Plastic Anti-Neutrino Detector Array (PANDA)

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Reactor monitoring

Inspection by IAEA

- Nonproliferation of nuclear technology
- Current inspection tools are "**intrusive**", such as
  - -- neutron monitoring beside reactor cores
  - -- fuel monitoring before and after reactor operation

-> Burden for both operator and inspector

International Atomic Energy Agency

IAEA proposed a "**non-intrusive**" inspection tool.

Final Report: Focused Workshop on Antineutrino Detection Safeguards Applications (2008)

Reactor monitoring using an antineutrino detector

- **High penetration** -> can be detected outside a reactor building
- **No alternative source** -> cannot hide reactor operation

-> Suitable for inspection !

Reactor antineutrino

Nuclear fission of ^{235}U -> **neutron-rich nuclei**

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow \mathrm{X}_1 + \mathrm{X}_2 + \cdots + \mathrm{n} + \mathrm{n} + \cdots$$

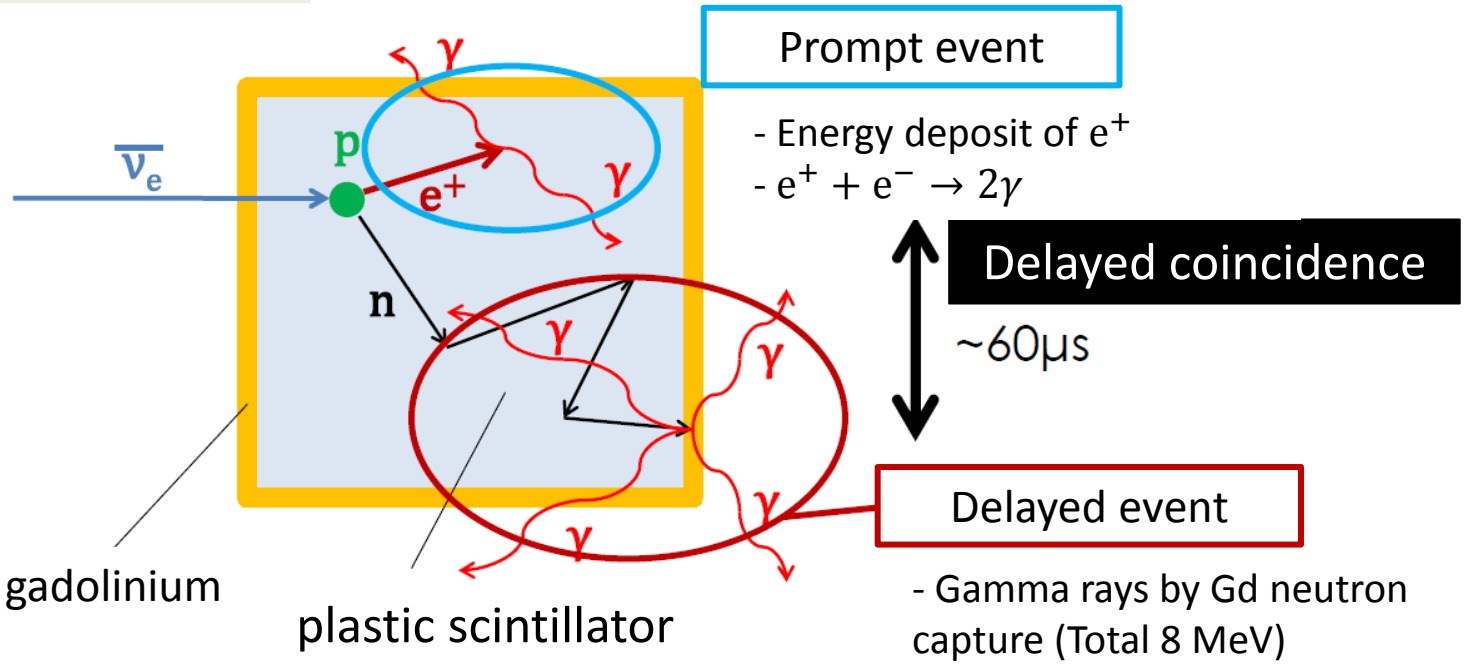
β decay of neutron-rich nuclei -> **antineutrino**

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{X}' + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$

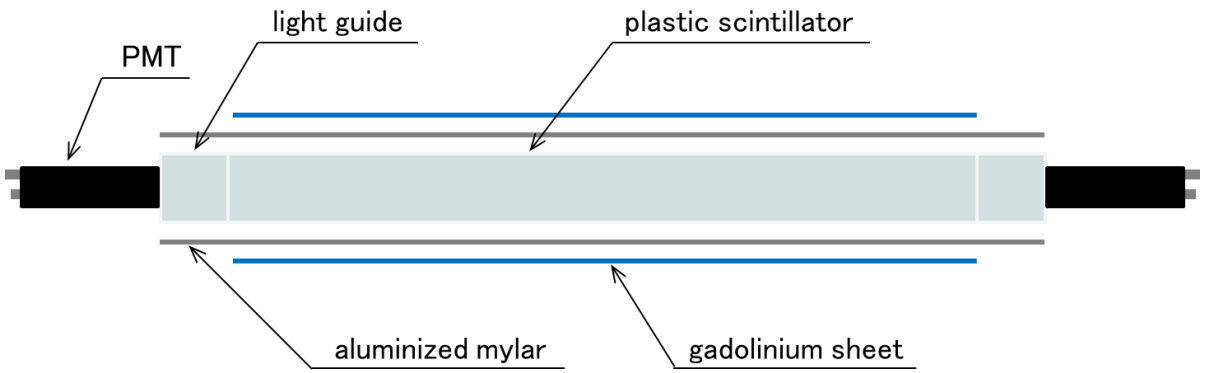
$$^{A}_{Z+1}\mathrm{X}' \rightarrow {}^{A}_{Z+2}\mathrm{X}'' + \cdots$$

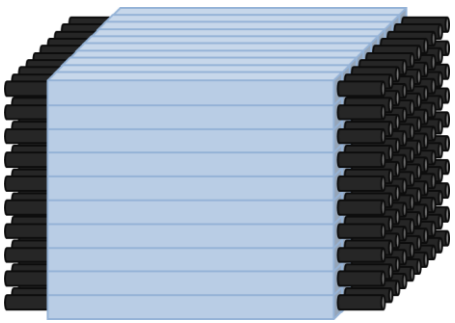
- 6 antineutrinos
- 200MeV
  per fission

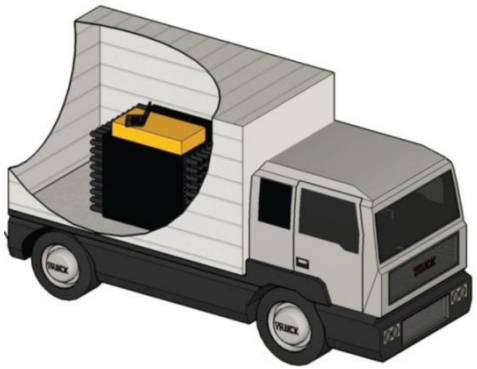
- - 3GW$_{th}$ reactor emits
  6×10^{20} neutrinos/s

