Time of flight identification with FAZIA

EuNPC 2018
Bologna, September 2\textsuperscript{nd} – 7\textsuperscript{th}, 2018
The FAZIA telescope

The telescope stages

1. 300 µm reverse-mounted Si detector;
2. 500 µm reverse-mounted Si detector;
3. 10 cm CsI(Tl) crystal read by a photodiode.

To achieve the best possible energy resolution and A and Z identification Si detectors come from a nTD ingot cut at random angle to avoid channeling effects.
The FAZIA telescope

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2. 500 µm reverse-mounted Si detector;
3. 10 cm CsI(Tl) cristal read by a photodiode.

*To achieve the best possible energy resolution and $A$ and $Z$ identification Si detectors come from a nTD ingot cut at random angle to avoid channeling effects.*
The FAZIA telescope

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To achieve the best possible energy resolution and A and Z identification Si detectors come from a nTD ingot cut at random angle to avoid channeling effects.
The FAZIA block

2 telescopes are connected to a FEE card.
The FAZIA block

8 FEE cards are connected to a block card via a back plane.
The FAZIA block

Block card, power supply and half bridge
FEE cards
Detectors

Block is mounted on a copper base in which water flows to provide cooling
The FAZIA block

- **48 V DC power supply**
- **Regional board**
- **Back plane**
- **Half-bridge and power supply cards**
- **Block card**
- **FEE card #0**
- **FEE card #7**

**Block ‘0’**
- **Block card**
- **Half-bridge and power supply cards**
- **Back plane**
- **FEE card #0**
- **FEE card #7**

**Block ‘n’**
- **Block card**
- **Half-bridge and power supply cards**
- **Back plane**
- **FEE card #0**
- **FEE card #7**

> up to 36 block cards are connected to a regional board via a full duplex 3 Gb/s optical link
FAZIA electronics

<table>
<thead>
<tr>
<th>Front-end</th>
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<td>• Analogue chain: charge preamplifiers and anti-aliasing filters</td>
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</table>

- Signals are immediately digitized with 14-bit ADCs: energy resolution is better than 1% from 5 MeV to 4 GeV.
- Common clock distribution for synchronous sampling.
- Signals are online processed on FPGAs.

Pros and cons:
- Compactness and modularity
- Very good isotopic discrimination capabilities
- High identification thresholds (2–10 MeV/μ)
FAZIA electronics

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FAZIA electronics

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Identification methods

$\Delta E - E$ correlation
- exploits the Bethe-Bloch energy loss relation
- identification threshold due to first layer thickness

Pulse Shape Discrimination$^a$
- charge collection depending on the impinging nuclei
- identification threshold corresponding to $\sim 50 \mu \text{m}$ penetration

$^a$ N. Le Neindre et al, Nucl. Instr. and Meth. A 701 (145), 2013
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Pulse Shape Discrimination\(^a\)
- charge collection depending on the impinging nuclei
- identification threshold corresponding to \( \sim 50 \mu m \) penetration

\( E - ToF \) correlation
- FAZIA implementation proposed here
- lowest identification threshold
- FURBO project

\(^a\) N. Le Neindre et al, Nucl. Instr. and Meth. A 701 (145), 2013
FURBO project

**FAZIA Upgrade for Radioactive Beam Operation**
(INFN grant for new staff researchers)
FURBO project

**FAZIA Upgrade for Radioactive Beam Operation**
(INFN grant for new staff researchers)

**Reduction of identification thresholds**
- Fundamental task to measure in future ISOL facilities (SPES, Spiral2, ...)
- Different possible solutions:
  - **time of flight** implementation (discussed here)
  - use of **thin** Si detectors as first stage
  - use of **alternative** detectors
Time of Flight measurement

Time of flight \( ToF \equiv t - t_0 \)

Flight base \( d = |\vec{x}(t) - \vec{x}(t_0)| \)

Kinetic energy \( E = \frac{1}{2} m \left( \frac{d}{ToF} \right)^2 \)

A start time mark is needed to measure ToF
Time of Flight measurement

**Time of flight** \( T\text{ToF} \equiv t - t_0 \)

**Flight base** \( d = |\vec{x}(t) - \vec{x}(t_0)| \)

**Kinetic energy** \( E = \frac{1}{2}m\left(\frac{d}{T\text{ToF}}\right)^2 \)

**Time reference in FAZIA**

- all acquired waveforms are referred to the validation time \( t_V \)
- applying a digital CFD algorithm to waveforms gives a time mark \( t_{CFD} = t - t_V + t_{off} \)
- \( t_V \) is the same for all detectors

