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Recent progress in time-of-flight and thin-foil proton recoil techniques for fusion neutron spectroscopy *

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Uppsala University

Outline:

- Neutron diagnsotics in fusion experiments
- The ToF technique; combined time – pulse height
- Non-magnetic thin-foil proton recoil; TPR
- Outlook and Conclusions

* Work performed within the European Fusion Development Agreement (EFDA), Topical Group Diagnostics

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INTRODUCTION

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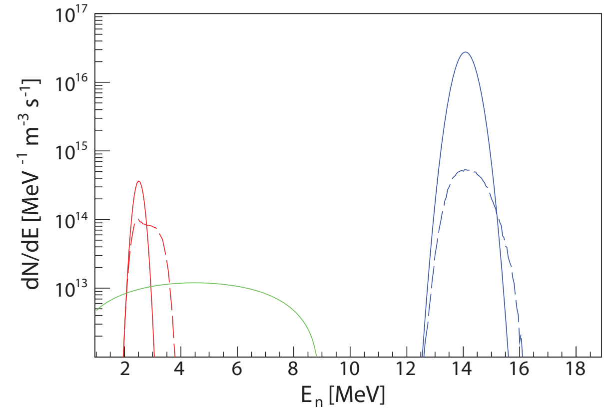
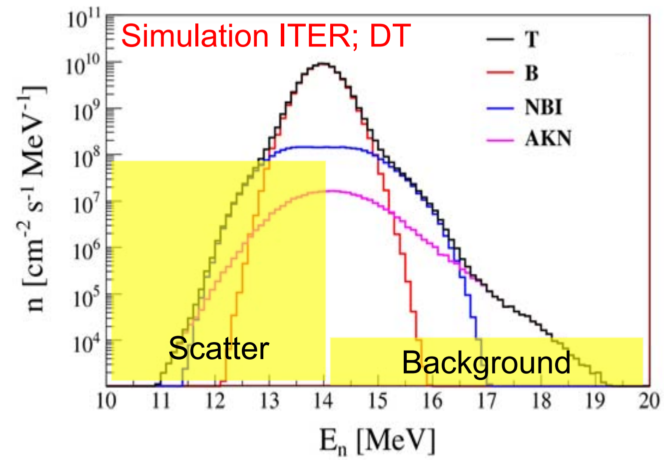
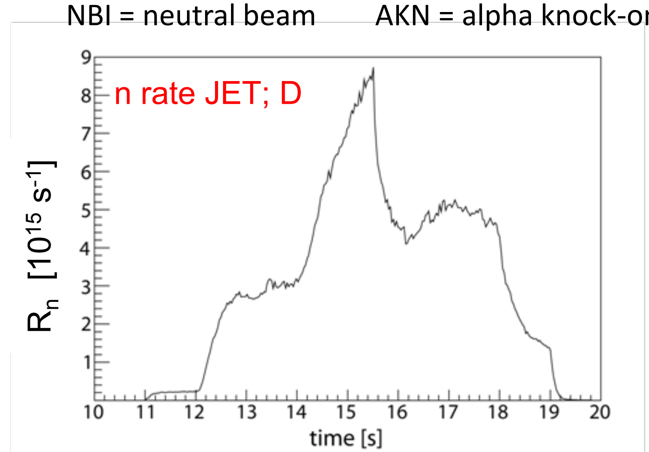
Neutron emission

- Fusion experiments with D and T fuel:
  - $d + d \rightarrow {}^{3}He + n$ (2.45 MeV)
  - $d + t \rightarrow {}^{4}He + n$ (14.0 MeV)
- “Impurities”
  - $d + \{{}^{3}He, {}^{4}He, {}^{9}Be, {}^{12}C, \ldots\} \rightarrow n + X$
- Plasma parameters: P_{fus}, T_i, $f(v_{ion})$,…
- Fuel ion velocity populations:
  - Thermal $\rightarrow f(E_n)$ Gaussian
  - RF heating $\rightarrow f(E_n)$ anisotropic, double humped
  - Beam heating, alpha heating, …
  - Spectral components (ITER):
    - Thermal bulk $S_n \sim 1$,
    - Beam heating $S_n \sim 0.1$,
    - RF heating $S_n \sim 0.01$,
    - α heating $S_n \sim 0.001$,
- Neutron emission variations:
  - Intensity; 0 - 10^{20} n/s (ITER)
  - Temporal (ms), spatial (cm)





T = total spectrum, B = thermal bulk
NBI = neutral beam AKN = alpha knock-on



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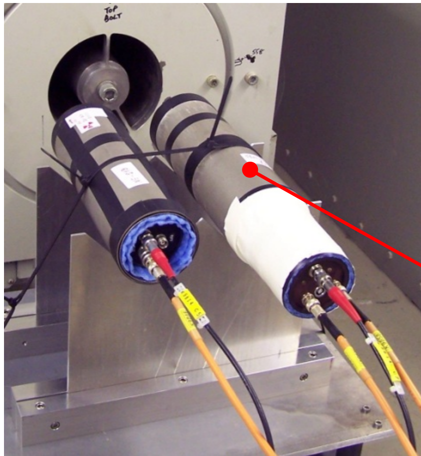
Challenges for fusion neutron diagnostics

- Provide information on relevant plasma/fuel ion parameters
  - Feed-back for active control; ms time frame
- Extended n source (100 m^3), "continuous" n emission (min)
  - Collimated LOS, direct + scattered spectral contributions
  - Reliable, robust techniques
- Harsh experimental conditions around the "reactor"
  - Neutron and gamma background
  - High-frequency EM interference
  - High levels of temperature, B-field
  - Competition over "real estate"; LOS, position, weight, space, …
- Requirements on neutron spectroscopy
  - Results on ms $\rightarrow$ spectroscopy on MHz signal rates (C_{cap})
    - High ε *OR* close to reactor core
  - Access to weak emission components $\rightarrow$ high S/B ratio > 10^4
    - Peaked, well-known response function (0 – 20 MeV)
  - Real-time information in ms $\rightarrow$ data acq., processing, transfer

Neutron spectroscopy techniques

Most “standard” n spectr. techniques tested in fusion (JET)



NE213, Stilbene, nat. + CVD diamond
Reginatto, Zimbal, RSI 79 (2008)- PTB work
Krasilnikov, Rev Sci Instr 69 (1997)
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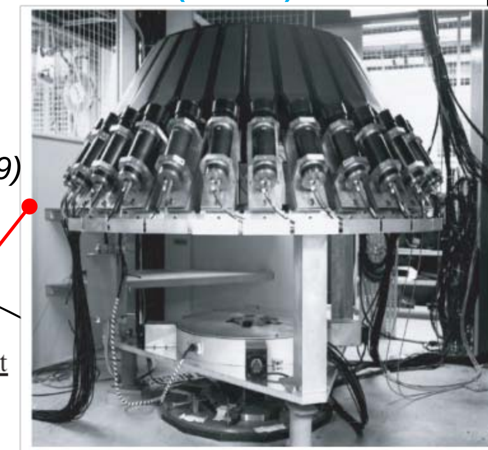
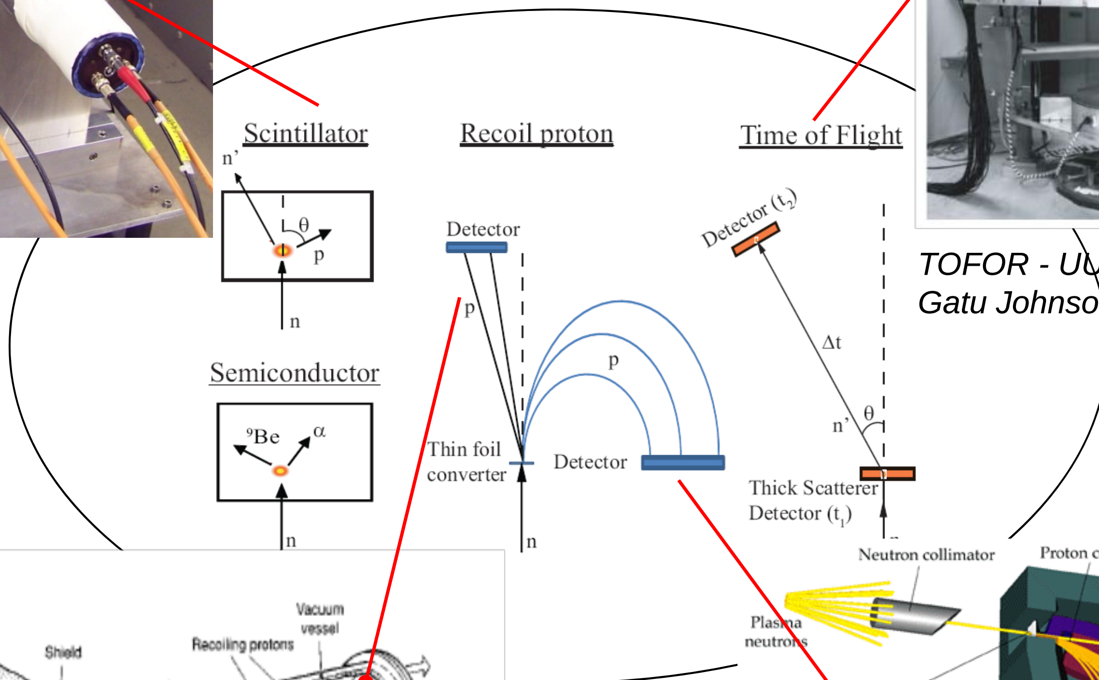
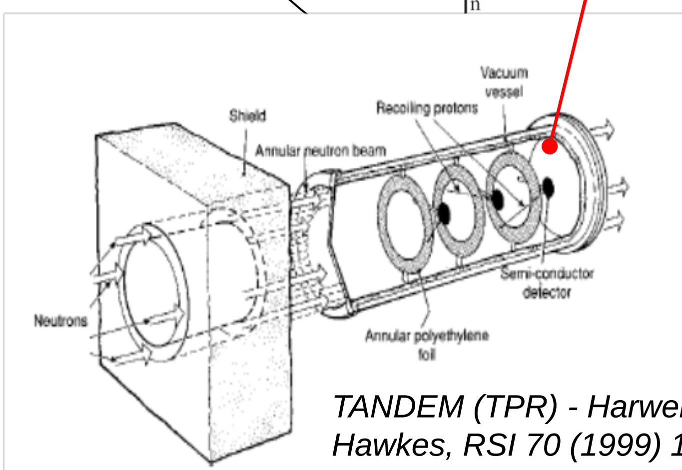
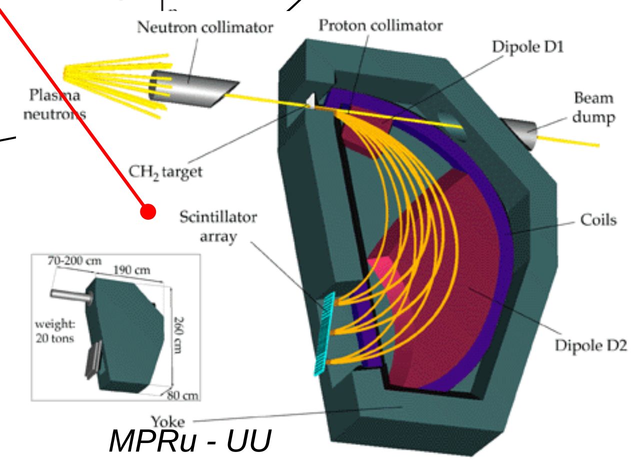