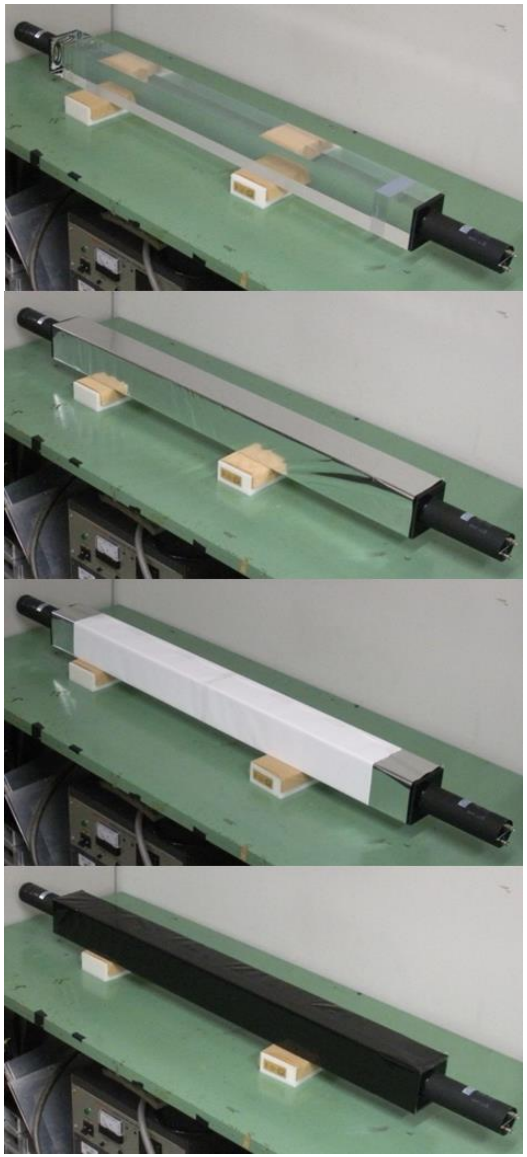


PANDA (Plastic Anti-Neutrino Detector Array)