A **start** time mark is needed to measure ToF
Time of flight in heavy-ion collisions

$$ToF \equiv t - t_0$$
Time of flight in heavy-ion collisions

\[ ToF \equiv t - t_0 \]

Start detector needed
Time of flight in heavy-ion collisions

\[ \text{ToF} \equiv t - t_0 \]

Start time mark from accelerator RF
Time of flight in heavy-ion collisions

\[ \text{ToF} \equiv t - t_0 \]

\[ \Delta t \equiv t_{RF} - t_0 \]

constant

\[ E_{el} = \frac{1}{2} m_{el} v_{el}^2 \]
Time of flight in heavy-ion collisions

\[ \text{ToF} \equiv t - t_0 \]

\[ \Delta t \equiv t_{RF} - t_0 \]

constant

\[ E_{el} = \frac{1}{2} m_{el} \left( \frac{d}{t_{el} - t_0} \right)^2 \]
Time of flight in heavy-ion collisions

\[ \text{ToF} \equiv t - t_0 \]

\[ \Delta t \equiv t_{\text{RF}} - t_0 \]

constant

\[ t_0 = t_{\text{el}} - d_{\text{el}} \sqrt{\frac{m_{\text{el}}}{2E_{\text{el}}}} \]
**Time of flight in heavy-ion collisions**

\[ \text{ToF} \equiv t - t_0 \]

\[ \Delta t \equiv t_{RF} - t_0 \]

\[ \Delta t = t_{RF} - t_{el} + d_{el} \sqrt{\frac{m_{el}}{2E_{el}}} \]
Time of flight in heavy-ion collisions

\[ ToF \equiv t - t_0 \]

\[ \Delta t \equiv t_{RF} - t_0 \]

\( \text{constant} \)

\[ ToF = t - t_{RF} + \Delta t \]
Time of flight in heavy-ion collisions

\[ \text{ToF} \equiv t - t_0 \]

Proposed solution without a start detector or RF
Time of flight in heavy-ion collisions

\[ ToF \equiv t - t_0 \]

event by event correction

\[ E_{ref} = \frac{1}{2} m_{ref} v_{ref}^2 \]
Time of flight in heavy-ion collisions

$$ToF \equiv t - t_0$$

event by event correction

$$E_{ref} = \frac{1}{2} m_{ref} \left( \frac{d}{t_{ref} - t_0} \right)^2$$
Time of flight in heavy-ion collisions

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event by event correction

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\[ToF \equiv t - t_0\]

event by event correction

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Expected identification capabilities

\(^{12}\text{C} \quad \text{–} \quad ^{13}\text{C} \quad \text{discrimination}\)

FAZIA flight base: 1 m
Expected identification capabilities

$^{12}\text{C} - ^{13}\text{C}$ discrimination

FAZIA flight base: 1 m

PSD mass discrimination: 60 MeV

$\sigma_{ToF} = 0.19$ ns
Expected identification capabilities

$^{12}\text{C} - ^{13}\text{C}$ discrimination

FAZIA flight base: 1 m

PSD identification threshold: 25 MeV

PSD mass discrimination: 60 MeV

$\sigma_{ToF} = 0.64$ ns

$\sigma_{ToF} = 0.19$ ns
ISOFAZIA experiment at LNS

$^{80}$Kr beam @ 35 MeV/u

- Block 0
- Block 1
- Block 2
- Block 3

17.2°
2.4°

80 cm

First physics oriented experiment with FAZIA

Fully calibrated with mass ID up to $Z \sim 24$

In many events we have at least a fully identified particle which permits to recover $t_0$
ISOFAZIA experiment at LNS

- First physics oriented experiment with FAZIA

**target**

- **80Kr beam @ 35 MeV/u**
- **80 cm**
- **17.2°**
- **2.4°**

**blocks:**
- block 0
- block 1
- block 2
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**Remarks:**

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ISOFAZIA experiment at LNS

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ISOFAZIA experiment at LNS

courtesy of A. Buccola, Università di Firenze
ISOFAZIA experiment at LNS

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Identification thresholds

(with $FoM > 0.7$)$^a$

- $p$ 2 MeV
- $d$ 3 MeV
- $t$ 4 MeV

$^a$S. Carboni et al, NIM A 664 (251), 2012
ISOFAZIA experiment at LNS

p,d,t stopped in the first Si layer

- PSD doesn’t resolve $Z < 3$ isotopes
- $E - ToF$ allows to identify in mass $Z = 1$ down to 2 MeV
ISOFAZIA experiment at LNS