TOFOR - UU
Gatu Johnson, NIM A591 (2008)





TANDEM (TPR) - Harwell
Hawkes, RSI 70 (1999) 1134



MPRu - UU
Andersson Sundén, NIM A610 (2009)

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Neutron spectroscopy techniques

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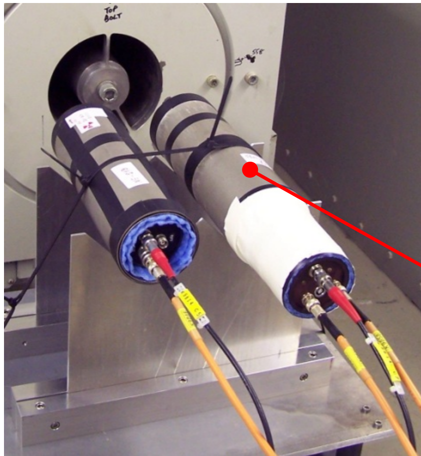

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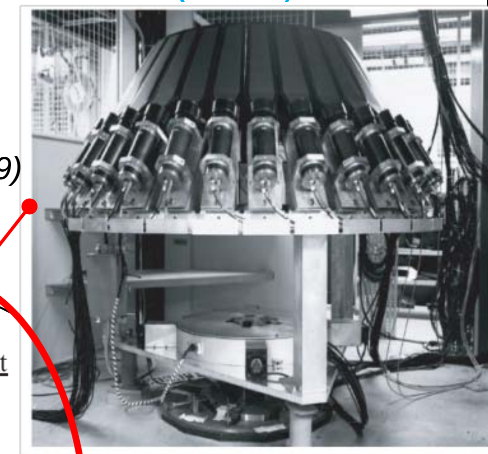

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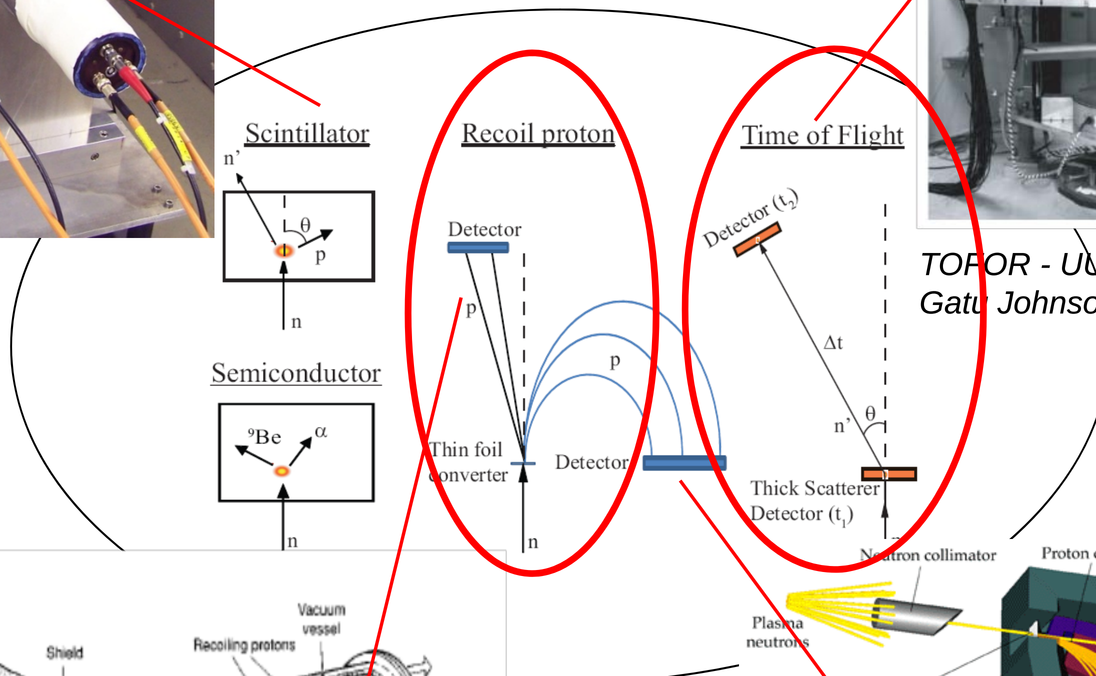

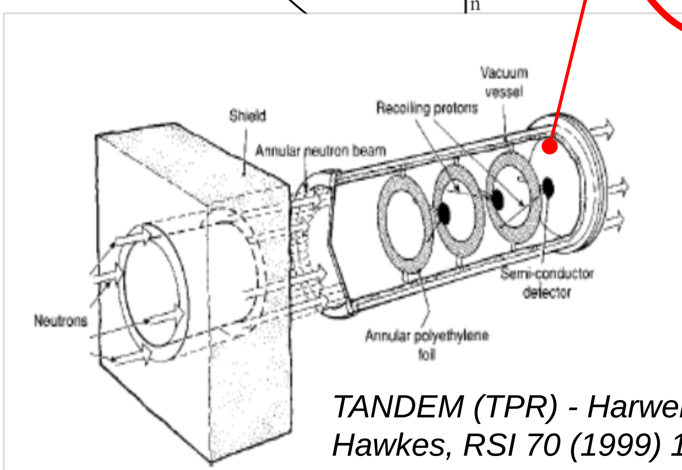

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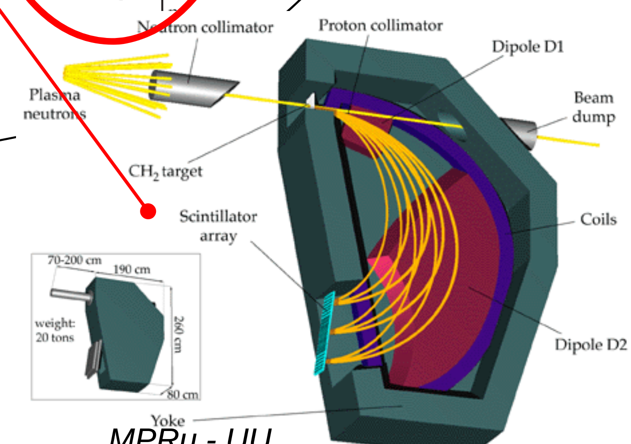

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Developments of the time-of-flight technique