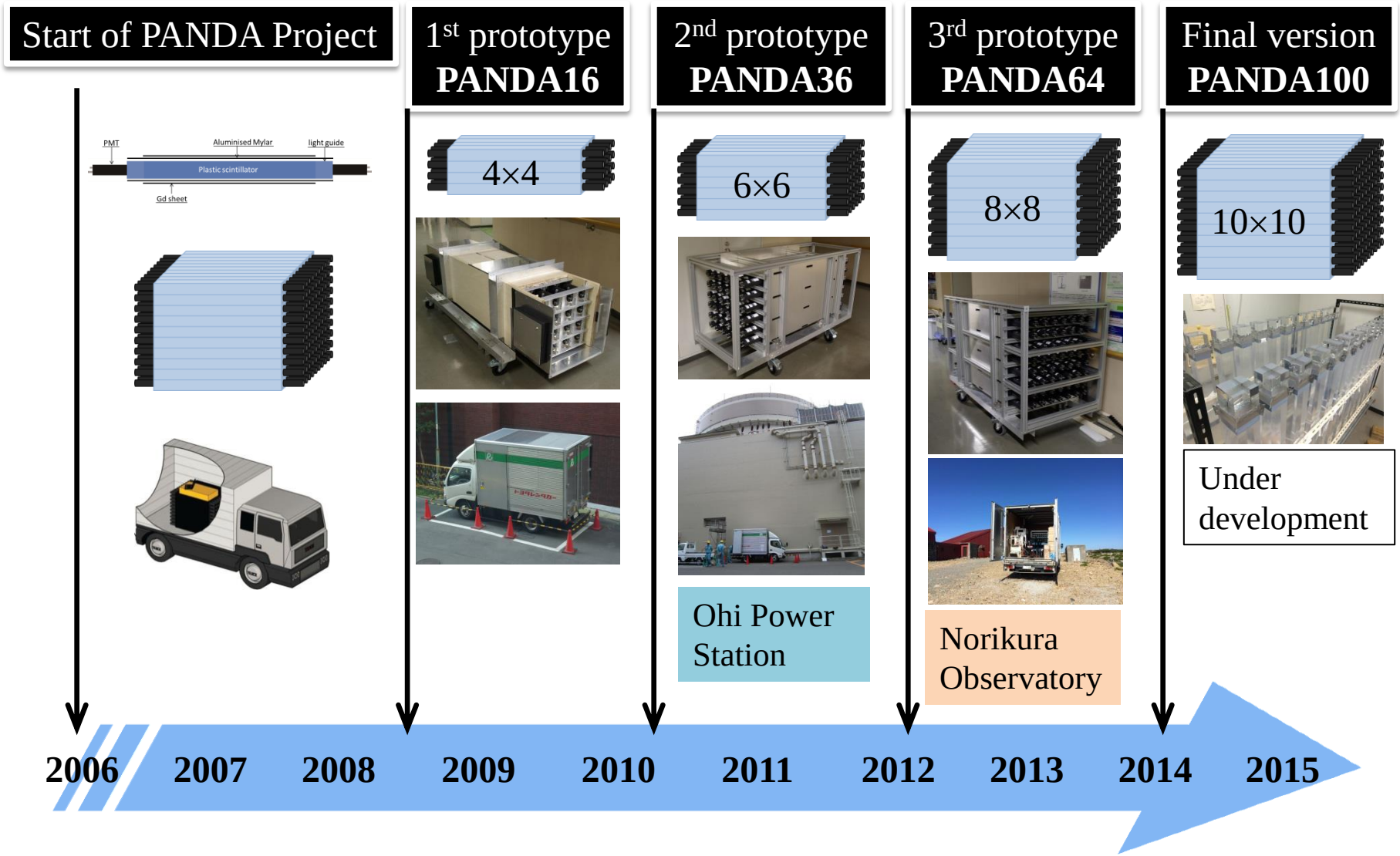




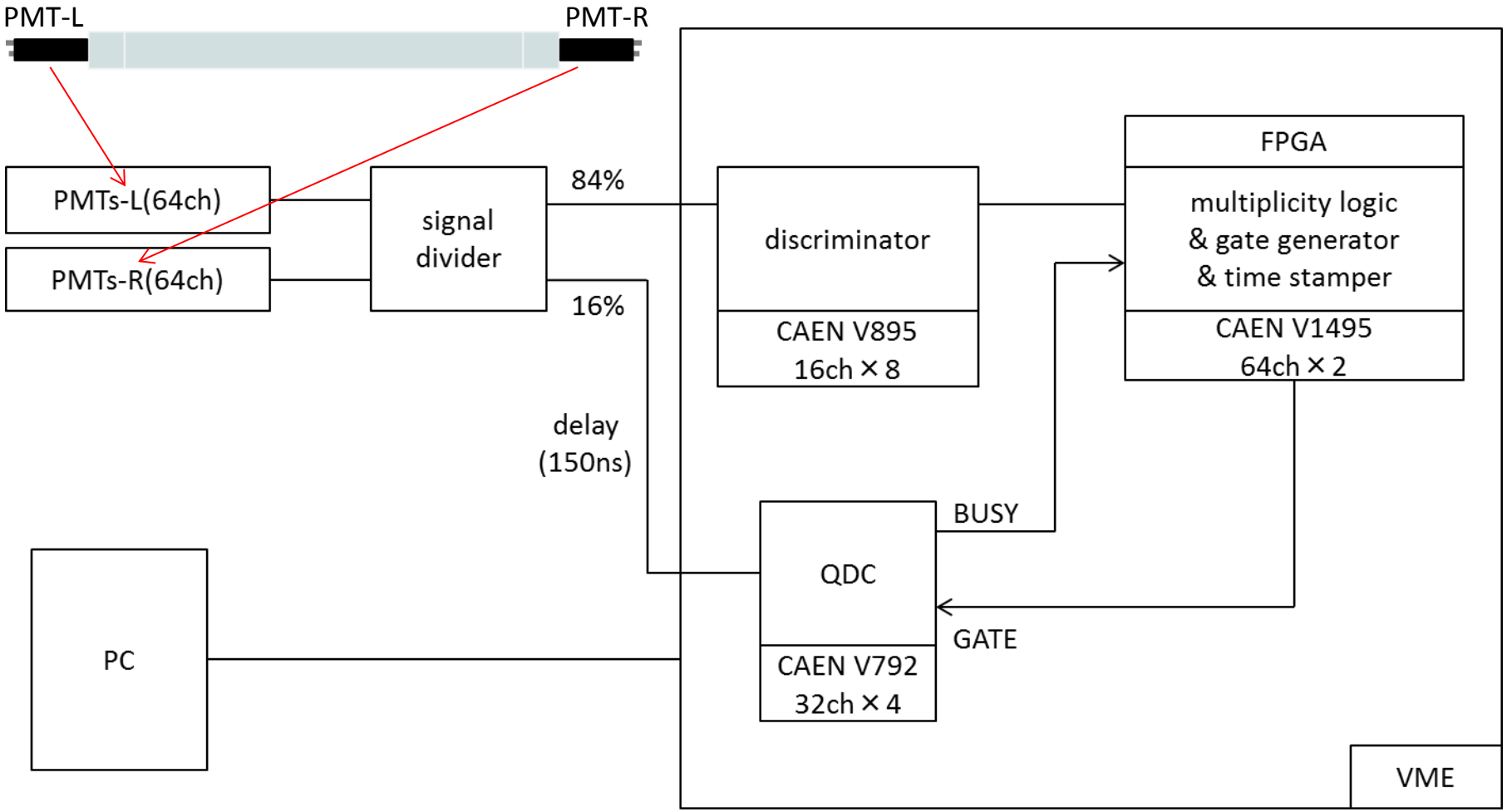


- Non-flammable plastic scintillator
- 10 × 10 segmented structure
- Measurement loaded on a van or a container

Time line


Start of PANDA Project
1st prototype
PANDA16
2nd prototype
PANDA36
3rd prototype
PANDA64
Final version
PANDA100
PMT
Aluminised Mylar
light guide
Plastic scintillator
Gd sheet
4×4
6×6
8×8
10×10
Ohi Power Station
Norikura Observatory
Under development
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015

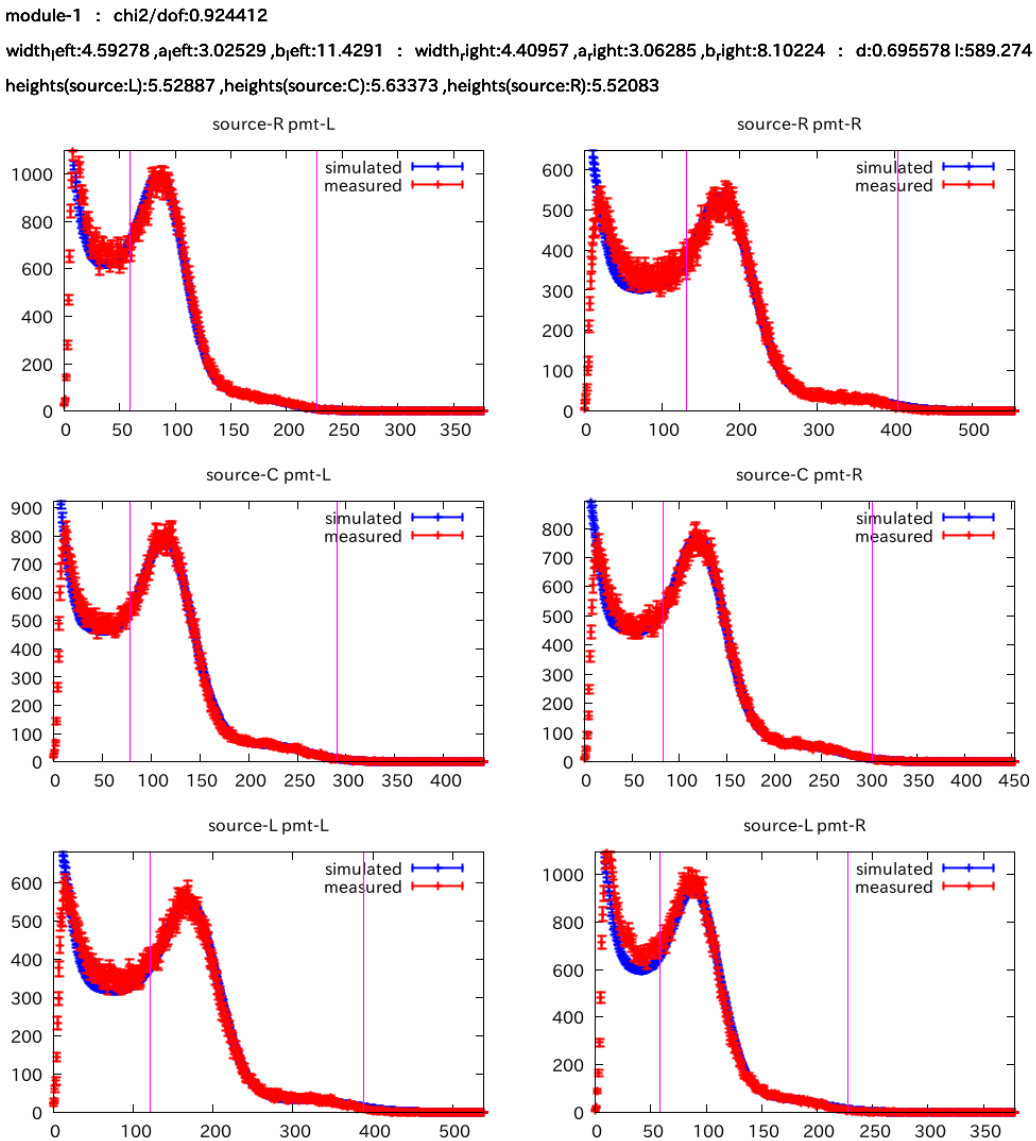
Data acquisition system (PANDA64)



