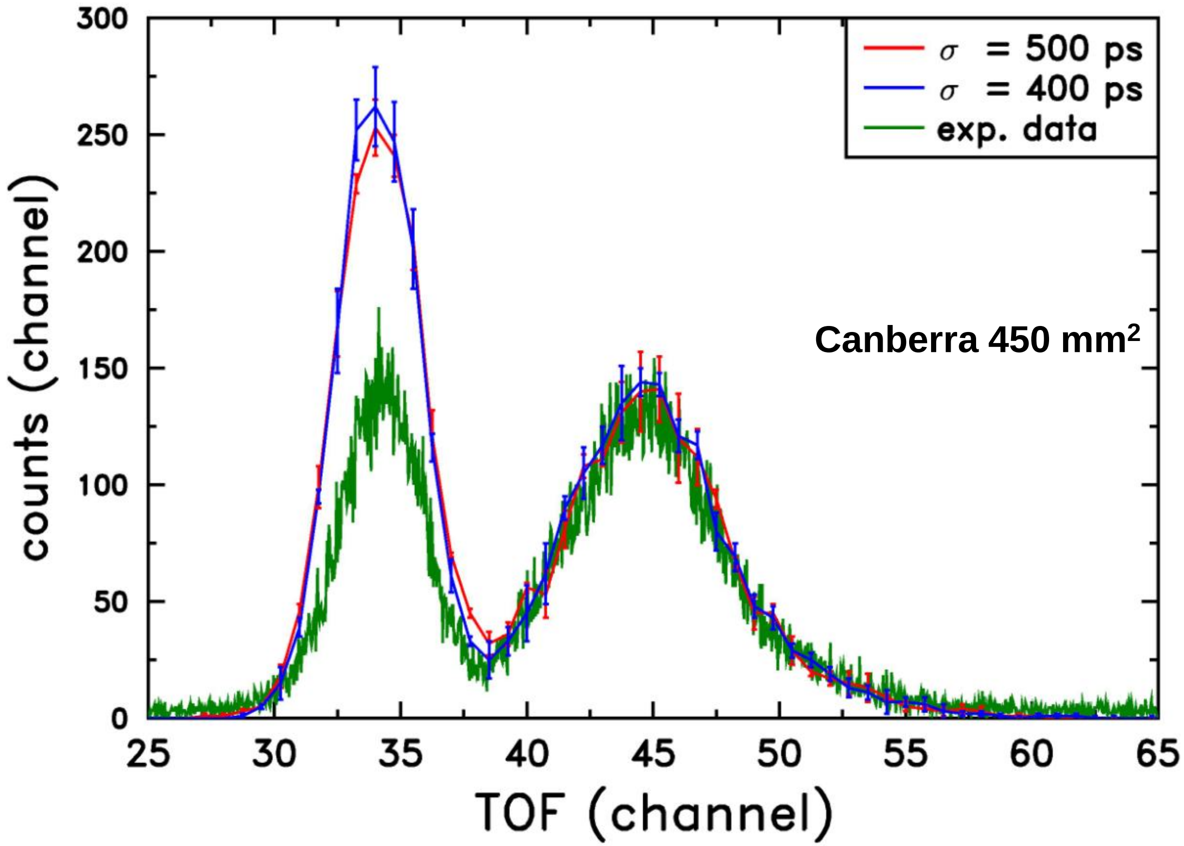
VERDI – FF distributions



Improved electronics

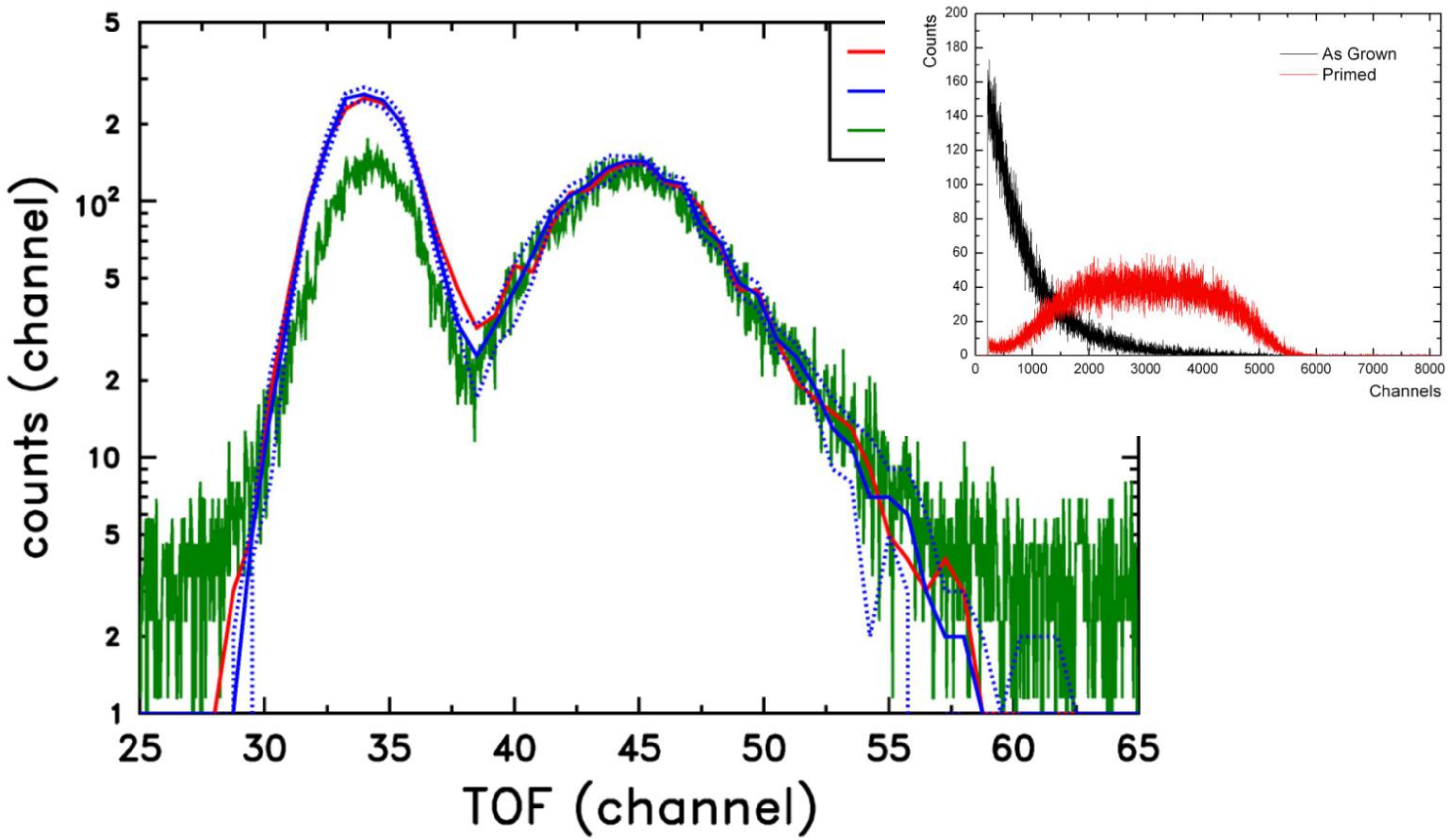
- ✓ **ORTEC 1GHz pre-amplifiers**
- ✓ **Signal boost with ORTEC VT120 (improved S/N)**
- ✓ **Timing-optimized energy (stop) detector from CANBERRA with a size of 450 mm^2**

