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

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Outline:
• Neutron diagnostics 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
INTRODUCTION
Neutron emission

- Fusion experiments with D and T fuel:
  - \( d + d \rightarrow ^3\text{He} + n \) (2.45 MeV)
  - \( d + t \rightarrow ^4\text{He} + n \) (14.0 MeV)

- "Impurities"
  - \( d + \{^3\text{He}, ^4\text{He}, ^9\text{Be}, ^{12}\text{C}, \ldots\} \rightarrow n + X \)

- Plasma parameters: \( P_{\text{fus}}, T_i, f(v_{\text{ion}}), \ldots \)

- 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 \( S_n \sim 0.01 \)
    - \( \alpha \) heating \( S_n \sim 0.001 \)

- Neutron emission variations:
  - Intensity; 0 - 10^{20} n/s (ITER)
  - Temporal (ms), spatial (cm)
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 → spectroscopy on MHz signal rates ($C_{\text{cap}}$)
    - High $\varepsilon$ OR close to reactor core
  - Access to weak emission components → high S/B ratio > 10$^4$
    - Peaked, well-known response function (0 – 20 MeV)
  - Real-time information in ms → 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)
Lattanzi, Angelone, Pillon, Fus Eng Des (2009)

TOFOR - UU
Gatu Johnson, NIM A591 (2008)

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

MPRu - UU
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Most “standard” n spectr. techniques tested in fusion (JET)
Developments of the time-of-flight technique
Time-of-flight n spectroscopy

- Commonly used for 2.45 MeV n in D plasmas
- Continuous source of n:
  \[ \Rightarrow \text{Double scattering in S1 + S2} \]
- Elastic n,p scattering in fast plastic scintillators
  \[ \Rightarrow \text{2-body kinematics = correlated time, energy} \]
- 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 (\( \approx \) MHz)
- \( C_{\text{cap}} \approx 500 \text{ kHz} \) (S:B \( \approx 1 \)); \( C_{\text{max}} \approx 50 \text{ kHz} \) (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 \textit{time AND pulse height measurements exist!}
  - Integral over waveform = pulse height \( \sim E_p \)
  - Digital CFD \( \rightarrow \) time of waveform \( \rightarrow t_{\text{TOF}} \)

\[ E_n = \frac{2m_n R}{t_{\text{tof}}^2} \]
ToF: From time stamp to full waveform

OLD: Free running time stamps
   Only time information

NEW: Full waveform digitization
   Both time AND waveform info

• 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
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 ~ 10%)

![Simulation of D(T) measurement](image)
ToF: Waveform reconstruction

- Shannon’s sampling theorem
  - “If a signal \( Y(t) \) contains no frequencies higher than \( f_{\text{nyq}} \), it is COMPLETELY determined by giving its ordinates as a series of points spaced \( \Delta t = 1 / (2f_{\text{nyq}}) \) apart.”

- Use sinc fcn as base:
  \[
  Y(t) = \sum_i Y_i \frac{\sin((t - t_i)/\Delta t)}{(t - t_i)/\Delta t}
  \]

- 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 \( \geq 500 \) MHz, 12 bit!
ToF: SP Devices board ADQ-412

- Purchase of digitizer system based on preliminary simulation and digitizer studies
- PXIE digitizer boards, PXIE crate, cables
- 3 digitizer 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 (software 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
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 → sampling at >300 MHz
- Sampling of waveform generator pulse:
  - Gaussian with FWHM = 7.5 ns:
    - Pulses cover > 11 bits
    - Electronic noise $\approx$ 1 bit
    - Coincidence between two channels
    - Sampling at 2 GHz
    - FWHM = 5.6 ps
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 from ADQ-412 cards:
  - 2 channels on same card
  - 2 channels on different cards
  - Sampling at 2 GHz
- FWHM of $\Delta t = t_{\text{chan}1} - t_{\text{chan}2}$, $\Delta t = 0.45$ ns
- Down sampling to find critical $f_s$
- Compare with **model**
  \[
  \text{FWHM} = \sqrt{\text{model}^2 + 0.45^2}
  \]
- $\Delta t = 0.45$ 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

FWHM = 0.45 ns

$f_s = 400$ MS/s
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 assess 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 adequate
ToF: Absolute time measurements

- 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
  - \( \Delta t \) from \( dt \) histogram of few 1000 "events"
- \( \Delta t \) 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)
First TOFOR data with ADQ-412

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

2.5 MeV DD neutrons at 65 ns

2011 data

Ohmic data from 2009
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 10cm²), 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 CH₂ foil as proton radiator
  - "Micron S1" Si detector (16 annular segments)
  - Vacuum chamber (<10⁻³ mbar), Aluminium to reduce capture γ
  - Lining of ⁶Li-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

- **MCNPX**
  - Simplified model of ITER Port Cell
  - Monte Carlo \( n + \gamma \) transport code

- **FISPACT**
  - Activation code for fission and fusion applications

- Data exchange routines

*EFDA TG Diagnostics, Garching, April 2011*
TPR: s/b assessment

- MCNPX $\rightarrow$ scattered neutron background
- FISPACT $\rightarrow$ 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" …

EFDA TG Diagnostics, Garching, April 2011
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:

<table>
<thead>
<tr>
<th>Setting</th>
<th>Energy (MeV)</th>
<th>FWHM/E (%)</th>
<th>$\varepsilon$ (cm$^2$)</th>
<th>Foil t (mm)</th>
<th>Foil-det dist (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High resolution</td>
<td>14</td>
<td>2.5</td>
<td>5e-5</td>
<td>0.10</td>
<td>330</td>
</tr>
<tr>
<td>High efficiency</td>
<td>14</td>
<td>10</td>
<td>5e-4</td>
<td>0.32</td>
<td>180</td>
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<tr>
<td>&quot;Alpha knock-on&quot;</td>
<td>14</td>
<td>6</td>
<td>2e-4</td>
<td>0.20</td>
<td>230</td>
</tr>
<tr>
<td>Test, High efficiency</td>
<td>2.5</td>
<td>10</td>
<td>1e-4</td>
<td>0.014</td>
<td>170</td>
</tr>
</tbody>
</table>
Summary and Conclusions

• Developments of time-of-flight (ToF) and thin-foil proton recoil (TPR) techniques for fusion neutron spectroscopy

• 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
ToF: Leading edge Digital CFD

- 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 $y_{1/2} = 0.5 \cdot y_{\text{min}}$ 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 $y = 0.4 \cdot y_{\text{min}} \rightarrow 0.6 \cdot y_{\text{min}}$
  - Solve for $t$ at $y = 0.5 \cdot y_{\text{min}}$