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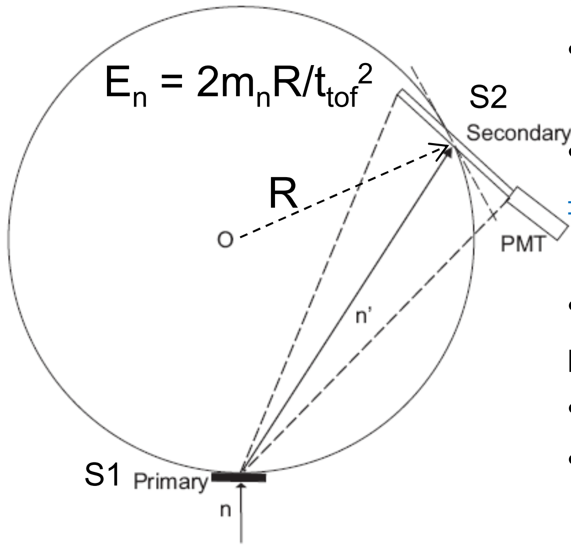
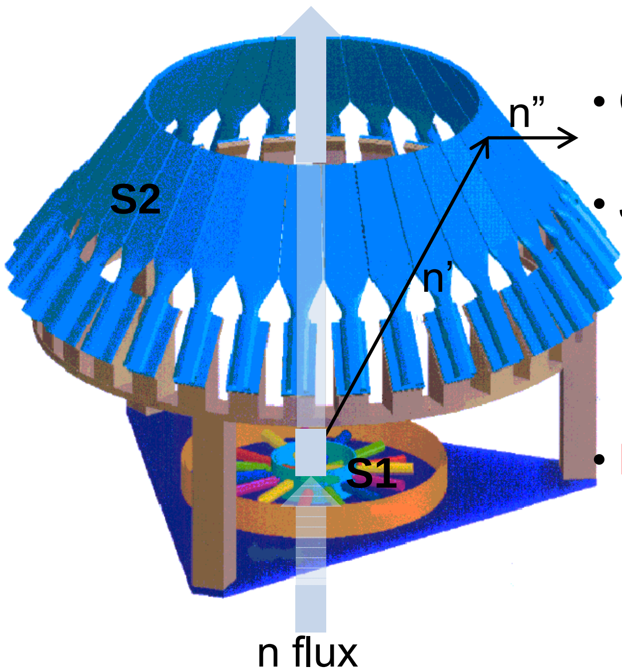
Time-of-flight n spectroscopy





- Commonly used for 2.45 MeV n in D plasmas
- Continuous source of n:
  - ⇒ Double scattering in S1 + S2
- Elastic n,p scattering in fast plastic scintillators

⇒2-body kinematics = correlated time, energy

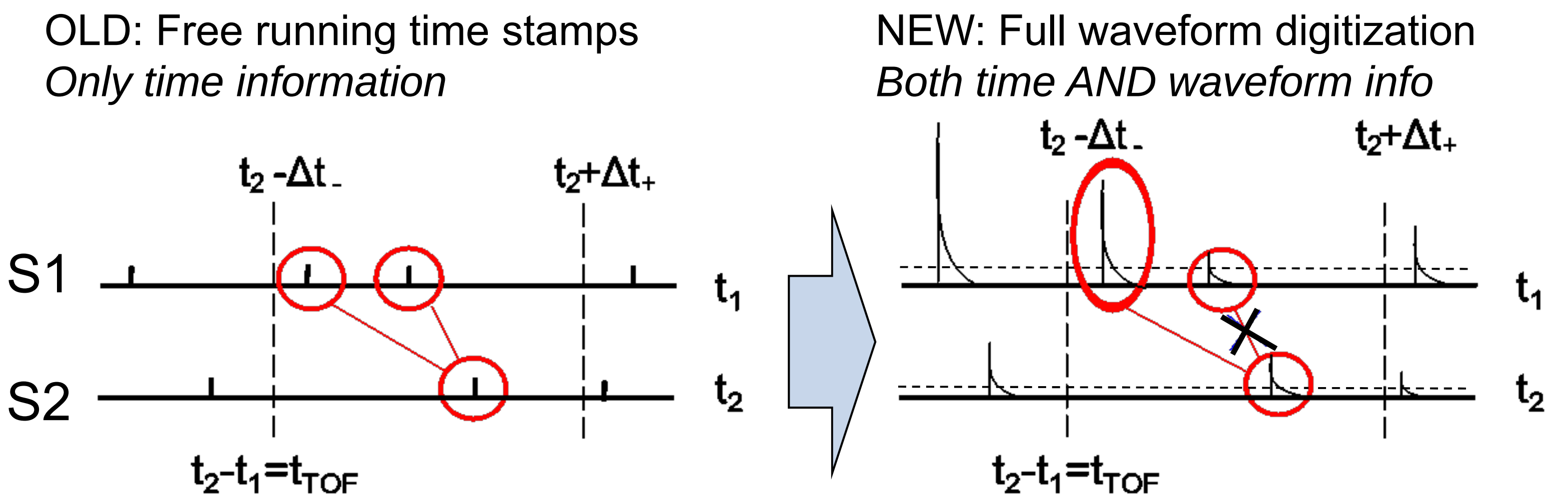
- If ONLY time info: Main Background = uncorrelated neutrons (random events)
- Signal $\propto R_n$, Bgr $\propto R_n^2 \rightarrow$ B:S $\propto R_n$ (R_n is n rate)
- Limitations:
  - ✓ System "paralysis" at high R_n
  - ✓ Rate in S1 (≈ MHz)

- C_{cap} ≈ 500 kHz (S:B ≈ 1); C_{max} ≈ 50 kHz (2009)

- JET TOFOR system installed 2005:
  - ✓Emphasis on rate capability
  - ✓Digital free-running time (only) stamping
  - ✓Separate, non-correlated pulse height spectra

- Developments in digital DAQ electronics:
  - ✓Waveform digitizers boards with capacity for time AND pulse height measurements exist!
  - ✓Integral over waveform = pulse height ~ E_p
  - ✓Digital CFD → time of waveform → t_{TOF}

ToF: From time stamp to full waveform



- OLD system: **All** eligible time stamps had to be used
- NEW system: Discriminate against events with unphysical combinations of time and pulse-height
- Other advantages of digital sampling of full waveform:
  - Improved time pick-off – reduce timing walk, improve energy resolution
  - Baseline restoration: corrected for RF pick-up, baseline shifts
  - Pile-up correction/rejection
  - Event identification (depending on detector material) – spikes, noise, …
  - On-board processing in FPGA for real time applications

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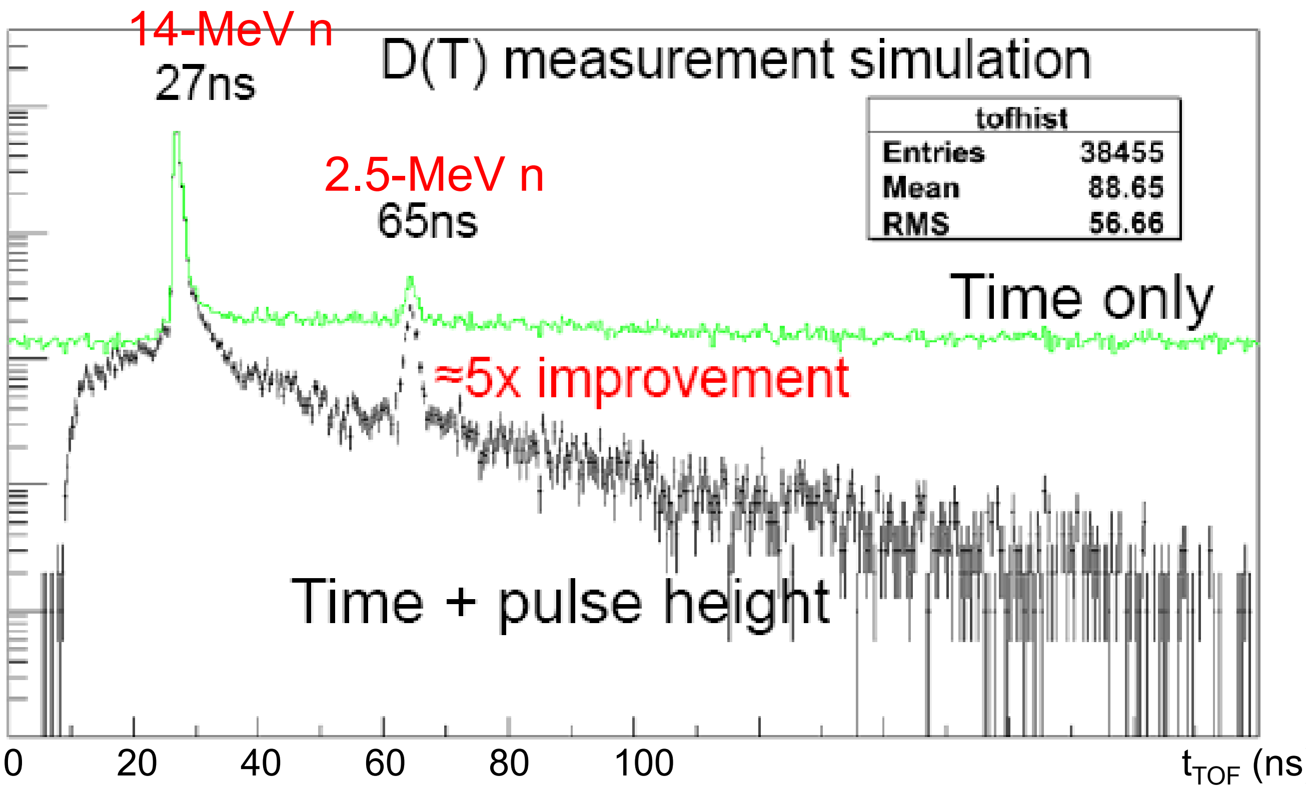
ToF: Simulation study