Best resolution, but…



- pCVDDD → Ortec 9306 (1GHz) + VT120: rise-time ≤1.2 ns
- PIPS → MSI 8 (SA, TFA + VT120)

Best resolution, but…



- **pCVDDD → Ortec 9306 (1GHz) + VT120: rise-time ≤1.2 ns**
- **PIPS → MSI 8 (SA, TFA + VT120)**

The experiment(s) @ KFKI

✓ Single (ν, E) experiment: $^{235}U(n_{th}, f) \Rightarrow Y(A, E_k)$

- with a 1×1 cm^2 pcCVDDD
- ^{235}U (113 μg)
- $\Phi_{n,th} \approx 5 \times 10^7/s/cm^2$
- **c_{th} > 2 FF/s or 10^6 FF/(120 h) per detector**
- **10 energy detectors → ε = 0.0026**

✓ Fission γ-ray spectral measurement

- pCVDDD serves as ultra-fast fission event trigger
- Use of 4 lanthanum halide detectors of various size
  - one Lanthanum-chloride (3" × 3", CIEMAT)
  - two Lanthanum-chloride (1.5" × 1.5")
  - one lanthanum bromide (2" × 2")
  - fission γ-ray count rate > 10/s or > 5 × 10^6/(120 h) per detector (1.5" × 1.5")

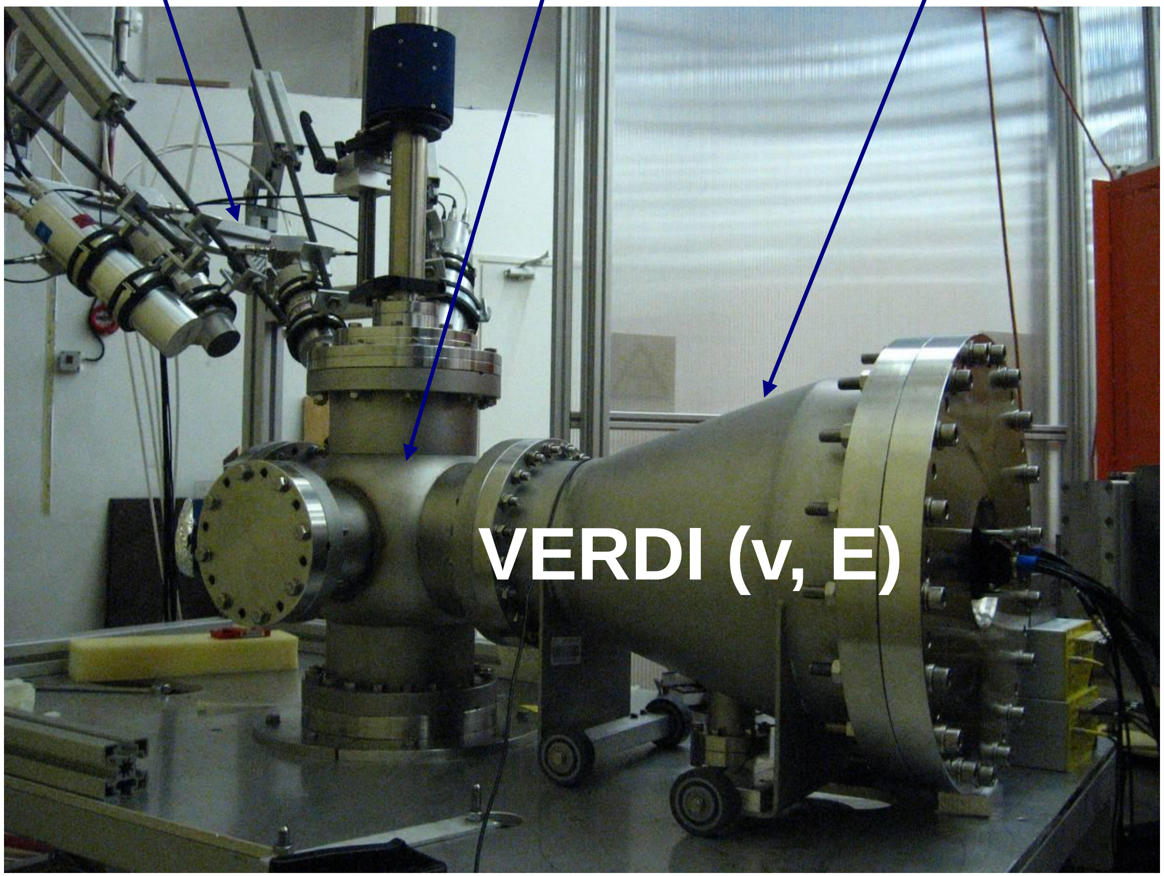
✓ *Integral measurement of the prompt neutron spectrum*

The experiment(s) @ KFKI

γ-ray detectors

sample holder/diamond

TOF section (pCVDDD, Ortec 1GHz, Can 450t)