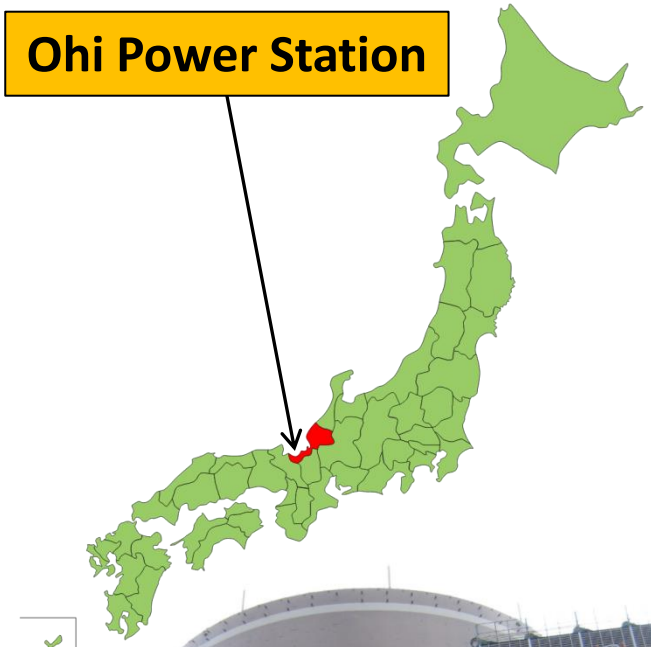
Calibration

- ^{60}Co at 3 positions next to every module

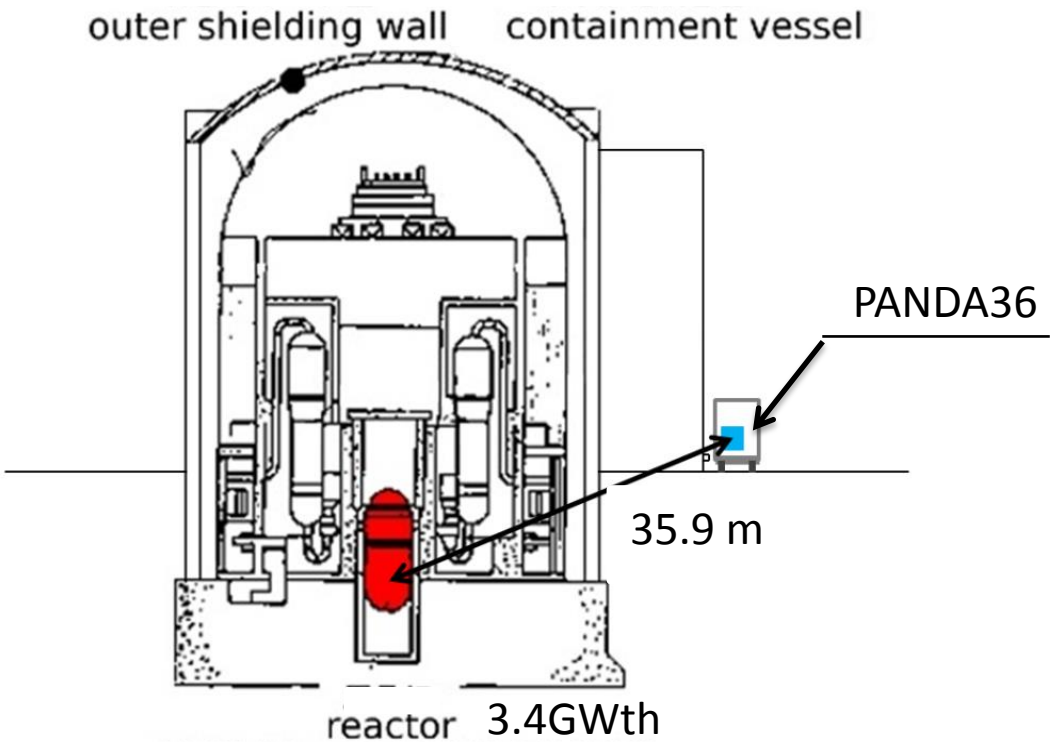
-> Reconstruction of
  - energy deposit
  - position



PANDA36 at Ohi



- Unit 2 : 3.42 GWth (PWR)
- Outside the reactor building (aboveground)
- 35.9m from the core
- 2011 November – 2012 January
- Reactor on (30 days) ; off (34 days)

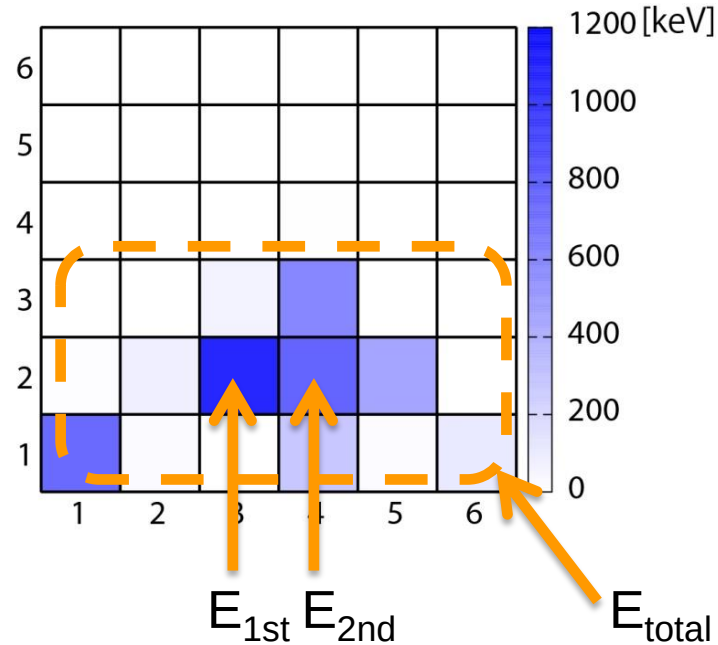


Background events

Accidental background

-- Environmental gamma-ray
-- Thermal neutrons

-> Can be estimated using a shifted time window



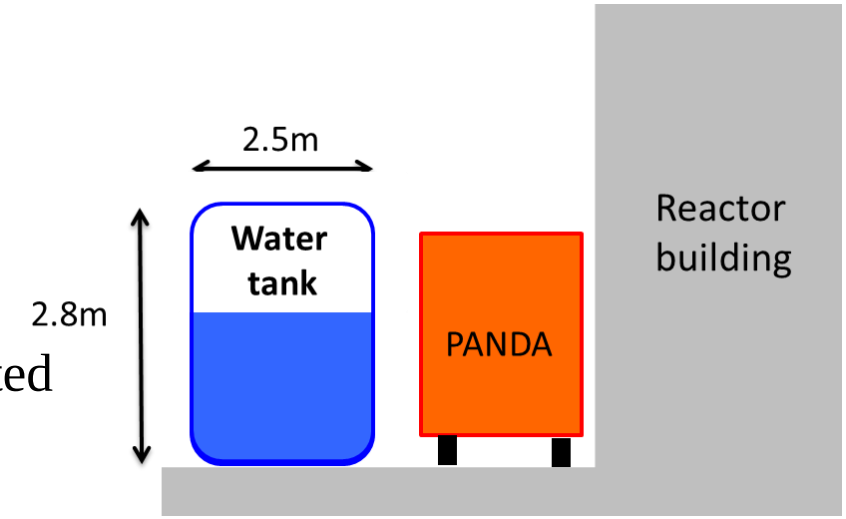
Correlated background

-- Fast neutrons
(prompt-like event : proton recoil)

-- Double neutron capture
(caused by muon spallation)

-- Long-lived cosmic ray activation product
(^{9}Li, ^{8}He)

-> Difficult to eliminate the effect of correlated background fluctuation
(e.g. water tanks installed around PANDA)