- 3 problems in today's fusion ToF systems:
  - ✓Multiple scattering of n gives tails in response function; unfolding issues
  - ✓Uncorrelated n gives accidental S1-S2 coincidences; high level bgr
  - ✓Analogue CFD not "perfect": E dependent time walk, poor E resolution
- Correlated time AND energy deposition measurements can reduce problems:
  - ✓Most multi-scatter events have "wrong" correlation t(tof)-E(S1)
  - ✓Most accidentals have "wrong" correlations t(tof)-E(S1)
  - ✓Full waveform gives improved event time pick-off
- Below: Simulation of D(T) measurement ($n_T/n_D \sim 10\%$)



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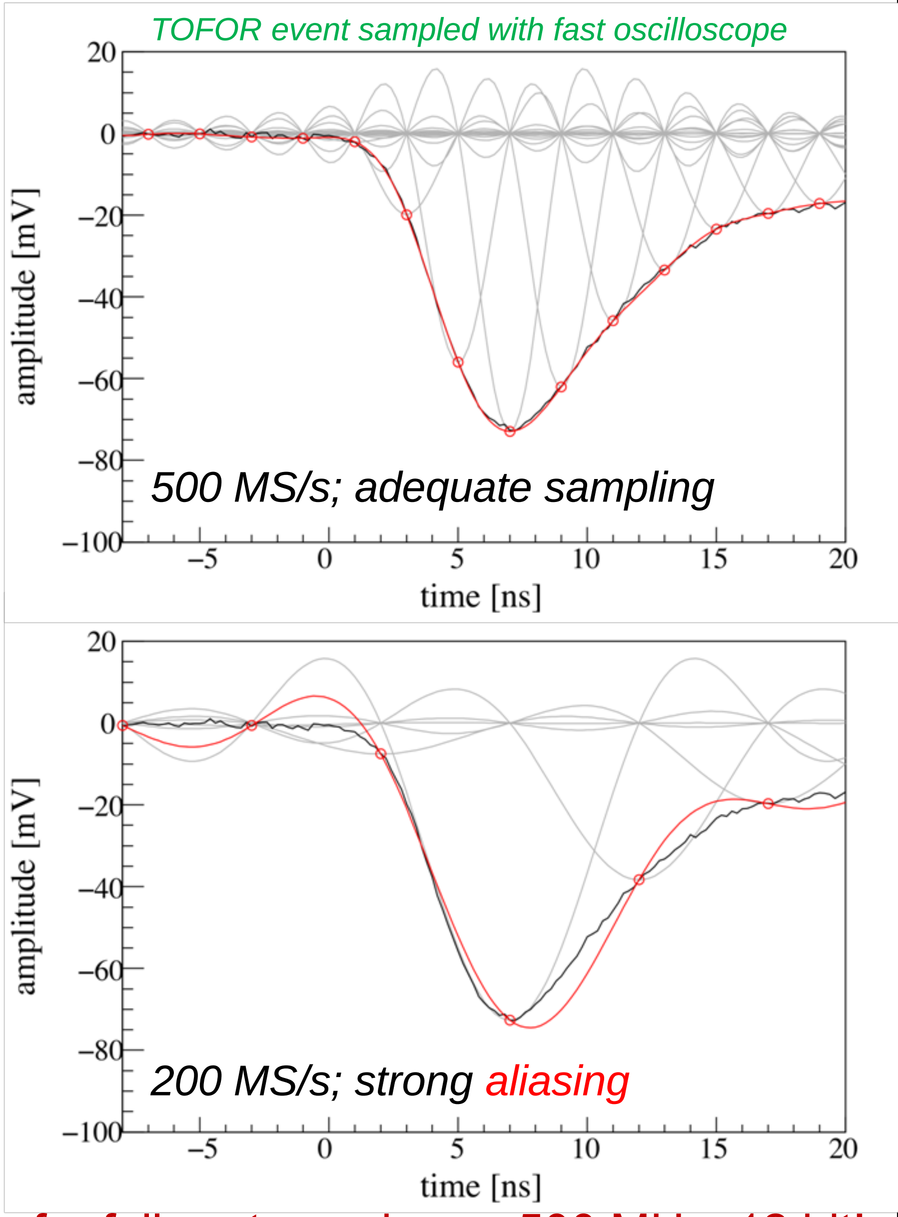
ToF: Waveform reconstruction

- Shannon's sampling theorem
  - "If a signal $Y(t)$ contains no frequencies higher than f_{nyq}, it is COMPLETELY determined by giving its ordinates as a series of points spaced $\Delta t = 1 / (2f_{\mathrm{nyq}})$ apart."
- Use sinc fcn as base:

$$Y(t) = \sum_{\mathrm{i}} Y_{\mathrm{i}} \frac{\sin((t - t_{\mathrm{i}})/\Delta t)}{(t - t_{\mathrm{i}})/\Delta t}$$

- If possible, test sample signal after FULL processing chain at high rate, high bit resolution
- Investigate effect on reconstruction from down sampling of real signal
- Example: ToF events sampled at 2GS/s, 14 bits (black)
  - Upper panel: down sample to 500 MS/s (red dots)
  - Lower panel: down sample to 200 MS/s (red dots)



Determine suitable sampling rate for full system – here ≥500 MHz, 12 bit!

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ToF: SP Devices board ADQ-412

- Purchase of digitizer system based on preliminary simulation and digitizer studies
- PXIe digitizer boards, PXIe crate, cables
- 3 digitzer boards purchased from SP-Devices, Linköping, Sweden
  - PXIe interface
  - 4 channels / card
  - Sampling @ 1 GS/s (4 ch), 2 GS/s (2 ch)
  - ADC 12 bit resolution
  - Flexible trigger options
  - Time synchronization options
  - Boards biased for negative pulses
  - Optional FPGA programming for on-board processing
- Development issues - software
  - Re-arm time ≈200 ns (dead time)
  - Fixed memory records of 1024 samples
  - Fast streaming of data to extern. storage

ToF: timing aspects and requirements

A) Programme to study time resolution as function of sampling rate and pulse amplitude (bit coverage):

1) Synthetic (sofware generated) data
2) Waveform generator data
3) Scintillator data – cosmic muons

B) Study performance of specific DAQ digitizer boards (SPD ADQ 412) to assess their applicability to a ToF system:

1) Intra-board time calibration
2) Intra-board time synchronization – common start
3) Absolute time reference – JET Hz clock

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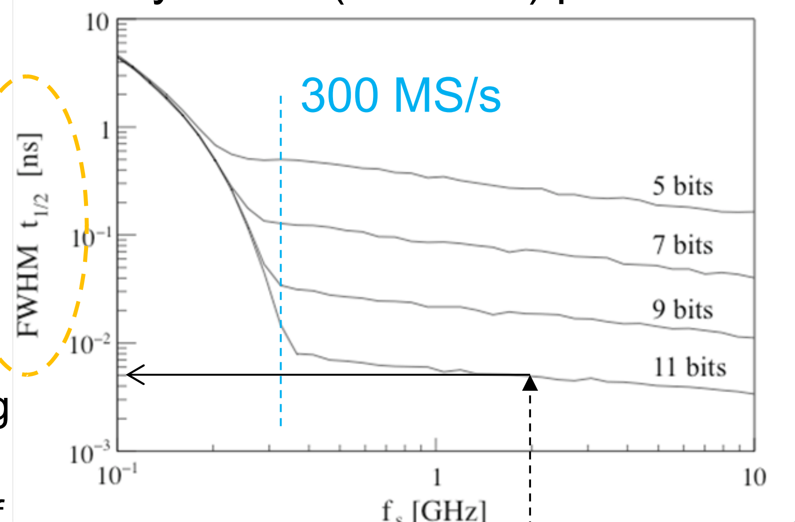
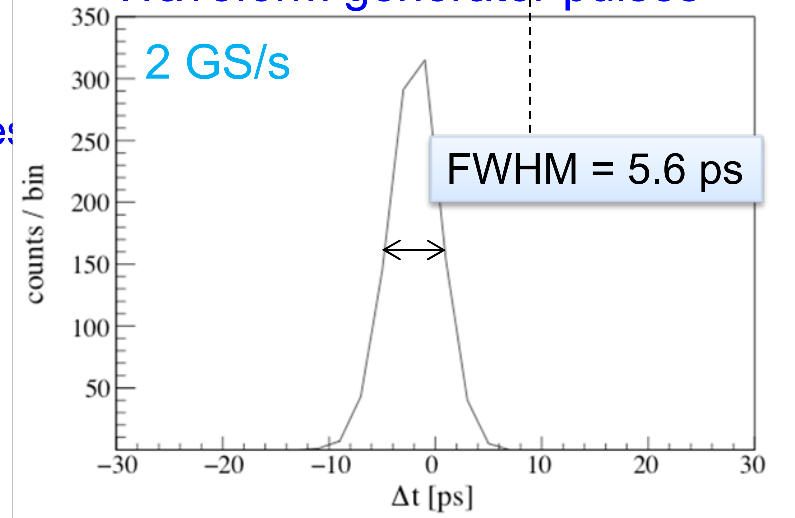
ToF: Gaussian pulses t resolution