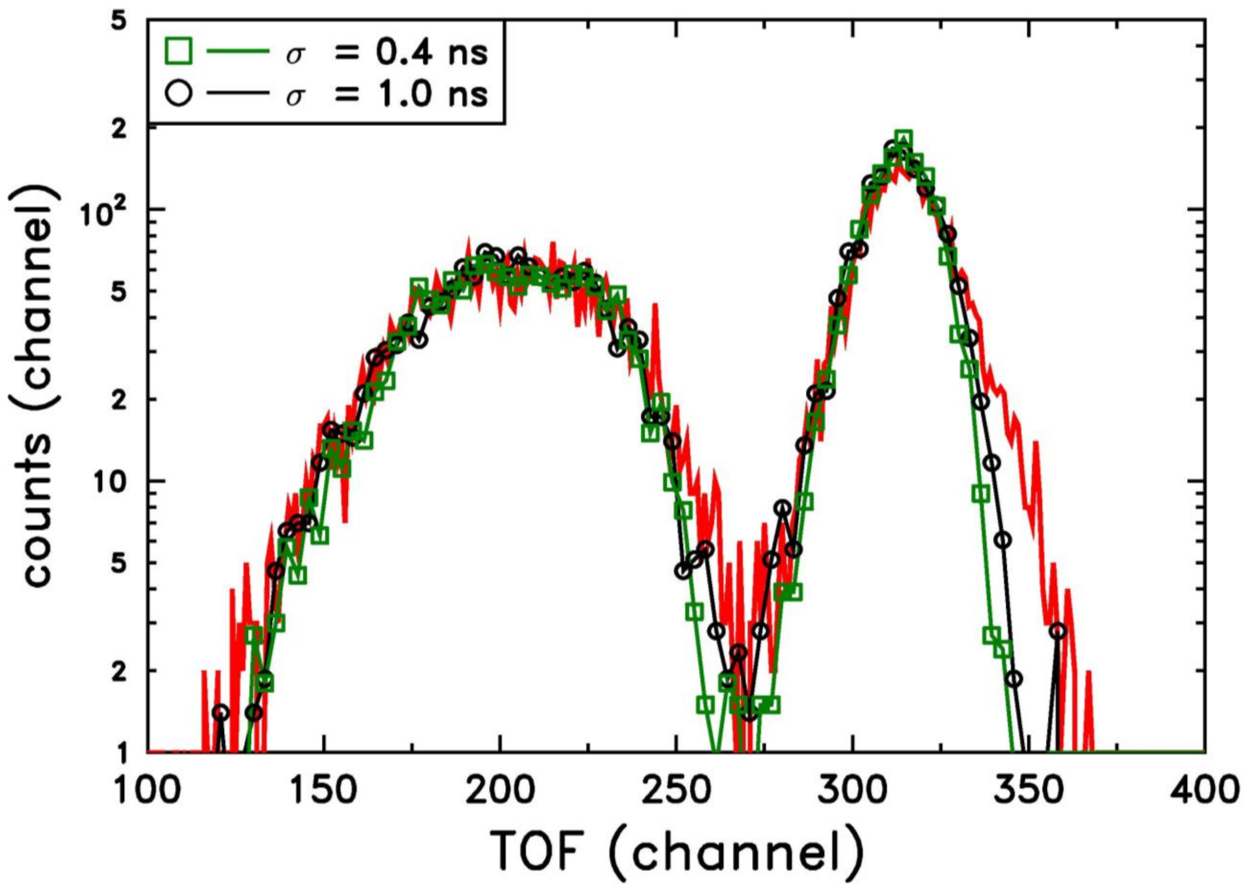


$LaCl_3$ 1.5"× 1.5"

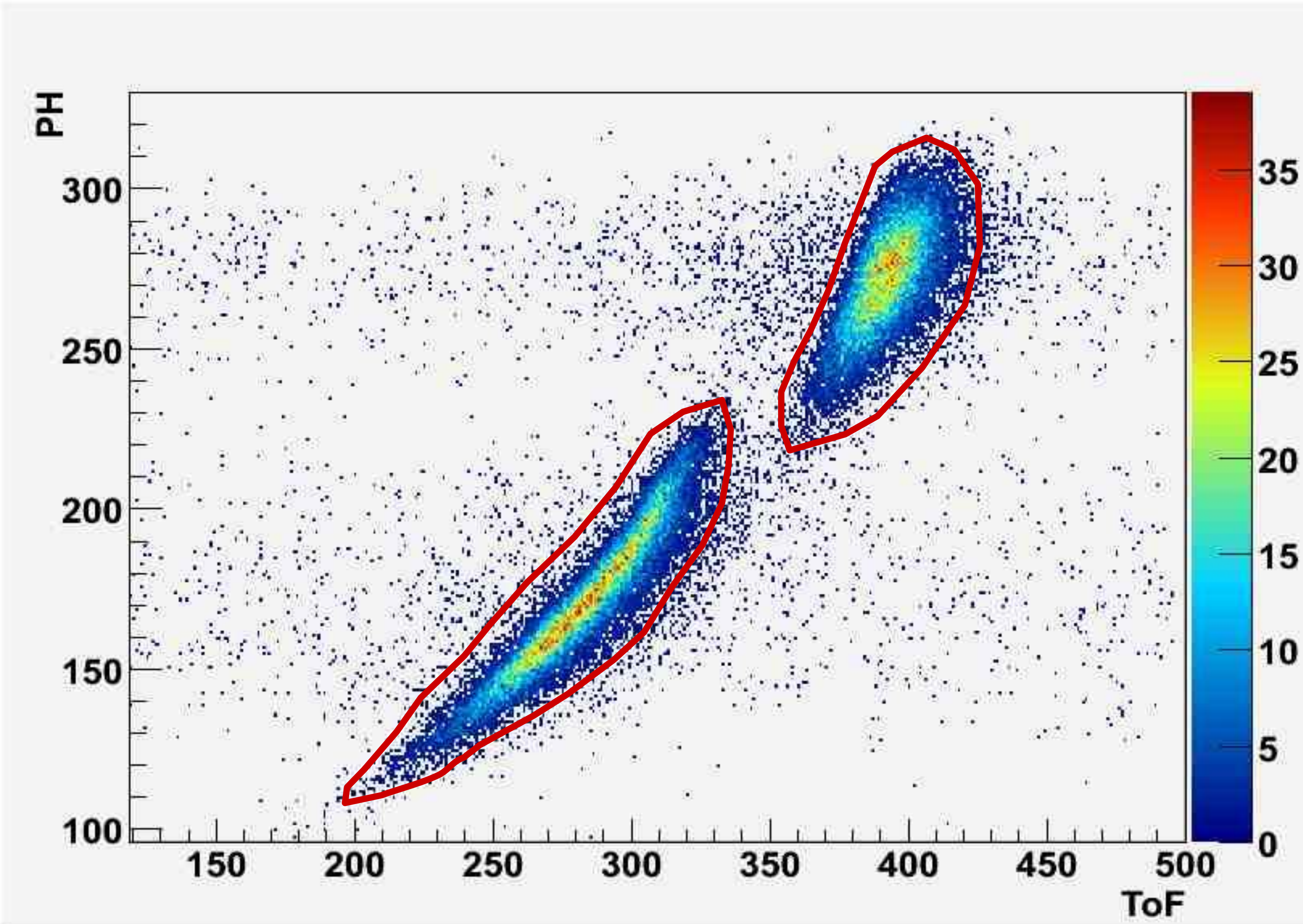
$LaBr_3$ 2"× 2"

$LaCl_3$ 3"× 3"