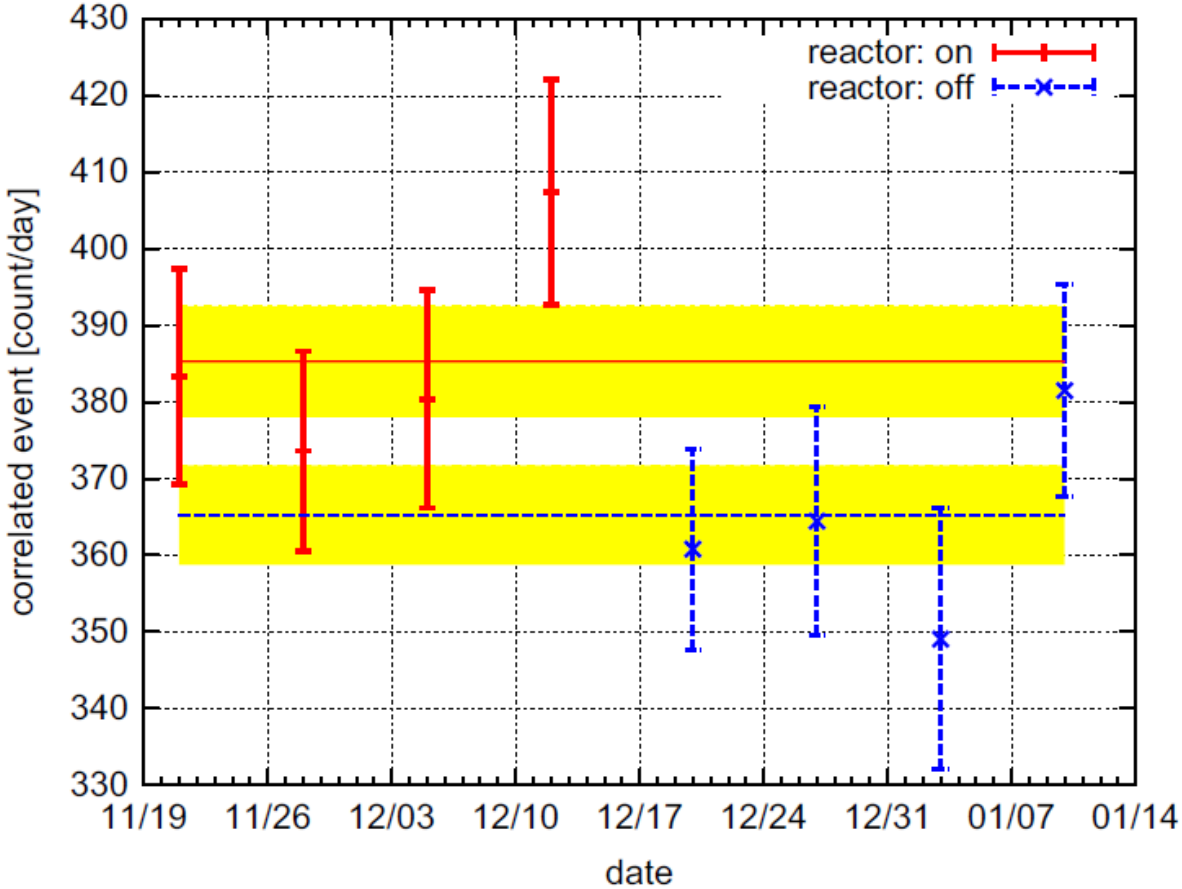


Selection cuts

	for antineutrino-like events	for fast neutron events
	Selection 1	Selection 2
Software trigger	At least two modules in inner 16 modules deposit energy of 150 keV or more.	At least two modules in inner 16 modules deposit energy of 150 keV or more.
Prompt	$3\ \text{MeV} \leq E_{\text{total}} \leq 6\ \text{MeV}$	$3\ \text{MeV} \leq E_{\text{total}} \leq 6\ \text{MeV}$
	$E_{2\text{nd}} \leq 520\ \text{keV}$	$E_{2\text{nd}} \geq 700\ \text{keV}$
Delayed	$3\ \text{MeV} \leq E_{\text{total}} \leq 8\ \text{MeV}$	$3\ \text{MeV} \leq E_{\text{total}} \leq 8\ \text{MeV}$
	$\frac{E_{3\text{rd}}}{E_{\text{total}}} \geq \frac{E_{1\text{st}}/E_{\text{total}} - 0.5}{5}$	$\frac{E_{3\text{rd}}}{E_{\text{total}}} \geq \frac{E_{1\text{st}}/E_{\text{total}} - 0.5}{5}$
Time window	$8\ \mu\text{s} \leq t \leq 150\ \mu\text{s}$	$8\ \mu\text{s} \leq t \leq 50\ \mu\text{s}$
Fiducial cut	The highest energy deposit is in inner 16 modules	The highest energy deposit is in inner 16 modules
Muon veto	There is no event with $E_{\text{total}} > 8\ \text{MeV}$ within 250 μs before the delayed event.	There is no event with $E_{\text{total}} > 8\ \text{MeV}$ within 250 μs before the delayed event.
Detection efficiency	**3.15±0.93 %**	**0.271±0.93 %**

Neutrino event rate

	Efficiency
Prompt	
Trigger	28.6%
Etotal cut	44.2%
E2nd cut	82.2%
Fiducial cut	93.5%
Prompt Total	9.7%
Delayed	
Trigger	48.8%
Etotal cut	79.1%
E3rd cut	91.9%
Delayed Total	35.5%
Time window	91.2%
TOTAL	3.15%



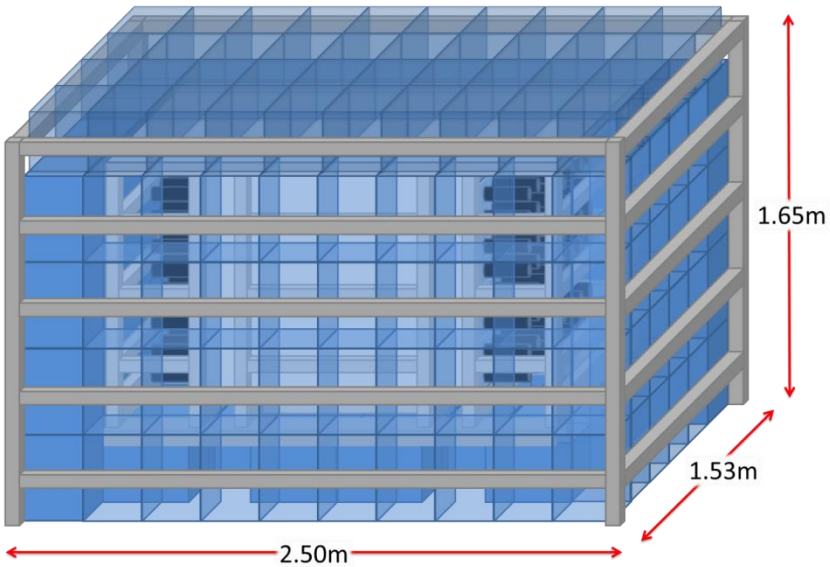
Observed: 21.8 ± 11.4 events/day

Expected: 17.3 ± 6.2 events/day

S. Oguri *et al*. Nuclear Instruments and Methods in Physics Research Section A 757 (2014) 33-39.

Shield construction (PANDA64)

24cm-thick 4π water shield (3.3 ton) around PANDA64 in 20ft container



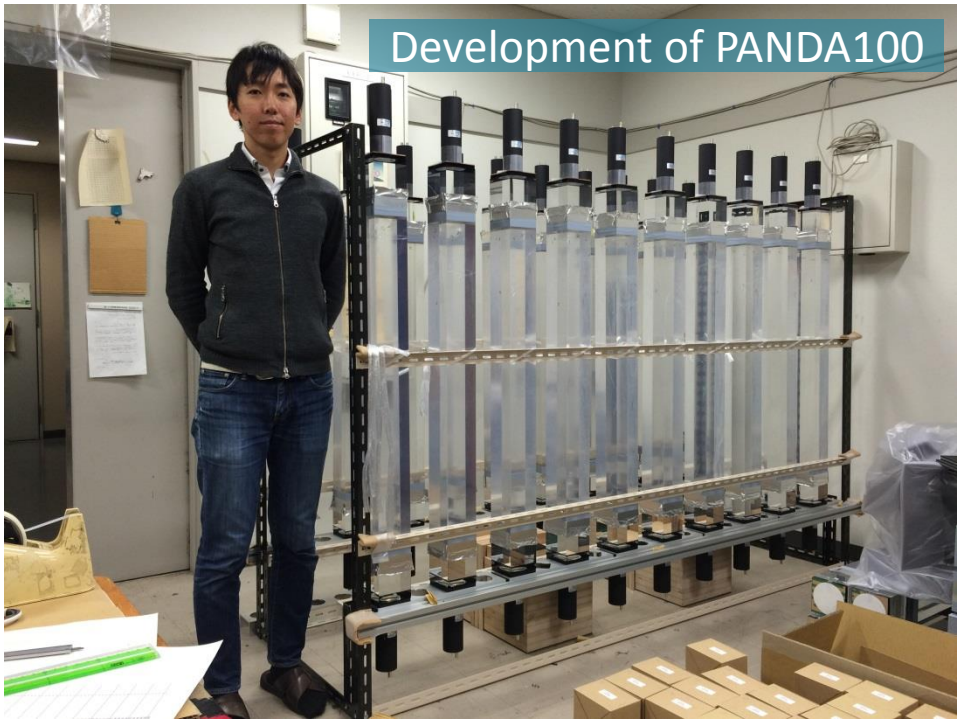
Trigger rate at Hongo	~9.3 kHz (1 of 64 modules > 150 keV)
Dead time by DAQ	~13% (latest version : < 10%)
Muon rate (E_{total}> 8 MeV)	~160 Hz (dead time by muon: 3.94%)
Correlated BG rate	~1700 events/day (−40% vs no shield)
Accidental BG rate	~500 events/day (−70% vs no shield)