- Time resolution performance tested on *synthetic* (and *generator)* pulses
  - FWHM of pulses: 7.5 ns
- Sampling of synthetic Gaussian pulse (calculated at 1 THz – 1 ps)
  - Down sampling: f_s from 0.1 to 10 GHz
  - Pulse amplitude covering 5 to 11 bits with noise +/- 1 bit (lsb)
- Timing capability depends on sampling frequency and bit resolution
  - Critical f_s given by frequency content of Gaussian pulse
  - 99.9% of information below about 150 MHz $\rightarrow$ sampling at >300 MHz
- Sampling of waveform generator pulses – Gaussian with FWHM = 7.5 ns :
  - Pulses cover > 11 bits
  - Electronic noise ≈1 bit
  - Coincidence between two channels
  - Sampling at 2 GHz
  - FWHM = 5.6 ps

Synthetic (software) pulses



Waveform generator pulses

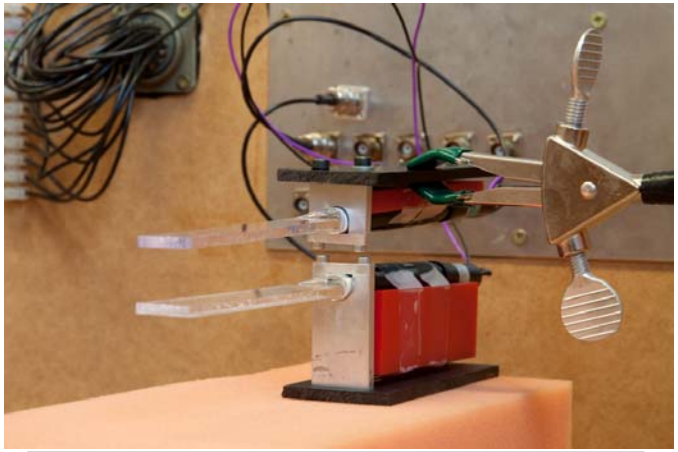


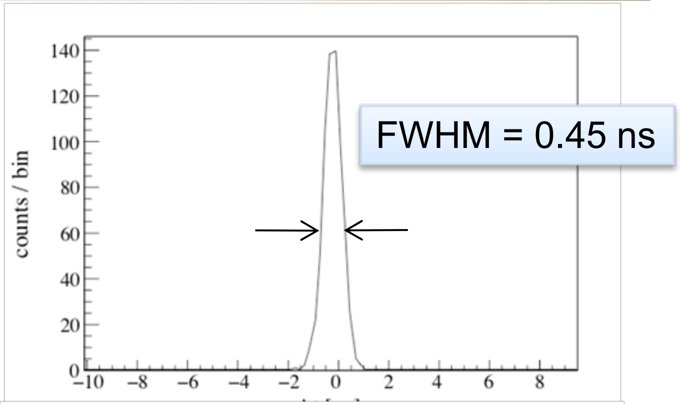
ToF: Tests with cosmic muons

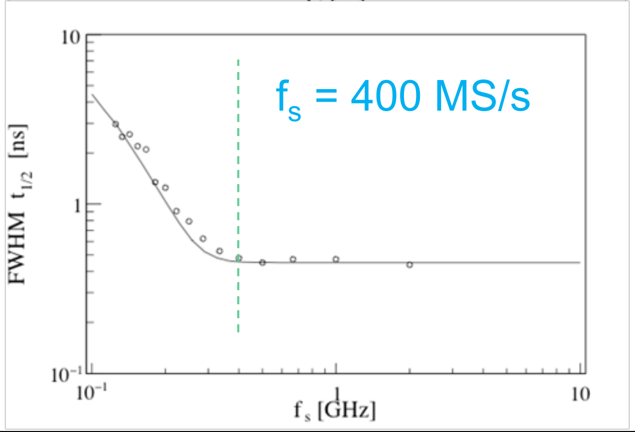
- 2 scintillators in coincidence
- Model of signal pulse shape taking into account : light emission timing, PMT timing, cable transfer function
- Data fromADQ-412 cards:
  - 2 channels on same card
  - 2 channels on different cards
  - Sampling at 2 GHz
- FWHM of dt = $t_{chan1} - t_{chan2}$, Δt = 0.45 ns
- Down sampling to find critical f_s
- Compare with model

$$\mathrm{FWHM} = \sqrt{\mathrm{model}^2 + 0.45^2}$$

- Δt =0.45 ns is time resolution of detector setup with this PMT
  - No improvements going above about 0.4 GHz sampling
- Contributions to time resolution:
  - PMT Transient Time Spread
  - Geometry, light collection
  - Electronic noise







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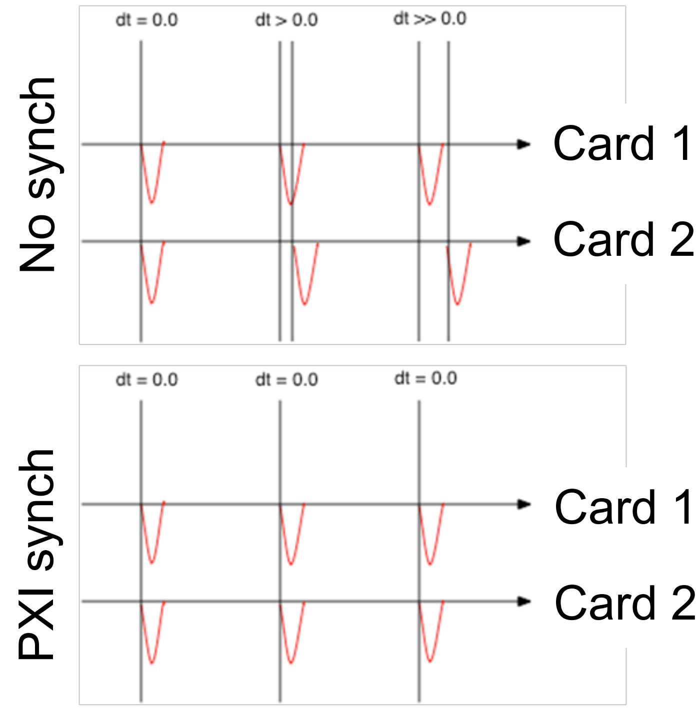
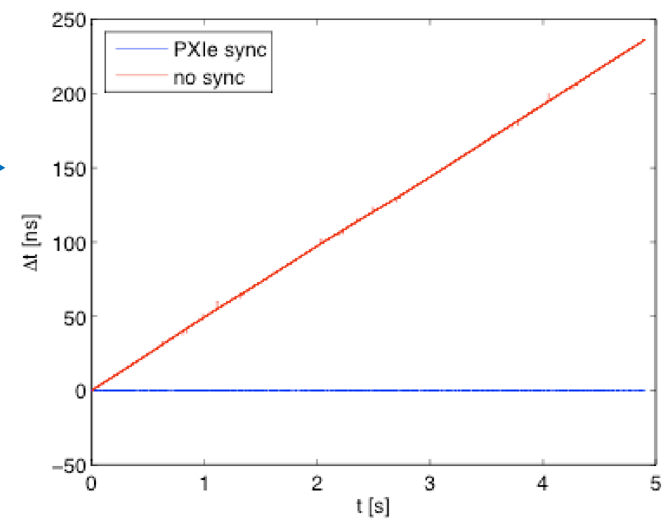
ToF: ADQ-412 synchronization

- Multiple boards with different ADC clocks - vital to keep relatively synchronization
  - Relative difference between must be < 100 ps over several minutes or it will contribute to an extra broadening of the TOF
- PXIe standard offers 10 MHz clock as synch reference on the crate backplane
- A pulse generator running at 10 kHz for 5 s was used to asses the performance of the PXIe synch
  - Over 5 s, the relative time difference between the cards was below 5 ps
  - Same result for tests of several minutes
  - Time synch is adquate