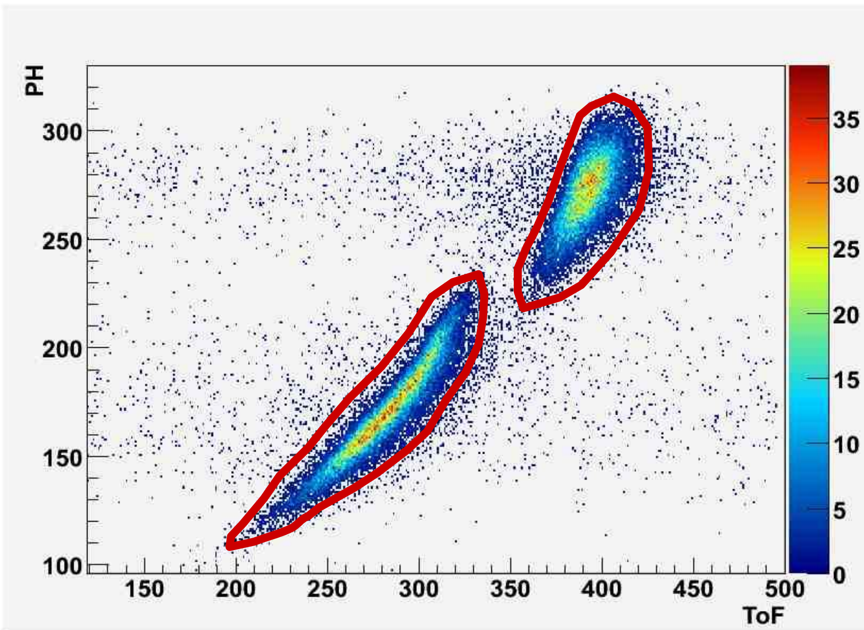
TOF spectrum from a *few h* - run

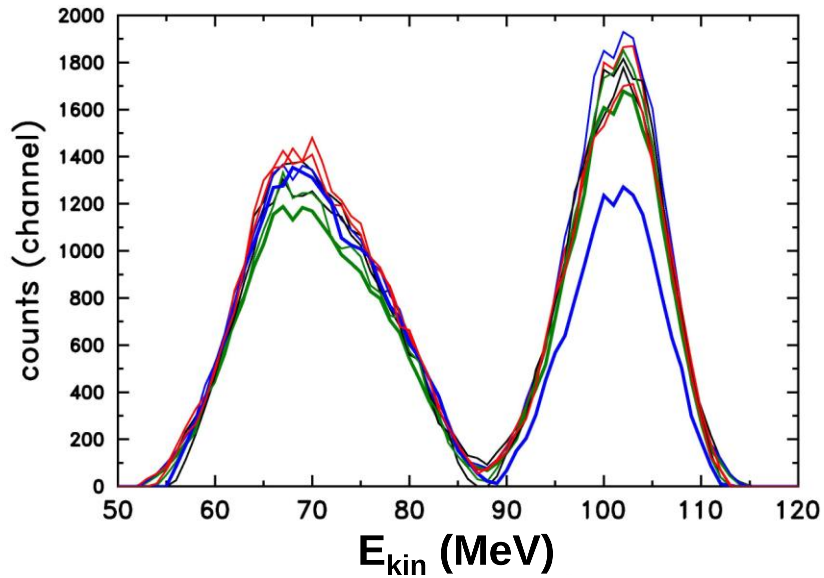


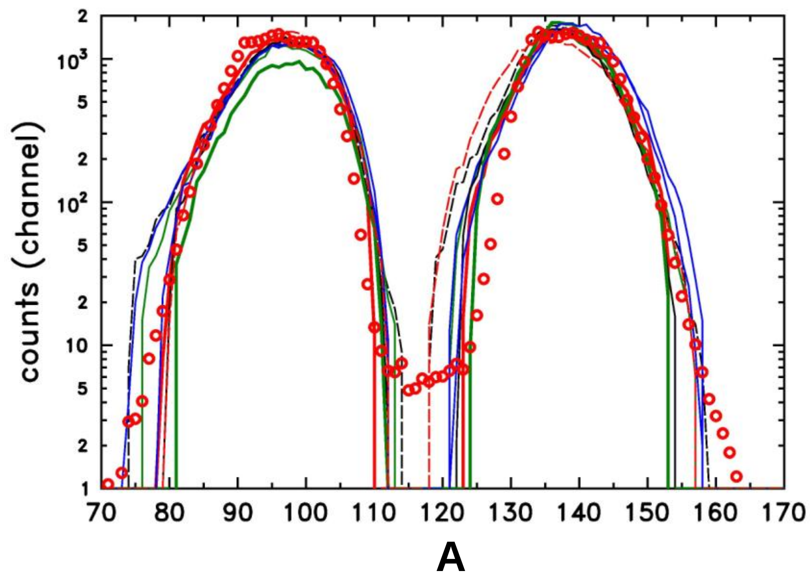
Pulse height vs. Time Of Flight



"cleaned" spectra







- **Polygons applied to spectra of all 8 detectors…**

Conclusions from the experiment at IKI:

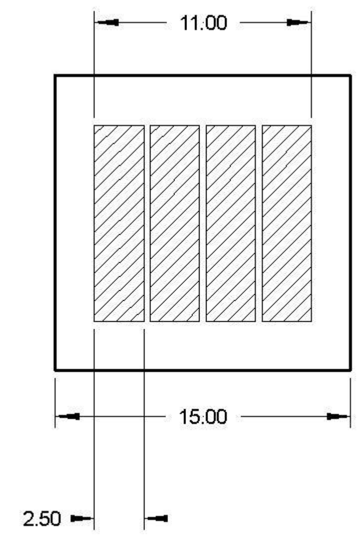
- ✓ **Single (v, E) spectrometer in principle operational; extension to 19 detectors straight forward**
- ✓ **Coupling of γ-ray (neutron) detectors for correlation experiments successfully tested (→ A. Oberstedt)**
- ➢ **Origin of the apparent "efficiency" problem of the pCVDDD has to be investigated**
- ➢ **Even the timing-optimized PIPS detectors from CANBERRA hardly do the job…**

More about diamonds…

- **pCVDD in 4-fold strip design**

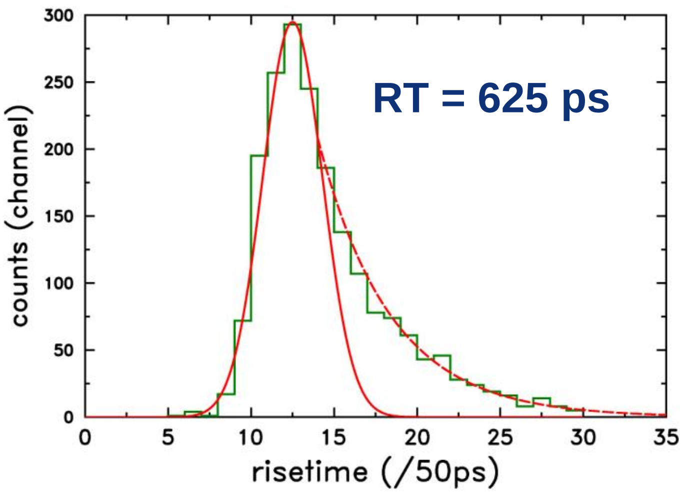
- **thickness 180 μm**
- **capacitance < 13 pF**

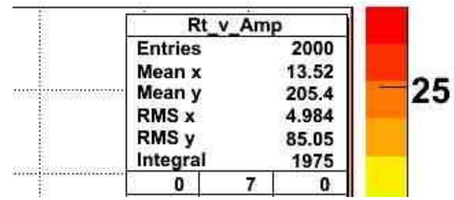
- **DBA-IV**
- **Oscilloscope: 1GHz, 20Gs/s**

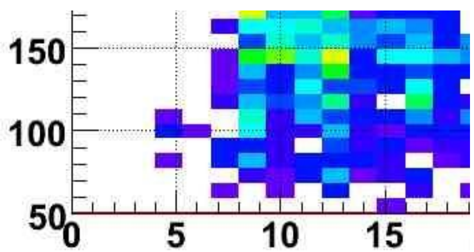


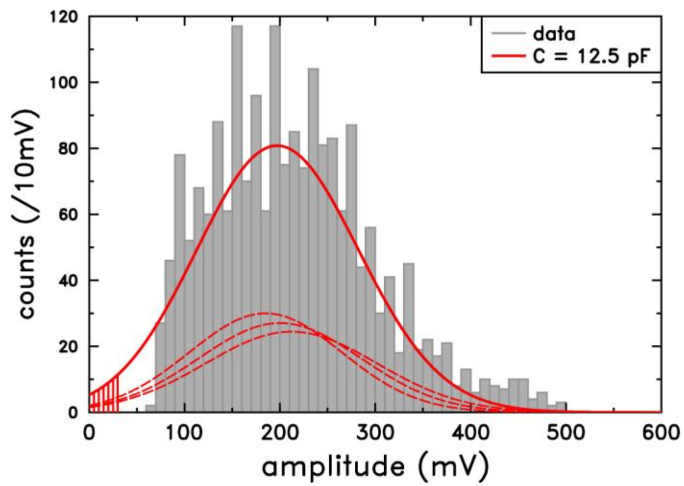
More about diamonds…

^{39}Pu, ^{241}Am, ^{244}Cm)