Current status and future plan

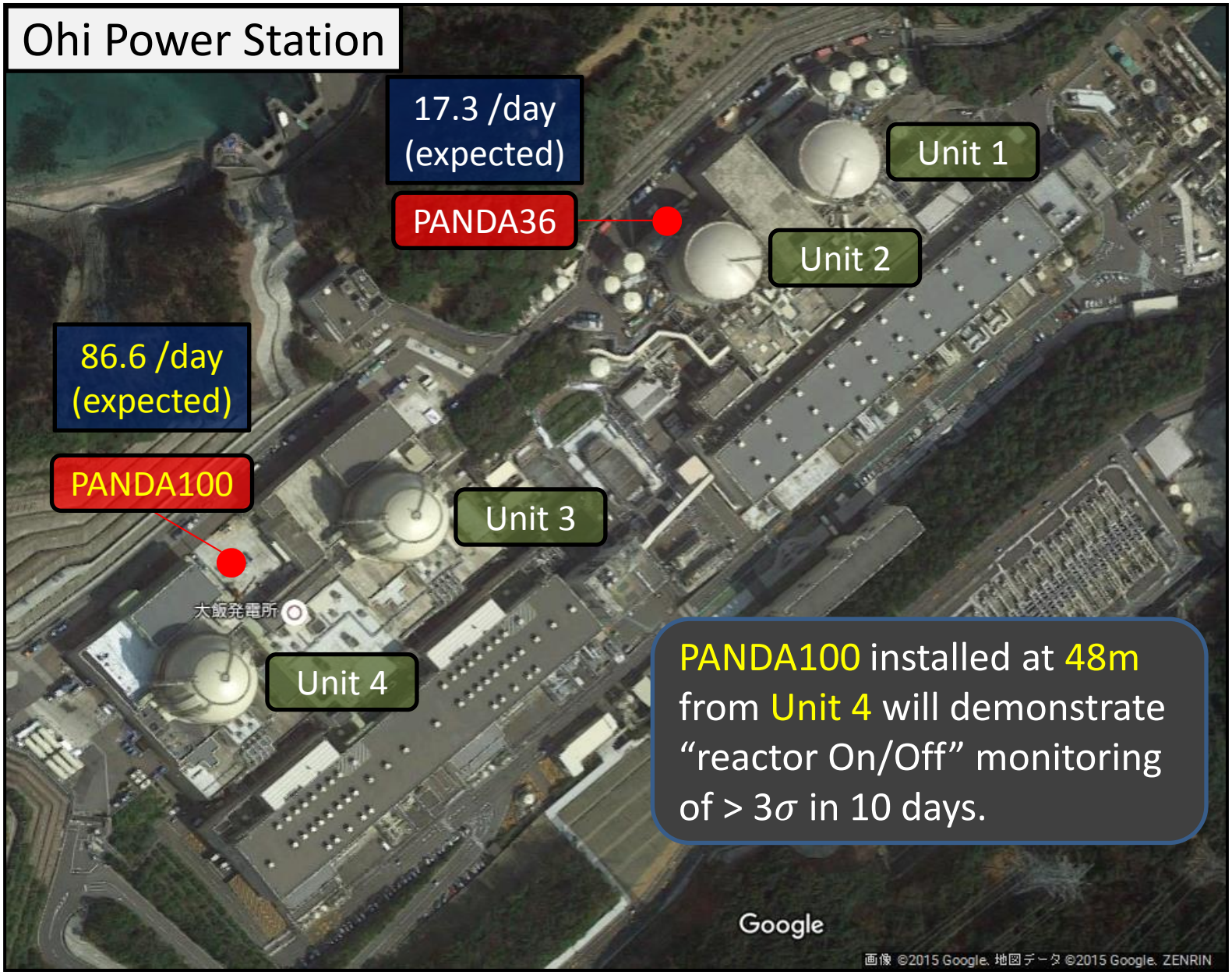
PANDA64: Development and test operation completed.
PANDA100: Under development. (will be developed by March 2016)

PANDA64 or PANDA100 are planned to be installed at Ohi Power Station in 2016.

PANDA prototype	IBD detection efficiency
PANDA36	3.2%
PANDA64	6.2%
PANDA100	9.2%

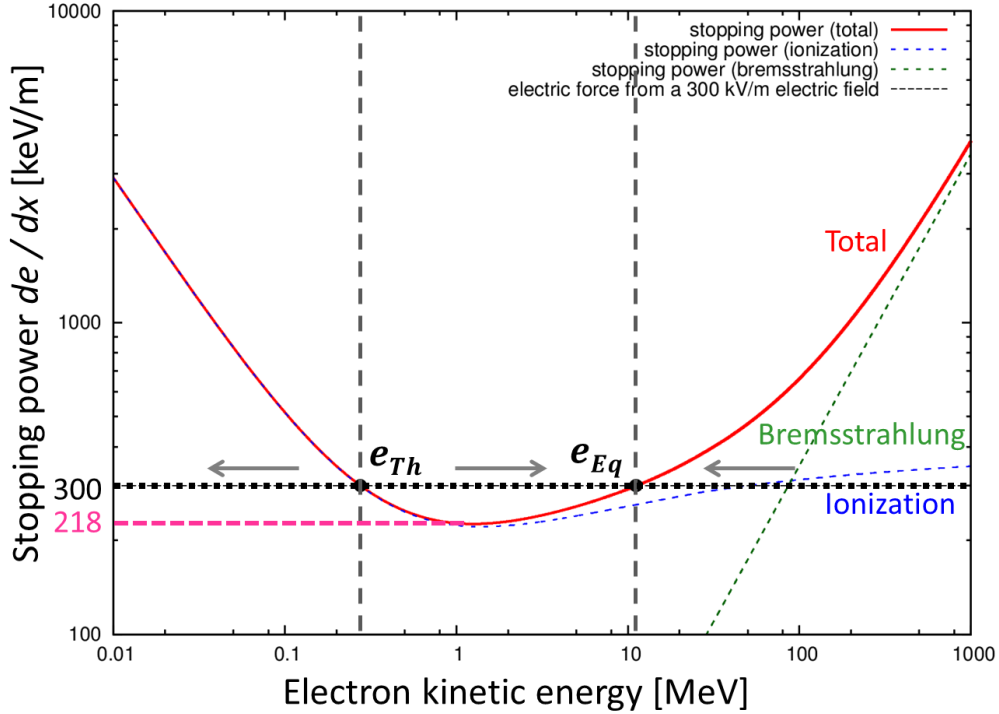


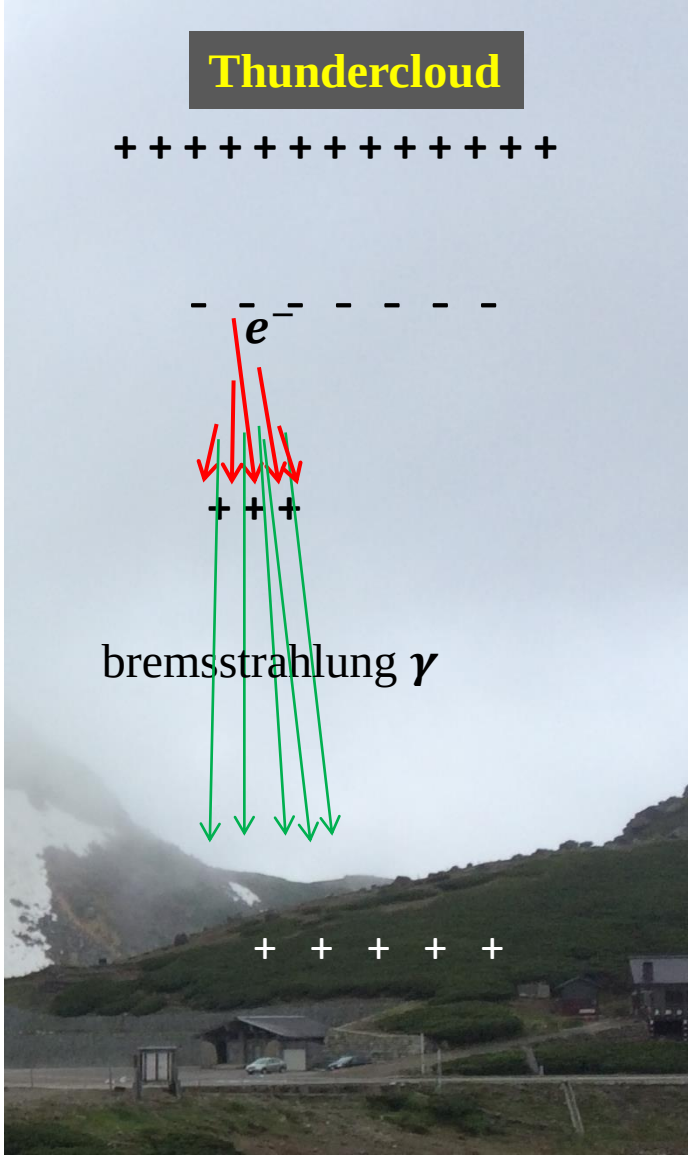
Ohi Power Station



PANDA100 installed at 48m from Unit 4 will demonstrate "reactor On/Off" monitoring of > 3σ in 10 days.