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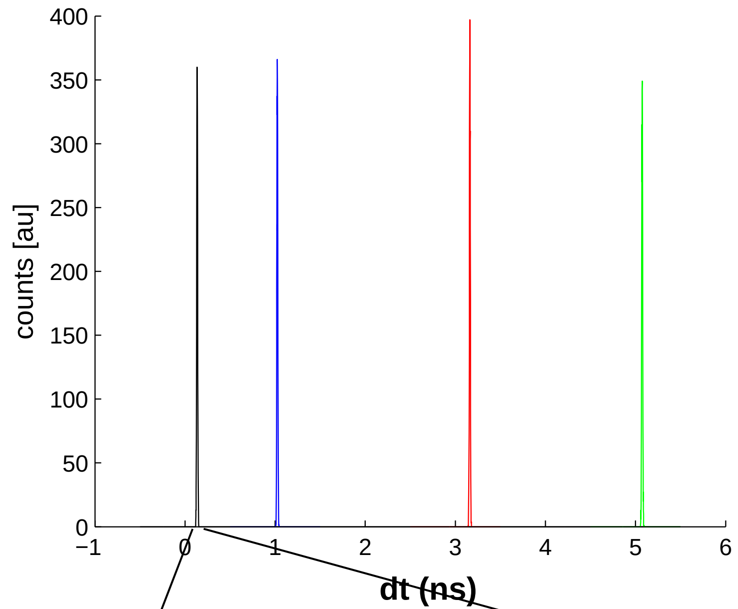
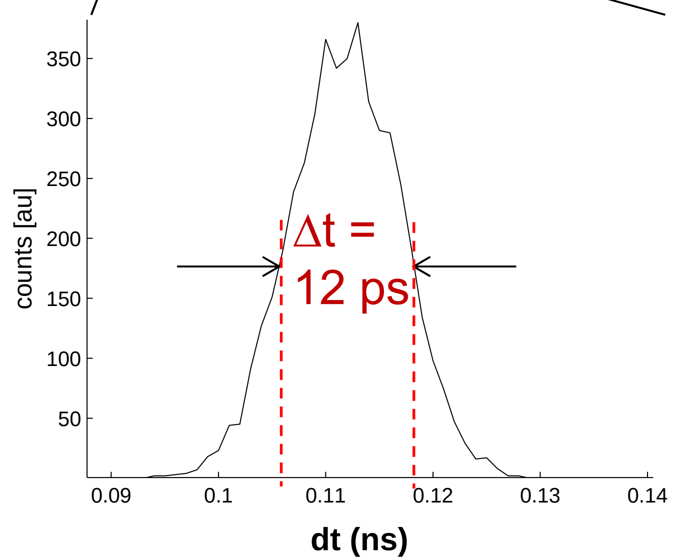
ToF: Absolute time measuremens

- Two different ADQ412 cards used
- Cards calibrated by PXI 10MHz clock
- ”Gaussian” pulses from Waveform Generator
    - Pulse width about 7.5 ns
    - Pulse amplitude about 9 bits
- Time differences of ADQ412 input by Lemo cables
    - Cables of 3, 4, 5 ns used
    - 3 ns difference by using Lemo adaptor (3+3 ns)
- Pulses sinc reconstructed
- Time for each pulse determined by digital CFD
- Absolute time difference dt measured for:
    - dt = 0, 1, 3 (+0.1 adaptor?), 5 ns cable difference
    - Δt from dt histogram of few 1000 ”events”
- Δt about 10-15 ps as expected





ToF status summary

- Requirements on digitizer determined from analysis of scintillator pulses after FULL signal processing chain (here 1-2 GHz, 12 bit)
- Simulation study gives correlation between pulse amplitude and t (E) resolution for ALL pulse amplitudes
- Sinc (sin(x)/x) reconstruction gives ”true” waveform
- Recoil particle energy from integration of sinc-reconstructed pulse – ”no” dependence on sample points
- Time of waveform from sinc-reconstructed pulse – ”true” CFD performance can be achieved
- Inter-board synchronization verified
- Intra-board synchronization from PXI crate 10 MHz clock
- Performance of 3x 4 channel system in PXI crate studied:
  - Common START options tested
  - Waveform generator pulses tested
  - 2x Scintillator system coincidences tested
- System ready to be tested on real ToF system (JET)

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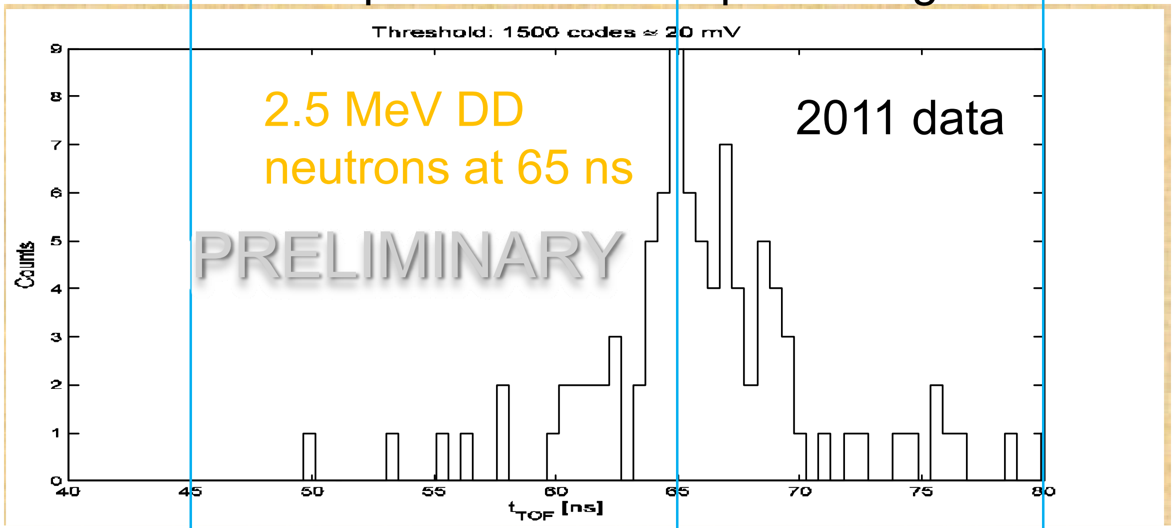
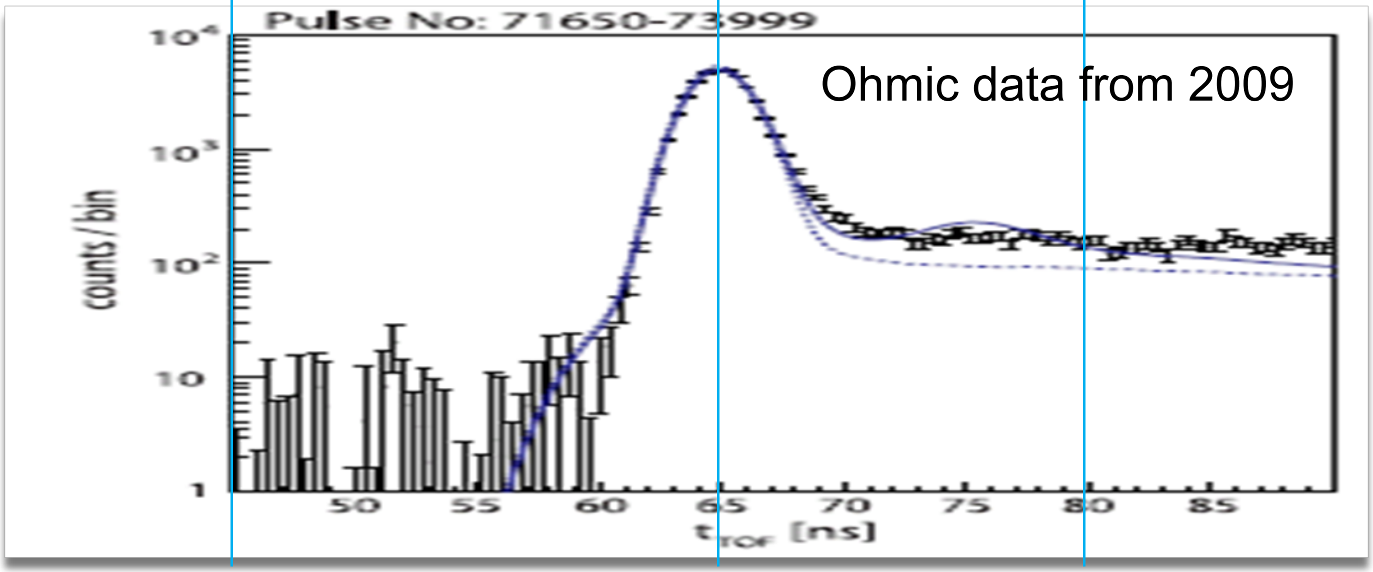
First TOFOR data with ADQ-412

- Data for 3 low-yeild JET pulses
- Collected FridayNov. 25, 2011 in parallel with normal TOFOR DAQ
- Only low threshold imposed – no time-pulse height correlation (yet)





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Developments of the non-magnetic thin-foil proton recoil technique