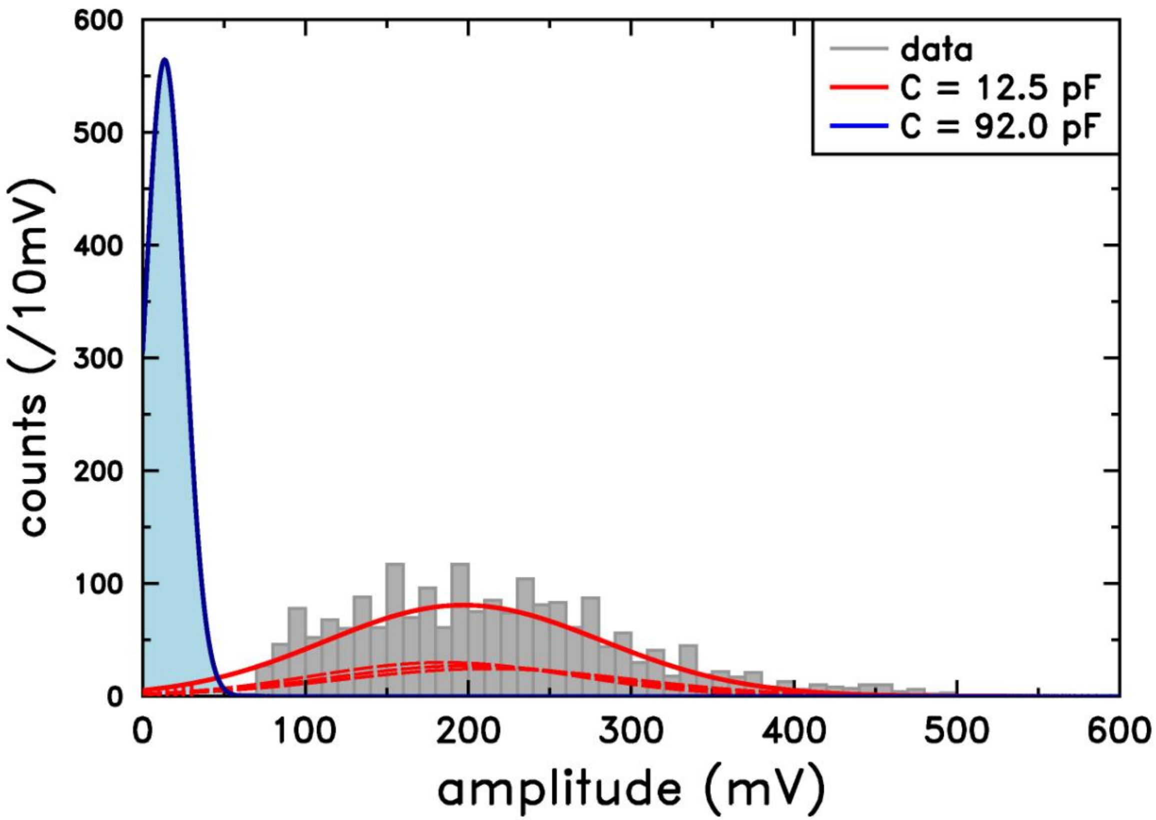




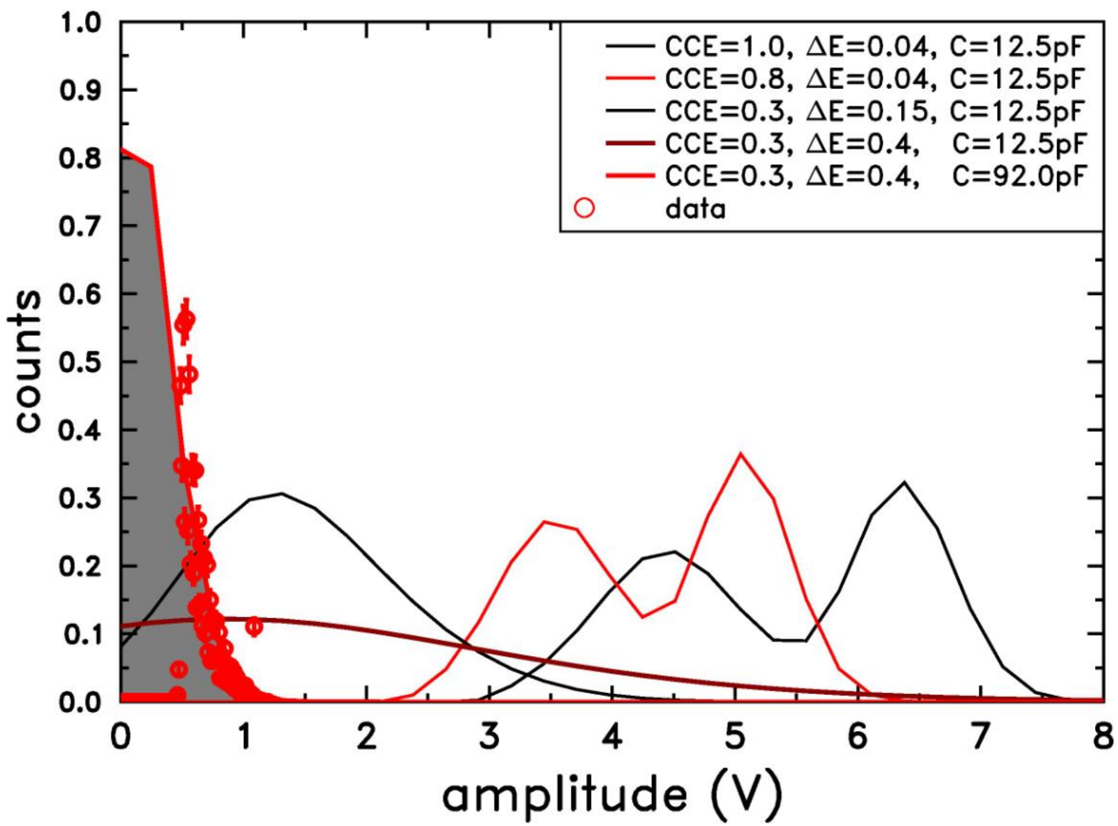




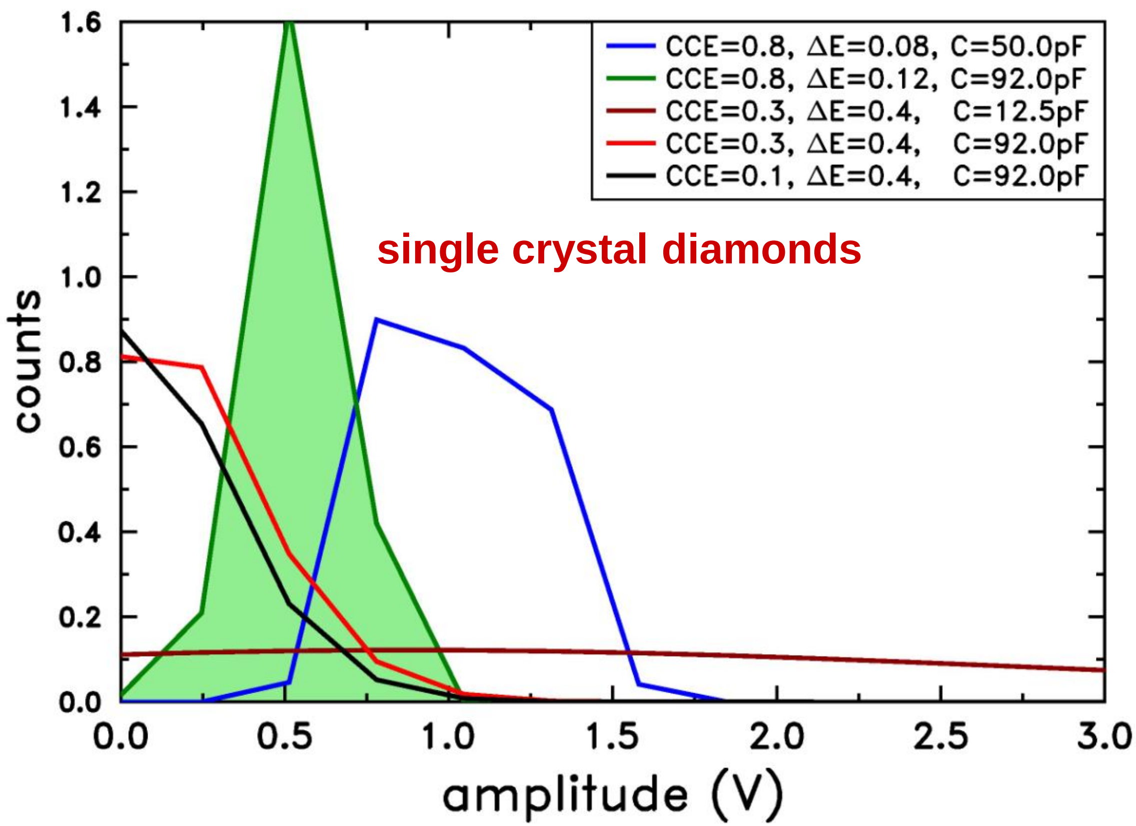
More about diamonds…



More about diamonds…



The transmission fission trigger



Conclusions and outlook

- ✓ The VERDI TOF spectrometer for correlation measurements of fission fragment properties under development and already in a serious testing phase
- ✓ The first TOF section of the VERDI spectrometer operational with up to 19 energy detectors
- ✓ TOF resolution better than or equal to 400 ps ⇨ $\Delta A = 2 - 3$ u
- ✓ With modern broadband amplifiers and… $\Delta A = 1 – 2$ u is in reach

- ✓ Artificial diamond detectors provide an ultra-fast fission trigger ($\tau < 280$ ps)
- ✓ With broadband pre amplifiers and/or waveform digitization ($\tau < 180$ ps)
- ✓ Radiation hard for characteristic neutron and fission-fragment doses

- ❖ Loss of (light) fission fragments due to low CCE in pCVD diamond material has been investigated by simulating the response as a function of the detector capacitance
- **The capacitance of a pCVDDD may not exceed 15pF !!!**

Conclusions and outlook

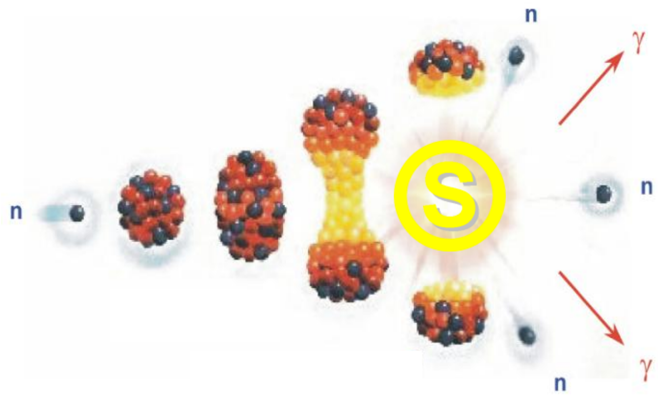
In the near future:

- ✓ **Complete VERDI as a double TOF spectrometer (end of 2010)**
- ✓ **Build a transparent fission trigger**
- ✓ **Should principally work when made from ultra-thin pCVD diamond material, however with very limited detection effciency**
- ✓ **From simulations based on experimental results: sc-diamond should do the job (C_d < 50pF)**
  - ✓ under investigation
  - ✓ thickness ≤ 5 μm, 16-fold segmented
  - Tests with fission fragments when suitable ^{252}Cf source available

- ✓ **Efforts to find silicon detectors with better timing characteristics**

Nothing without a good team!

MONNET technical team: Th. Gamboni, W. Geerts, C. Chaves de Jesus, M. Vidali



T. Belgya, R. Borcea, A. Göök, F.-J. Hambsch, Z. Kis, T. Martinez, A. Oberstedt, L. Szentmiklosi, K. Takács

This work was supported by the EFNUDAT programme of the European Commission (agreement number 31027)

The collaboration

Örebro University

Technical University of Darmstadt

CIEMAT

IKI, Institute of Isotopes (HAS)

CEA/DAM Ile-de-France

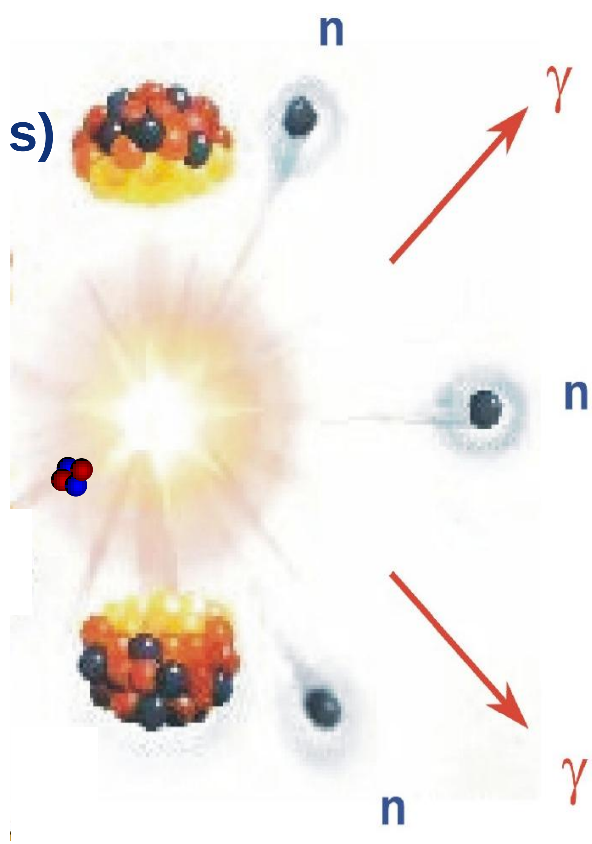
Joint Research Centre IRMM

The nuclear fission process

prompt neutrons (10^{-18} s)

prompt γ-rays (10^{-18} s)

fission fragments (10^{-21} s)