**p,d,t stopped in the first Si layer**

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**ToF accuracy limitations**

- even with a common clock the ADCs are not synchronous (delays introduced by fan-in/fan-out and ADC aperture jitter)
- a synchronization procedure is mandatory
ISOFAZIA experiment at LNS

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Illuminate all Si1 detectors with the same fast infrared pulse
Timing accuracy test in Florence

100 ms

100 ns

PULSER

infrared LED

$t_0$

$t_{\text{ref}}$

$t$

$t$

$t_{\text{ref}}$

$t_0$

FAZIA block

ToF technique

ToF ID

Synchronization

Conclusions

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000000

0000

00
Timing accuracy test in Florence

Expected:
\[(t - t_{ref})_0 = \delta t\]
Timing accuracy test in Florence

Expected:

\[(t - t_{\text{ref}})_{\text{del}} = \delta t + t_{\text{del}}\]
Timing accuracy test in Florence

![Graph showing timing accuracy with and without delay. The x-axis represents Event, and the y-axis represents $t - t_{ref}$ in nanoseconds (ns). The graph shows data points with and without delay, indicating the difference in timing accuracy.]
Timing accuracy test in Florence

(-1412 ± 5) ps

(-1214 ± 7) ps
Timing accuracy test in Florence

![Graph showing the timing accuracy test with and without delay. The x-axis represents the event number, ranging from 0 to 1600, while the y-axis represents the difference in time (t-t_ref) in nanoseconds, ranging from -1.8 to -0.8.]

- **With delay**:
  - The mean difference is approximately -1.2 ns.
  - The standard deviation is ±8 ps.

- **Without delay**:
  - The mean difference is approximately -1.4 ns.

These results indicate a significant difference in timing accuracy between the two conditions, with the delay condition showing a higher deviation from the reference time.
Timing accuracy test in Florence

Expected \( (t - t_{ref})_{del} - (t - t_{ref})_0 = t_{del} \approx 207 \text{ ps} \)

GOOD AGREEMENT

with delay \((198 \pm 8) \text{ ps}\)

without delay

Event

0 200 400 600 800 1000 1200 1400 1600

[Graph showing time difference distribution with and without delay]
Timing test

The same timing test performed on the test bench was repeated during the mounting of FAZIAPRE experiment at LNS giving a measured delay of $(203 \pm 13)$ ps (added delay was nominally 207 ps)
FAZIAPRE experiment at LNS

**Timing test**

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**Permanent infrared LED**

*During the FAZIAPRE experiment, the infrared LED was mounted inside the scattering chamber and was kept on during all the shift (at a 0.1 Hz rate) to trace channel delays*
FAZIAPRE experiment at LNS

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Calibration and identification still in progress...
Summary and conclusions

- Possibility to perform precise time measurements with FAZIA thanks to the ADC clock distribution
  - common clock doesn’t guarantee a perfect synchronization
  - observed time differences between channels up to 1–2 ns
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  - trace possible variations of the channel delay during the run
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- $E - tof$ correlation may significantly reduce the energy threshold for mass discrimination in FAZIA
  - even without any correction is possible to discriminate $Z = 1$ isotopes down to $2$ MeV
  - expected precision on time measurements: $\sim 500$ ps after delay corrections
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  - even without any correction is possible to discriminate $Z = 1$ isotopes down to 2 MeV
  - expected precision on time measurements: $\sim 500$ ps after delay corrections
- LED pulses tested during FAZIAPRE experiment
  - we need particle identification and calibration to produce $E - ToF$ correlations (work in progress...)