TPR: Detection principle

•The spectrometer is based on the *thin-foil* principle

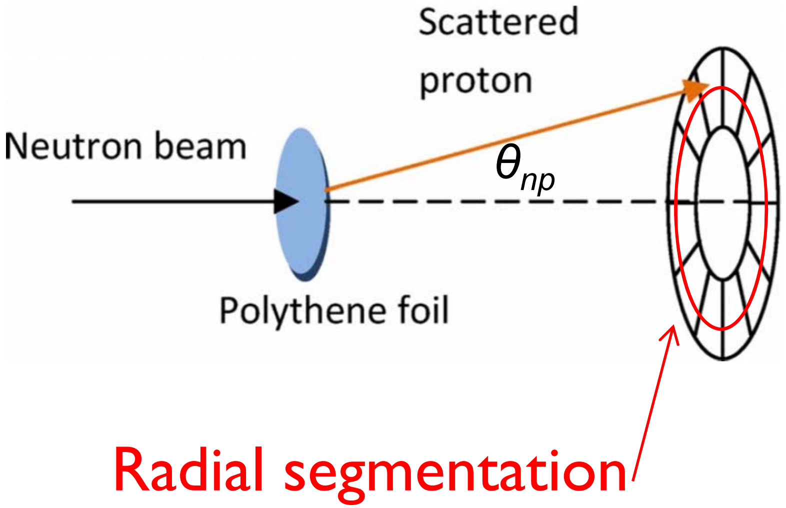
•Collimated neutrons impinge a thin foil, which in turn radiates protons due to elastic scattering

•$E_p = E_n \cos^2(\theta_{np})$

•A suitable segmented detector (semi-conductor or scintillator) detects the protons and their energies

•Performance (efficiency, resolution) given by geometry (foil thickn, foil-detector distance, …) and detector characteristics

•Local vacuum chamber to avoid proton energy loss and scattering

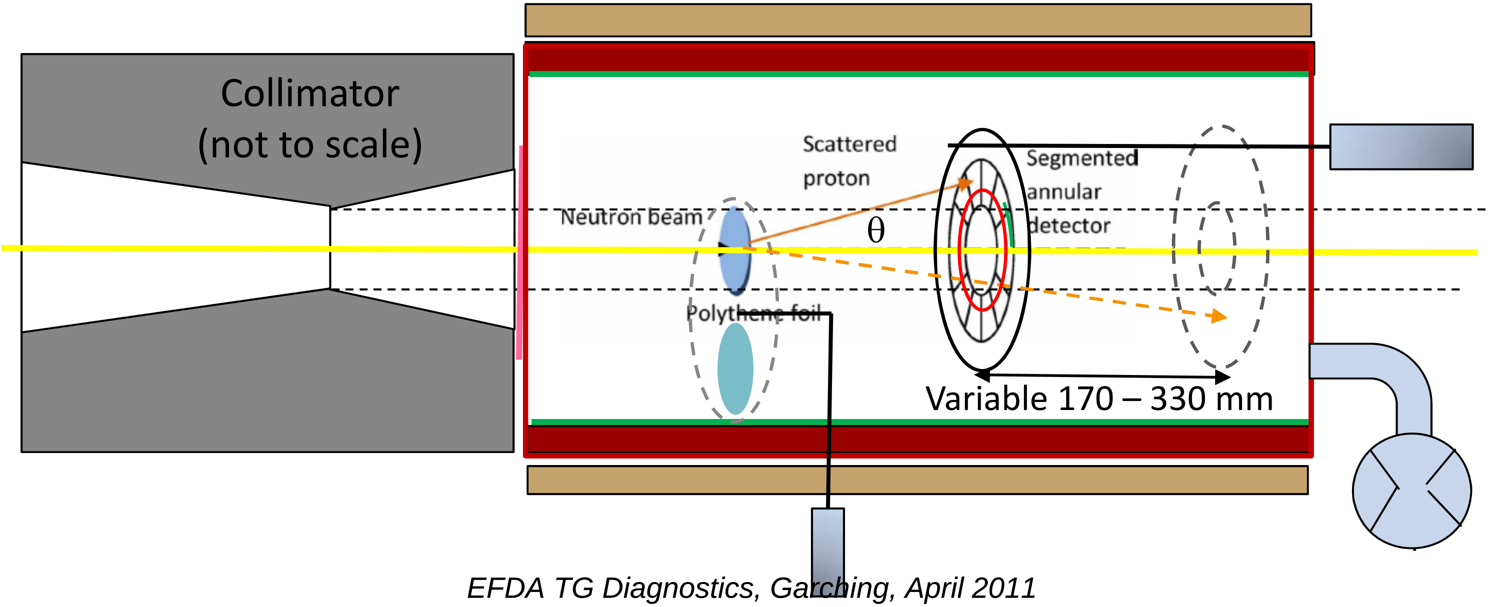


Detector placed close to n beam = Detector exposed to scattered neutrons

Thin-foil Proton Recoil spectrometer

- Central foil (here 10cm^2), annular detector: Si(1mm) + Si(1mm) OR Si + YAP

- Conceptual design:
  - ✓ Tapered **neutron collimator**
  - ✓ **Gd** (or similar) foil to reduce thermal flux through collimator
  - ✓ Thin **CH_2** foil as proton radiator
  - ✓ ”Micron S1” Si detector (16 annular segments)
  - ✓ Vacuum chamber (<10^{-3} mbar), **Aluminium** to reduce capture γ
  - ✓ Lining of **^{6}Li-doped plastic** to absorb thermal neutrons in chamber
  - ✓ **Magnetic shield** to reduce ITER field in region of proton recoils
  - ✓ Tandem system



TPR simulations; MCNPX, FISPACT

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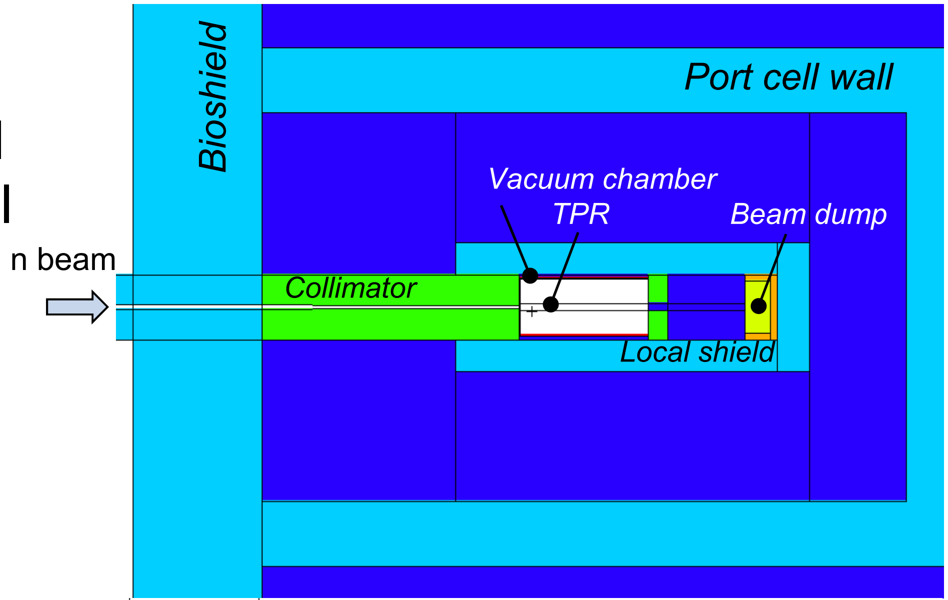
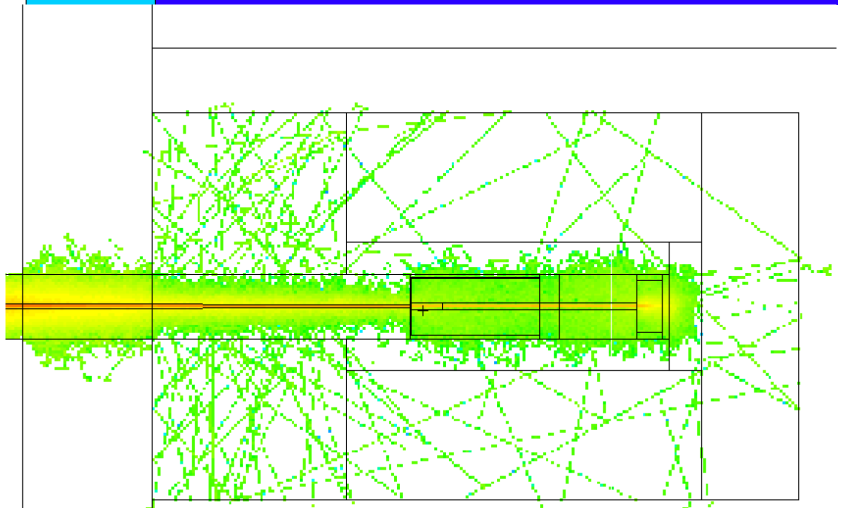
- MCNPX
  - Simplified model of ITER Port Cell
  - Monte Carlo n + γ transport code
- FISPACT
  - Activation code for fission and fusion applications
- Data exchange routines