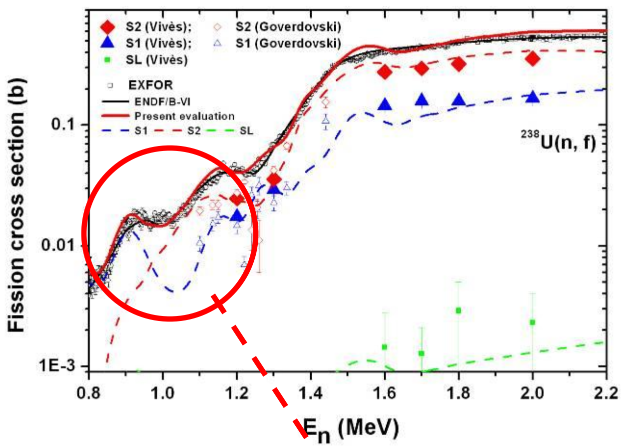


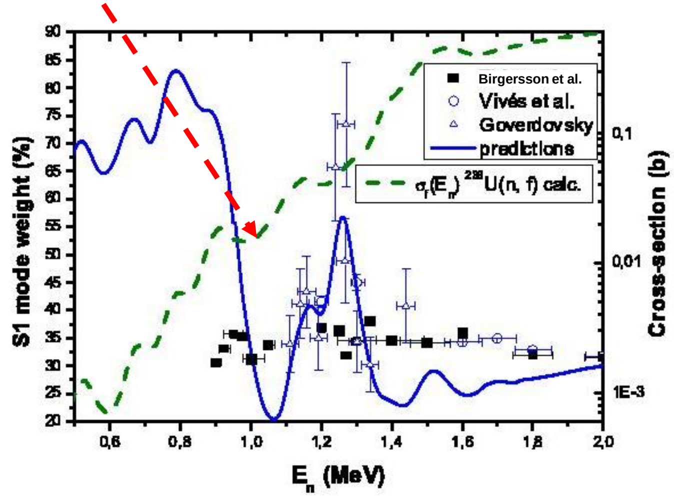
ternary α, t, d

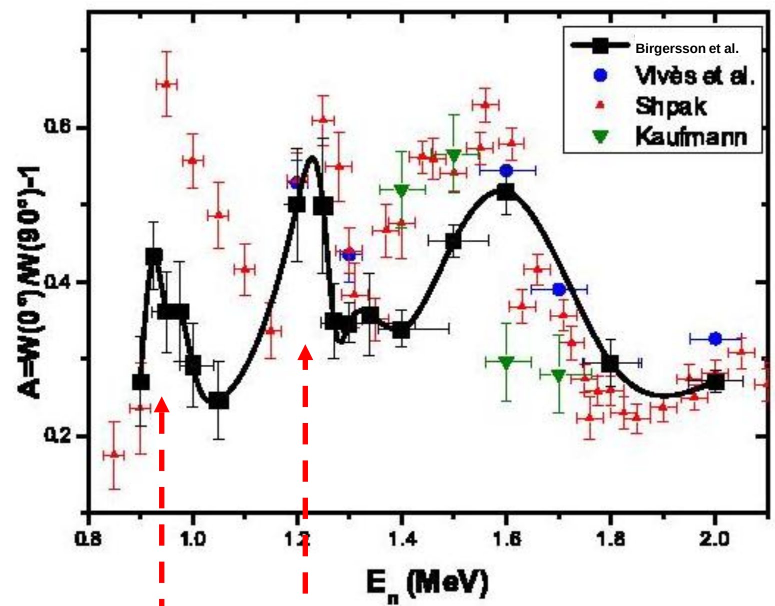
kinetic energy prompt γ-rays	heat
prompt neutrons (delayed neutrons)	chain reaction
ternary α, t, d	gas production in the fuel (waste)
fission fragments	decay heat, toxicity (waste)

FF properties in cross-section resonances

o ^{238}U (n, f) @ E_n = 0.9 – 2 MeV







E* ≈ 5.8 MeV

E* ≈ 6.1 MeV

E. Birgersson et al., Nucl. Phys. A817 (2009) 1-34

Motivation

- **Prediction of γ-heating for design of Gen-IV reactors**
  - about 10 % of total energy released in the core of a standard nuclear reactor by fission γ-rays
  - about 40 % of those due to prompt γ-decay of fission products
- **Modelling requires uncertainty not larger than 7.5 % (1σ)**
  - but: present γ-ray emission data determined in early 1970's,
  - underestimating γ-heating with 10 - 28 % for ^{235}U and ^{239}Pu

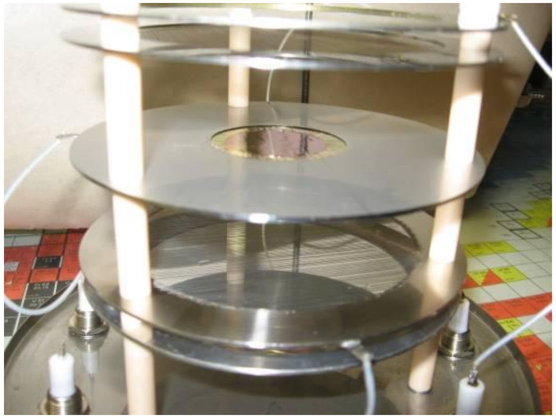
⇨ **OECD NEA Nuclear Data High Priority List:**

⇨ **measurement of prompt γ-ray emission from ^{235}U(n,f) and ^{239}Pu(n,f)**

Momentum conservation :

$$\left.\begin{array}{l} A^*_1 v_1 = A^*_2 v_2 \\ A^*_1 E_1 = A^*_2 E_2 \end{array}\right\} \quad \boxed{\frac{E^*_1}{E^*_2} = \frac{A^*_2}{A^*_1}}$$

0.



1. $E^*_{i1} = E^0_i + PHD_{i0}(A^*_{i0} - \nu_{i0}, Z_i, E_{kin,i0}) + \Delta E_{i0}(A^*_{i0} - \nu_{i0}, Z_{i0}, E_{kin,i0})$

   ⇨ $A^*_{i1}, \nu_{i1}, TKE_1, PHD_{i1}$

2. $E^*_{i2} = E^0_i + PHD_{i1}(A^*_{i1} - \nu_{i1}, Z_i, E_{kin,i1}) + \Delta E_{i1}(A^*_{i1} - \nu_{i1}, Z_{i1}, E_{kin,i1})$

   ⇨ $A^*_{i2}, \nu_{i2}, TKE_2, PHD_{i2}$

…

j. $E^*_{ij} = E^0_i + PHD_{ij-1}(A^*_{ij-1} - \nu_{ij-1}, Z_i, E_{kin,ij-1}) + \Delta E_{ij-1}(A^*_{ij-1} - \nu_{ij-1}, Z_{ij-1}, E_{kin,ij-1})$

   ⇨ $A^*_{ij}, \nu_{ij}, TKE_j, PHD_{ij}$

Double velocity (2v) technique

Momentum conservation :

$$\left.\begin{aligned} A^*_1 v_1 &= A^*_2 v_2 \\ A_{CN} &= A^*_1 + A^*_2 \end{aligned}\right\}$$

$$A^*_1 v_1 = (A_{CN} - A^*_1)\, v_2$$

$$A^*_1 = v_2 / (v_1 + v_2) \, {}^*A_{CN}$$

$$A^*_2 = A_{CN} - A^*_1$$

$$E^*_{kin,i} = A^*_i \, v_i^2$$

- ✓ No a-priori need of neutron emission data
- ✓ Mass resolution determined by timing resolution

- ⇘ up to now quite low geometrical efficiency♥
- ⇘ Same holds for recoil mass-separators: (v, E)

♥ Cosi Fan Tutte ($\varepsilon \approx 5\times10^{-5}$)

VERDI – the "energy" side

Axial ionisation chamber:

- ✓ Simple to construct and to use
- ✓ No radiation damage
- ✓ Very good intrinsic energy resolution

- ❖ Difficult to make a large area detector
- ❖ Energy loss in the entrance window
- ❖ Timing characteristics???