FAZIA block
ToF technique
ToF ID
Synchronization
Conclusions

Summary and conclusions
FAZIA collaboration

Thanks for your attention
Backup slides
Front-end electronics

FEE card

- Designed at IPN, Orsay
- 2 FAZIA telescopes per card
- Programmable logic performs on-line analysis of sampled data
  - VHDL code has been mainly written by P. Edelbruck
- FEE supplies also the bias voltages of Si detectors

\(^a\)F. Salomon et al, J. Instrum. 11 (C01064), 2016
Front-end electronics

Detector connectors

- Detectors are connected using kapton cables
- Silicon side kapton connection:
  - ultra-sonic $\mu$bonding
  - conductive glue
Front-end electronics

Si 1

Si 2

CsI(Tl) + PD
Front-end electronics

Analog chain (for each telescope)

- 3 fixed gain charge pre-amplifiers
- High range signals are attenuated by a factor 4
- Low range signals are amplified by a factor 4
- Current signal by analog differentiation of charge signals
Front-end electronics

*analog chains*

Si 1 [P.A.] 8 V, 4 GeV range

Si 2 [P.A.] 8 V, 4 GeV range

CsI(Tl) + PD [P.A.] 8 V, 300 MeV Si-equivalent range
Front-end electronics

analog chains

Si 1

8 V, 4 GeV

Si 2

8 V, 300 MeV

CsI(Tl) + PD

8 V, 4 GeV

8 V, 300 MeV
Front-end electronics

analog chains  ADCs

Si 1

P.A.

x 1/4

14 bit

100 MS/s

2 V

Si 2

P.A.

x 1/4

14 bit

250 MS/s

1.5 V

d/dt

14 bit

250 MS/s

1.5 V

8 V, 4 GeV

4 GeV full-scale

250 MeV full-scale

8 V, 300 MeV

300 MeV Si-equivalent full-scale
Front-end electronics

<table>
<thead>
<tr>
<th>6 sampling ADCs per telescope</th>
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<tbody>
<tr>
<td><strong>Si 1</strong></td>
</tr>
<tr>
<td>14 bit, 100 MHz</td>
</tr>
<tr>
<td>14 bit, 250 MHz</td>
</tr>
<tr>
<td>14 bit, 250 MHz</td>
</tr>
<tr>
<td><strong>Si 2</strong></td>
</tr>
<tr>
<td>14 bit, 100 MHz</td>
</tr>
<tr>
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</tr>
<tr>
<td><strong>CsI(Tl)</strong></td>
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<tr>
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Front-end electronics

Xilinx Virtex-5 FPGAs

- Each FPGA processes signals from one telescope
  - signals stored in **FIFO memories** (up to 8192 samples)
- On-board **real-time** trapezoidal shaping
  - fast shaped signals to leading-edge discriminators
  - maximum of slow shaped signals to acquisition
  - no pole-zero correction
Front-end electronics

**analog chains**

- Si 1
  - P.A. x 1/4
  - 14 bit 100 MS/s 2 V
  - 14 bit 250 MS/s 1.5 V
  - d/dt
- Si 2
  - P.A. x 1/4
  - 14 bit 100 MS/s 2 V
  - 14 bit 250 MS/s 1.5 V
  - d/dt

**ADCs**

- 8 V, 4 GeV
- 8 V, 300 MeV
- CsI(Tl) + PD

**ADCs**

- 14 bit 100 MS/s 2 V
- 14 bit 250 MS/s 1.5 V
- d/dt

**FPGA**

- Local trigger box
- time stamp
- FIFO
- To DAQ

**Validation**

- trigger request
- validation
- system clock
Front-end electronics

HV generation

- DC/DC converters produce the Si detectors **bias voltages**:
  - 0–300 V for Si1 (140 V depletion voltage)
  - 0–400 V for Si2 (290 V depletion voltage)
- CsI(Tl) photodiode bias voltage from the Power Supply card:
  - **optocoupler switch** on FEE card.
Front-end electronics

Back plane connector
- Power supply and CsI(Tl) HV from power supply card
- Equalized 25 MHz **clock distribution** between FEE cards
- Star connection between FEE cards and block card:
  - FEE to BC: 2x400 Mb/s links (⇒ 800 Mb/s)
  - BC to FEE: 1x400 Mb/s link
- Slow control communication
Block Card

- Designed at INFN – Napoli
- Takes data from FEE cards via the back plane and builds up part of the event record
- Features a 3 Gb/s optical link to regional board
  - 16-bit 8b/10b GTX transceiver
- Fixed latency transmission\textsuperscript{a}:
  - all ADC clocks have the same phase (\(\sim 20\) ps skew)
  - digitized signals don’t have the 1 clock indetermination typical of asynchronous systems
- 25 MHz from fibre-recovered clock
  - PLL for \textit{jitter cleaning}