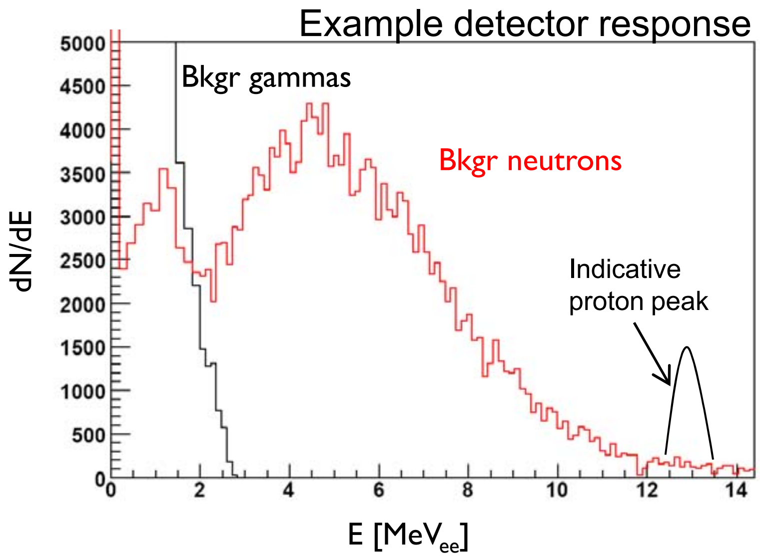


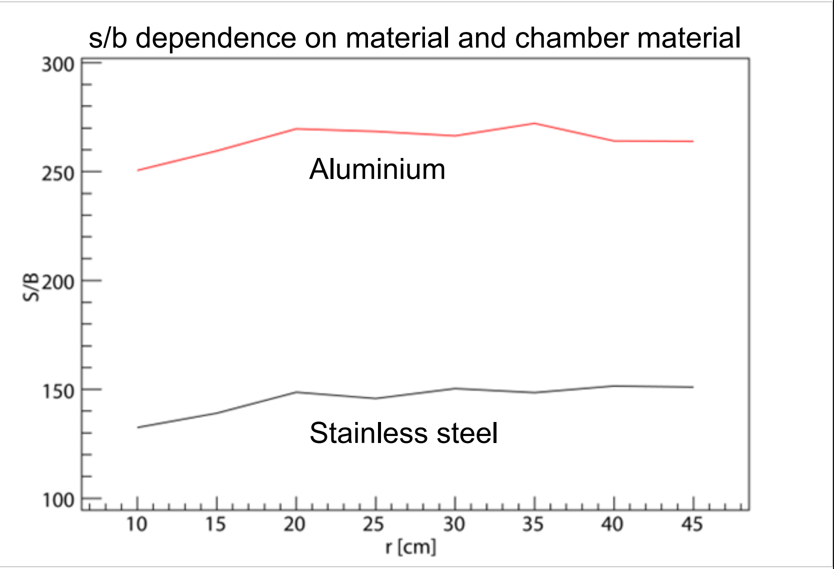
Example MCNPX result

TPR: s/b assessment

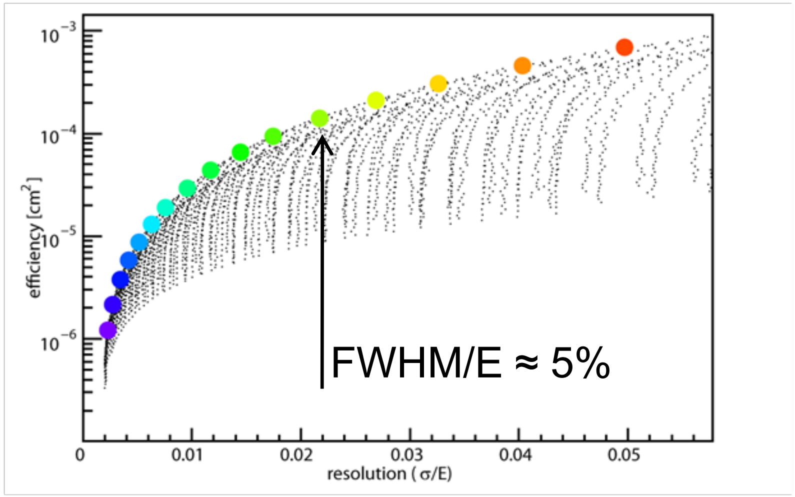
- MCNPX → scattered neutron background
- FISPACT → gamma background from vacuum chamber
- Background has been calculated varying:
  - ✓ vacuum chamber material (Al & SS)
  - ✓ vacuum chamber radius (10-40 cm)

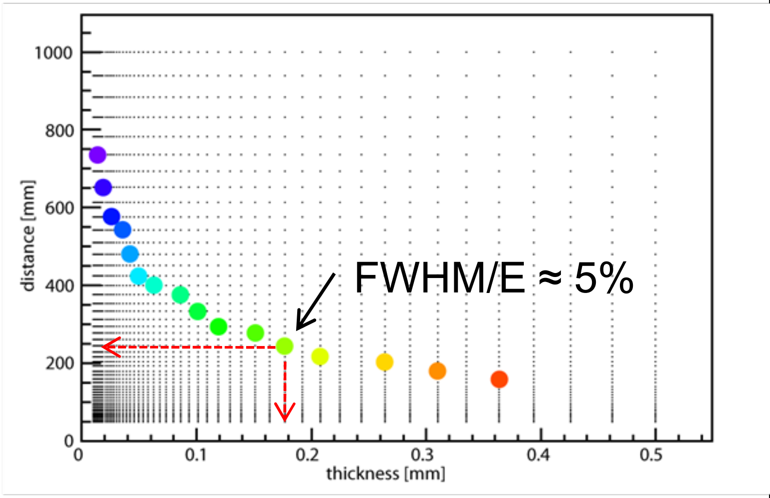
- Weak dependence on vacuum chamber radius
- Aluminium best material





TPR: working point assessment





- Simulation study using:
  - Vacuum
  - 2 mm thick detector
  - ”S2” design (Micron Ltd)
- Parameter scan over
  - Foil area
  - Foil thickness
  - Foil – detector distance
  - Detector segmentation

- ”Pareto frontier” plot gives optimum: highest efficiency for a certain resolution
- Optimal point gives foil thickness and distance
- Different working points for ”high resolution”, ”high efficiency”, ”α knock-on” …

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Preliminary results – full system

- Aluminium as structural material, graphite for foil holders
- Local vacuum chamber with as small radius as possible
- Coincidence detector 2x 1mm Si, OR Si + YAP
- Si detector w 4x 4 radial segments (16 electronics channels) per detector, 4x YAP segments
- Adjustable detector distance from foil (4 positions)
- Target foil changer (4 positions)
- Prepare 4 optimal working points:

Setting	Energy (MeV)	FWHM/E (%)	ε (cm^2)	Foil t (mm)	Foil-det dist (mm)
High resolution	14	2.5	5e-5	0.10	330
High efficiency	14	10	5e-4	0.32	180
”Alpha knock-on”	14	6	2e-4	0.20	230
Test, High efficiency	2.5	10	1e-4	0.014	170

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CONCLUSIONS

Summary and Conclusions

- Developments of time-of-flight (ToF) and thin-foil proton recoil (TPR) techniques for fusion neutron spectrosocpy
- ToF:
  - Development in commercial data acquisition technology now makes time AND waveform acquisition at high rates possible
  - A board suitable for fusion ToF n spectroscopy investigated (2-4 channel, 1-2 GS/s, 12 bit)
  - Developed model for assessing performance of digitizers (time and pulse height resolution) as fcn of sampling and amplitude
  - If possible, use high-performance digitizer in DAQ system position before deciding on full system; down sample in t and E
  - In 2012: Test the new pulse-height/time digitizing boards in a real ToF system (TOFOR @ JET)
- TPR:
  - s/b assessed in ITER like situation; s/b > 250 (Al; E_n = 14 MeV)
  - Engineering design during 2012
  - In 2012: Pilot tests of foil + Si detector system + Read-out

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ToF: Leading edge Digital CFD

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- Sinc reconstruction of pulse data set; data can be:
  - Down-sampled synthetic data
  - Generator measurements
  - Scintillator measurements
- Different methods for finding $t_{1/2}$ at $y_{1/2} = 0.5^* y_{min}$ of reconstructed pulse evaluated
  - Up sampling to 1 THz (1 ps); find t of point closest to $y_{1/2}$
  - Up sampling to 20 GHz 50 ps); linear interpolation
- Linear interpolation used in this work
  - Reasonable compromise between computational speed, memory and precision
  - Up sample the sinc-reconstructed signal to 20 GHz (50 ps time base)
  - Apply linear interpolation to points in interval $y = 0.4 \cdot y_{min} \rightarrow 0.6 \cdot y_{min}$
  - Solve for t at $y = 0.5 \cdot y_{min}$