Electron acceleration in thunderclouds





RREA (Relativistic Runaway Electron Avalanche)

Seed e^- -> Acceleration (+ bremsstrahlung γ)
-> Knock-on e^- -> Acceleration (+ bremsstrahlung γ)
-> Knock-on e^- -> .....

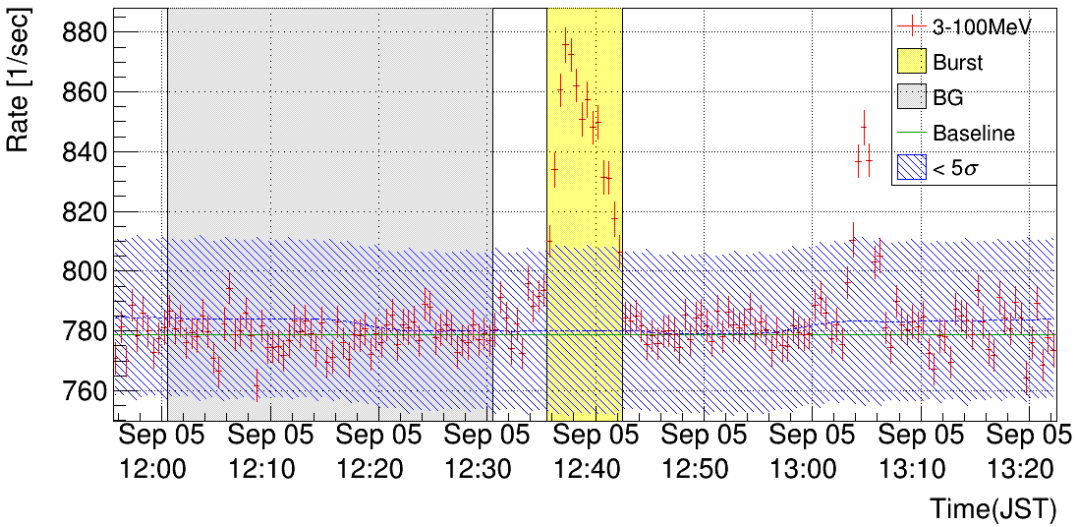
Observed at
mountaintops (summer) or <u>coastal areas (winter)</u>

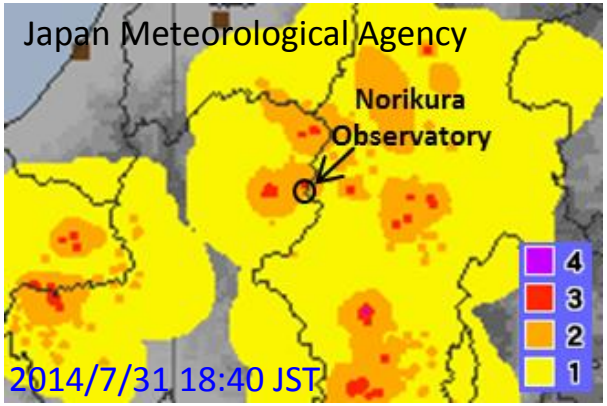
Observation 2011 & 2014

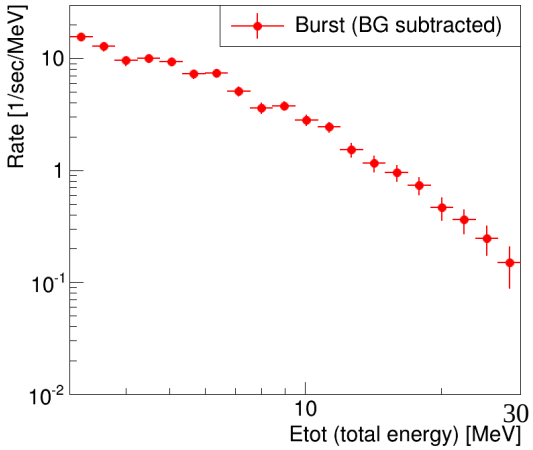
	Observation 2011	Observation 2014
Detector	PANDA36 (36 modules)	PANDA64 (64 modules)
Location	Ohi Power Station (coastal area, 10m)	Norikura Observatory (mountaintop, 2770m)
Season	2 months in winter	2 months in summer
Motivation	Reactor monitoring	Thundercloud bursts
Trigger	2 of inside 16 modules	1 of 64 modules