\textsuperscript{a}R. Giordano \textit{et al}, IEEE Trans. on Nucl. Science 58 (194), 2011
Fixed Latency test results

C1: Recovered clock

C2: Reference clock

(C1-C2) Skew histogram

(C1-C2) Skew trend

sdev 18 ps

6,666 µs

Histogram parameters

courtesy of A. Boiano, INFN – Napoli
Half bridge and power supply

**Half Bridge**
- Designed at INFN – Napoli
- **High power** voltage conversion from 48 V DC input:
  - 22 V (14 A) DC
  - 5.5 V (70 A) DC

**Power Supply**
- Designed at INFN – Napoli
- Converts 22 V to 13 V, −9 V, ±5 V and CsI(Tl) HV
- PIC monitors produced voltages together with 5.5 V from HB
  - power on/power off
  - under/over voltage protection
  - voltage/current limits
Regional Board

- Designed at Jagiellonian University, Krakow
- Features a Xilinx Virtex-5 FPGA
  - VHDL code has been written mainly at INFN – Napoli
- **36x** 3 Gb/s bi-directional optical links
  - to/from FAZIA blocks
  - fixed latency protocol
- **2x** 1 Gb/s optical ethernet links (1000Base-SX)
  - now only 1 is used ⇒ room for transmission speed increase
  - **UDP protocol** for low-latency transfer
- Possibility to connect GANIL **CENTRUM** module
Regional board
Regional board

Regional Board tasks

- **Slow control** management of all the electronics
  - data transmission and slow control use the same optical fibre

- **Trigger board:**
  - multiple majority logic for trigger validation
  - trigger scaling by a settable factor
  - master/slave trigger operation (for coupling)

- **Event building** from data coming from all the blocks
  - it may add the CENTRUM timestamp to each event

- **Transmission** of acquired data to servers
  - maximum speed achieved: $\sim 80$ MB/s ($\sim 640$ Mb/s)
Clock tree

125 MHz oscillator

150 MHz oscillator

Digital Clock Manager

Packet builder

Ethernet GTX

Block TX GTX

Block RX GTX

Block RX

Regional Board

FPGA

Acquisition and slow control
to blocks

from blocks
Clock tree

Regional Board

Block Card

Acquisition and slow control

to blocks

from blocks

25 MHz VCXO

150 MHz VCXO

25 MHz

150 MHz

PLL

PLL

RX / TX GTX

Packet catcher

25 MHz

150 MHz

oscillator

oscillator

Digital Clock Manager

Packet builder

Block TX GTX

Block RX GTX

Block RX GTX

125 MHz

150 MHz
Clock tree

FPGA

125 MHz oscillator
150 MHz oscillator

Digital Clock Manager

Packet builder

Ethernet GTX

Block TX GTX

Block RX GTX

Block RX

Packet catcher

to and from regional board

Regional Board

FPGA

25 MHz VCXO
150 MHz VCXO

PLL

PLL

RX / TX GTX

Packet catcher

to and from regional board

Block Card

Acquisition and slow control
to blocks
from blocks
Time measurement methods

Leading Edge Discriminator (LED)

\[ \sigma_{LED} = \frac{t_{rise}}{\text{SNR}} \]

Intersection between a fixed threshold \( T \) and the signal \( s(t) \)
Time measurement methods

Leading Edge Discriminator (LED)

\[ \sigma_{LED} = \frac{t_{rise}}{\text{SNR}} \]

Intersection between a fixed threshold \( T \) and the signal \( s(t) \)

Subject to amplitude and rise time walk
Time measurement methods

Constant-Fraction Discriminator (CFD)

\[ \sigma_{CFD} = \frac{t_{rise}}{\text{SNR}} \sqrt{1 + f^2} \]

Zero crossing of the bipolar signal
\[ b(t) = f \cdot s(t) - s(t - t_D) \]

\[ t_D \geq (1 - f)t_{rise} \]

Subject to rise time walk
Time measurement methods

Amplitude and Rise time Compensated CFD (ARC-CFD)

\[ \sigma_{ARC} = \frac{t_{rise}}{SNR} \frac{\sqrt{1 + f^2}}{1 - f} \]

Zero crossing of the bipolar signal \( b(t) = f \cdot s(t) - s(t - t_D) \)

\[ t_D < (1 - f)t_{rise} \]
FAZIA collaboration

Publications

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