Large area silicon detectors:

- ✓ Relatively cheap
- ✓ Easy to use
- ✓ Excellent pulse height stability
- ✓ Excellent energy resolution
- ✓ Promising timing characteristics (according to specs: t $\approx$ 200 ns)

- ❖ Subject to radiation damage

VERDI – the fission trigger

o μ-channel plate detectors:

- ✓ Very good intrinsic timing characteristics

- ❖ Difficult to handle
- ❖ Requires excellent vacuum $p < 10^{-6}$ mbar
- ❖ Subject to radiation damage (especially in an intense neutron field)???

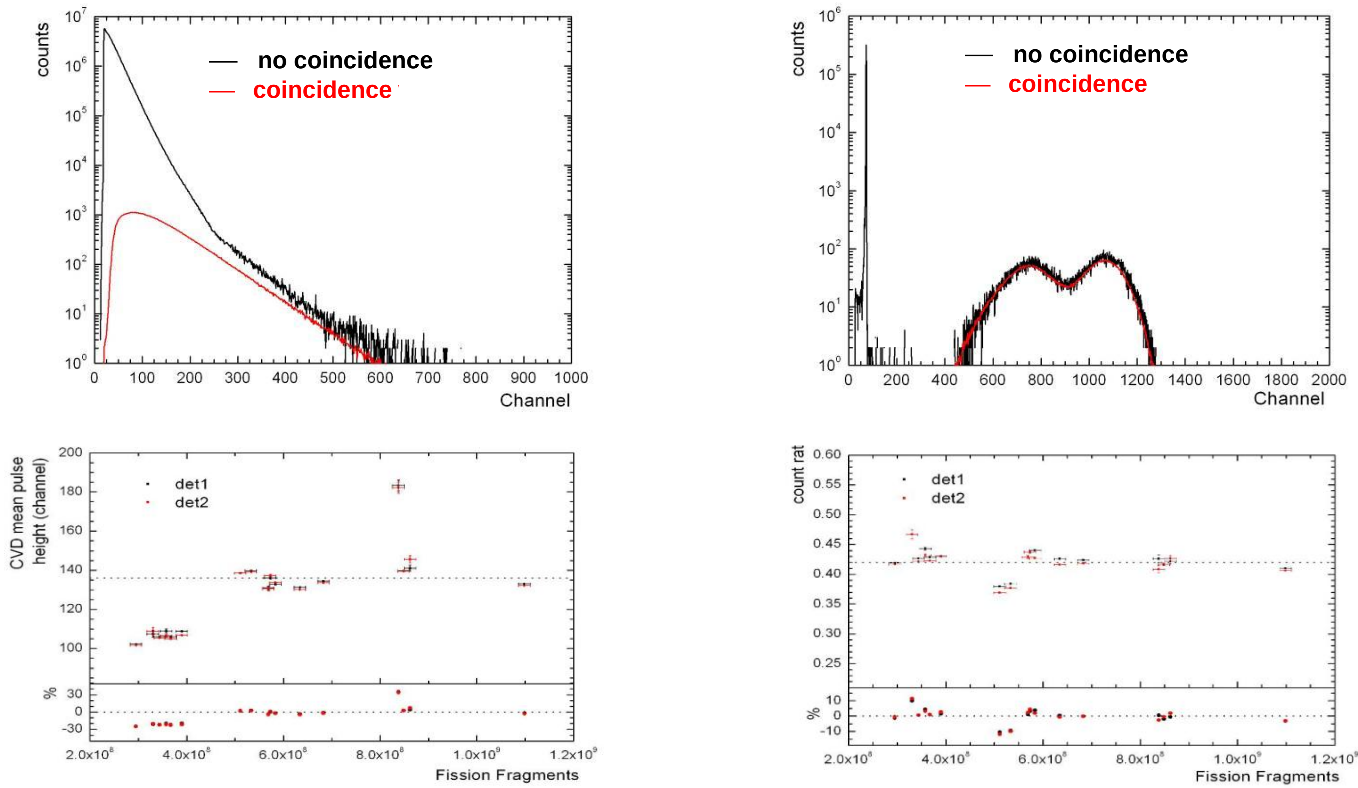
o Diamond detectors (p/s-CVDD material):

- ☒ New detector material
- ☒ Relatively few experimental results

- ❖ Pulse height stability of pCVDD difficult to predict and to maintain
- ❖ Difficult to produce (artificial) single-crystal diamonds
- ✓ Promising timing characteristics (with Ni-ion @ 30 MeV/u $\Delta t \approx 30$ ps)
- ✓ Radiation hard

- ❖ Never tested with fission fragments (0.5 MeV/u < E_{FF} < 2 MeV/u)

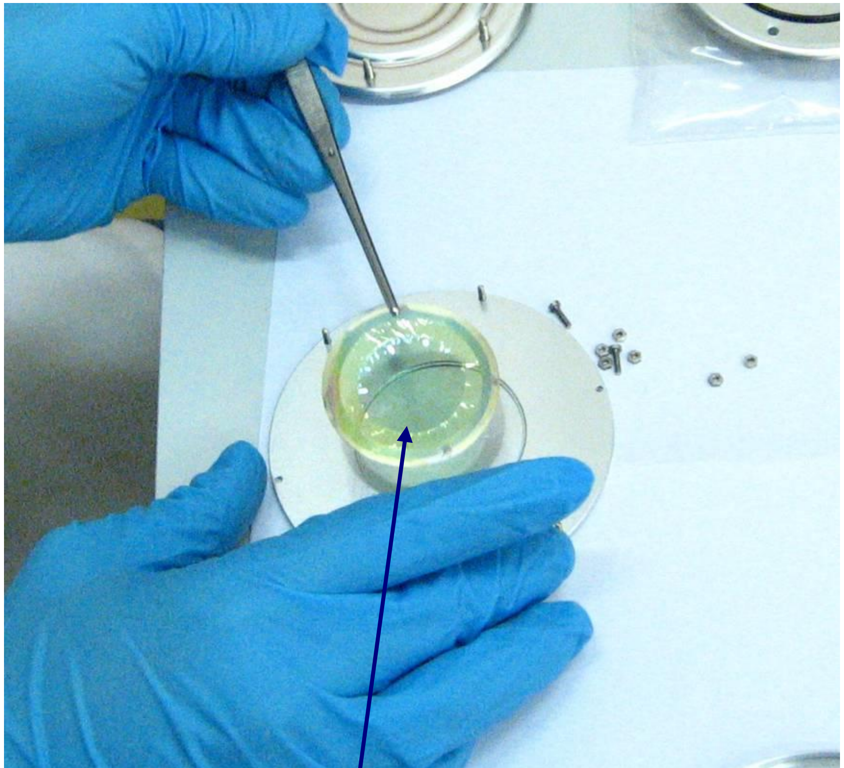
Pulse-height “analysis” and stabilitiy



- ✓ **Pulse height stability against radiation damage up to a fission-fragment dose of at least 1.2 × 10^9**

- ✓ **Including an α-particle dose of 4 × 10^{10} and a fast neutron dose of about 5 × 10^9**

The experiment(s) @ KFKI



^{235}U: 113 μg/cm^2
on 34 μg/cm^2 polyimide (PI)

mounted on top of the CVDDD

+

^{6}Li: 5 μg/cm^2
on 34 μg/cm^2 PI for calibration