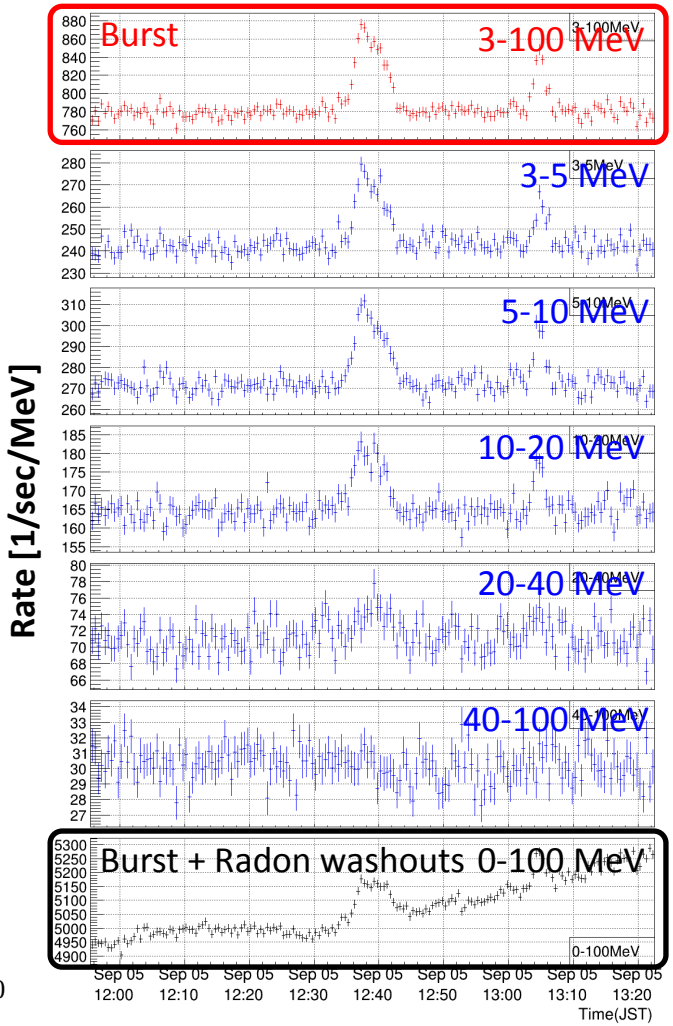



Thundercloud gamma-ray burst



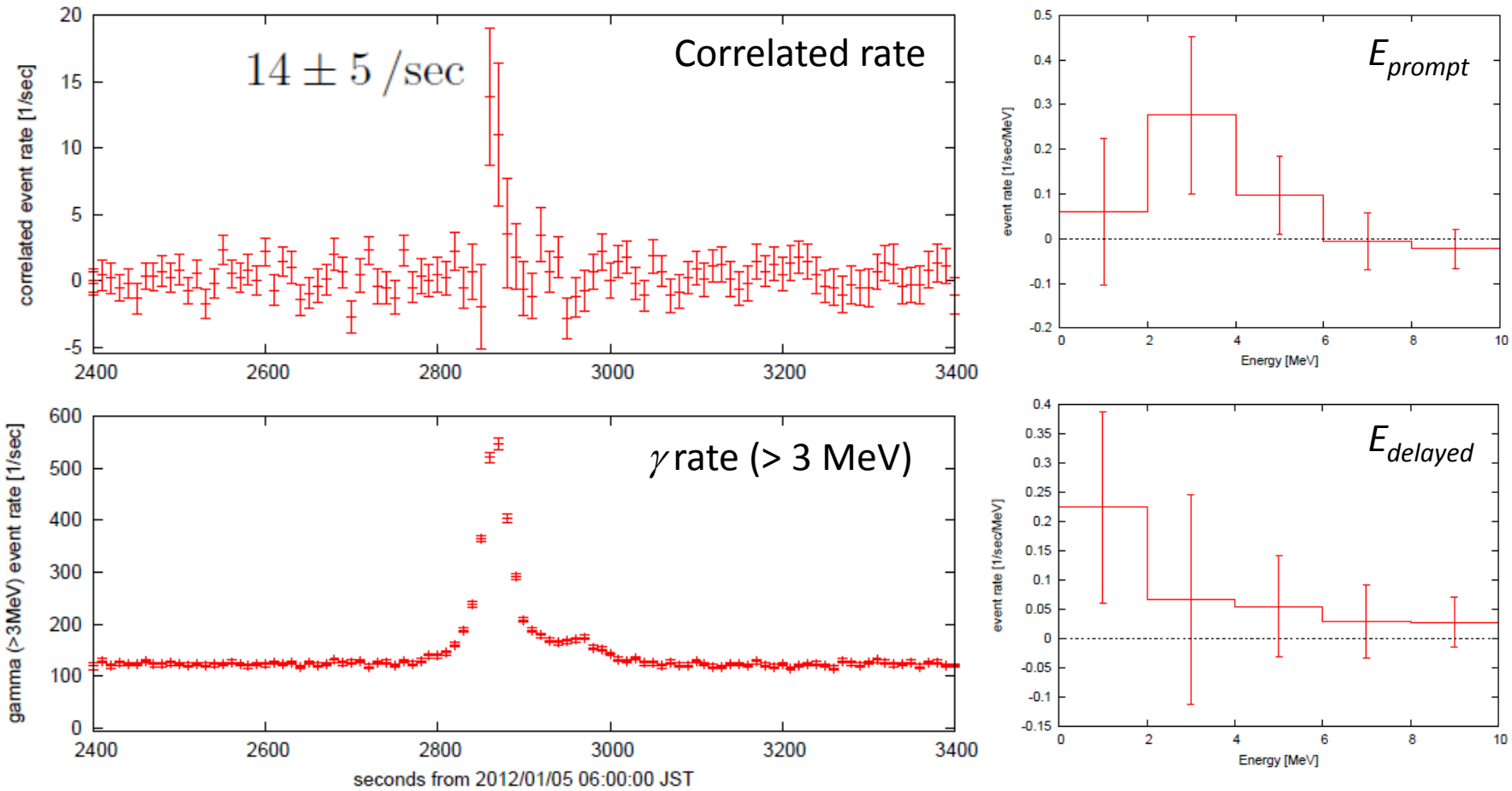






Ohi (10m) : 3 burst candidates detected in 62 days
Norikura (2770m) : 12 burst candidates detected in 54 days

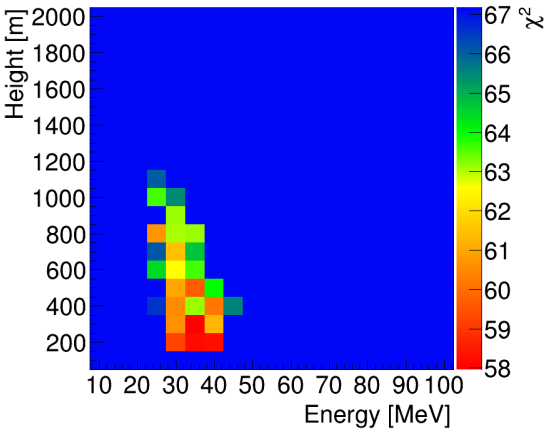
Neutron component in bursts (Ohi)

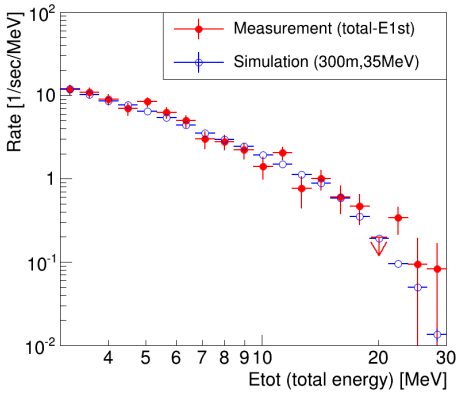


Neutron signal enhancement was detected by delayed coincidence method (Ohi/10m)

Estimation of electron source

Burst	Energy [MeV]	f_{source} [/sec/m^2]
20140708-1 (Norikura)	65	$(2.62 \pm 0.37) \times 10^2$
20140718-1 (Norikura)	50	$(1.66 \pm 0.22) \times 10^2$
20140719-1 (Norikura)	55	$(0.98 \pm 0.15) \times 10^2$
20140731-1 (Norikura)	35	$(6.78 \pm 0.34) \times 10^2$
20140822-1 (Norikura)	55	$(2.16 \pm 0.37) \times 10^2$
20140823-1 (Norikura)	40	$(1.28 \pm 0.04) \times 10^3$
20140826-1 (Norikura)	95	$(2.40 \pm 0.40) \times 10^2$
20140830-1 (Norikura)	80	$(0.95 \pm 0.12) \times 10^2$
20140830-2 (Norikura)	65	$(1.29 \pm 0.22) \times 10^2$
20140905-1 (Norikura)	50	$(1.45 \pm 0.14) \times 10^3$
20140905-2 (Norikura)	65	$(1.90 \pm 0.12) \times 10^2$
20140905-3 (Norikura)	40	$(4.48 \pm 0.38) \times 10^2$
20111225 (Ohi)	16	$(4.7 \pm 0.3) \times 10^5$
20120102 (Ohi)	16	$(1.4 \pm 0.0) \times 10^6$
20120105 (Ohi)	16	$(2.4 \pm 0.1) \times 10^5$





Runaway e$^-$ energy
Norikura > Ohi

Runaway e$^-$ flux
Norikura << Ohi

Summary

1. PANDA project

- Non-flammable plastic scintillator (10 × 10 segmented structure)
- Measurement loaded on a van or a container

2. Reactor monitoring by PANDA

- 6x6 prototype of PANDA (PANDA36) was Ohi Power Station Unit 2 (3.4GW_{th})
- Fully unmanned operation was demonstrated at ground surface
- Detected neutrino event rate was 21.8 ± 11.4 events/day
  (expected: 17.3 ± 6.2 events/day)
- Development of PANDA64 completed. Water shield reduces BG events.
- PANDA100 under development. IBD detection efficiency of 9.2% expected.
- Preparing for the measurement scheduled in 2016

3. Observation of thundercloud bursts

- 3 bursts detected by PANDA36 at Ohi Power Station (coast, 10 m)
- 12 bursts detected by PANDA64 at Norikura Observatory (mountain, 2770 m)
- Neutron signal enhancement detected using delayed coincidence