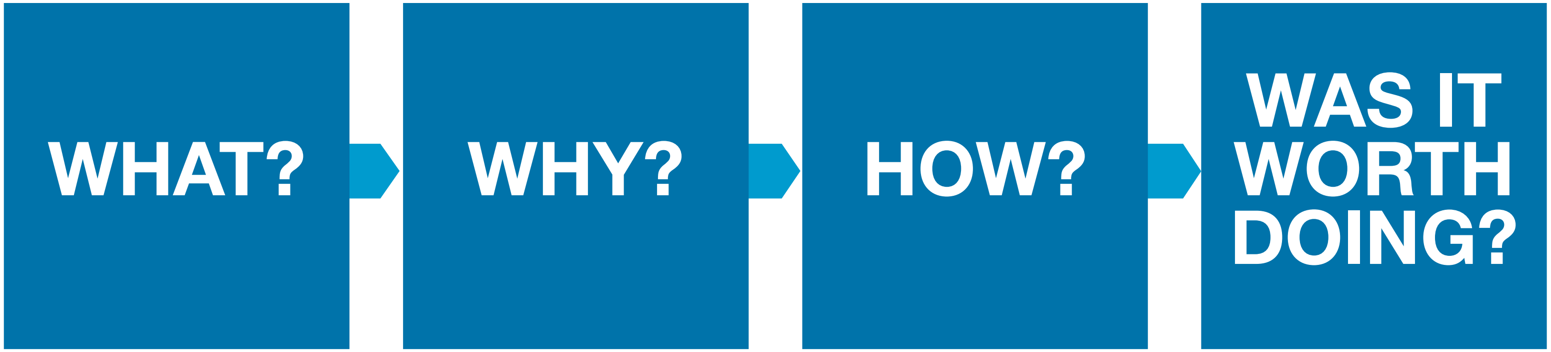
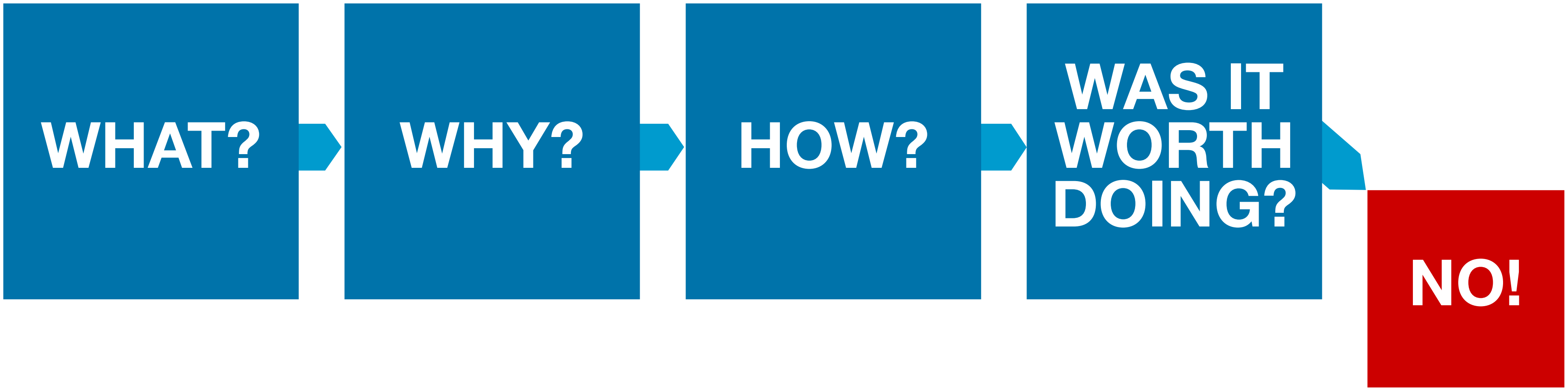
Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

FAST-NEUTRON SPECTROMETRY WITH A HIGH-RESOLUTION DYNAMIC-RECORD-LENGTH DIGITAL DATA ACQUISITION SYSTEM

POWERFUL NEW CONCEPT OF DATA ACQUISITION

L. Zavorka, M. Zbořil, A. Zimbal
AG 6.46 Neutron Spectrometry and Neutron Sources


WHAT?
WHY?
HOW?
WAS IT WORTH DOING?


WHAT?
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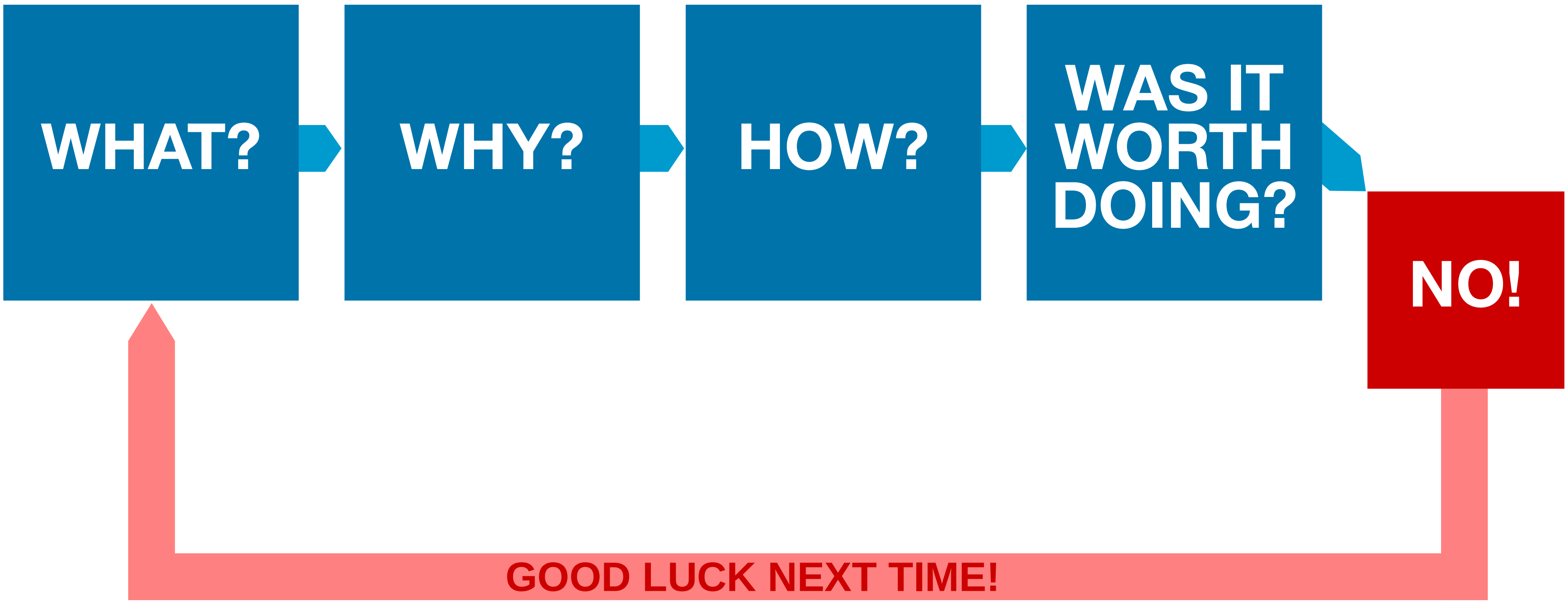
NO!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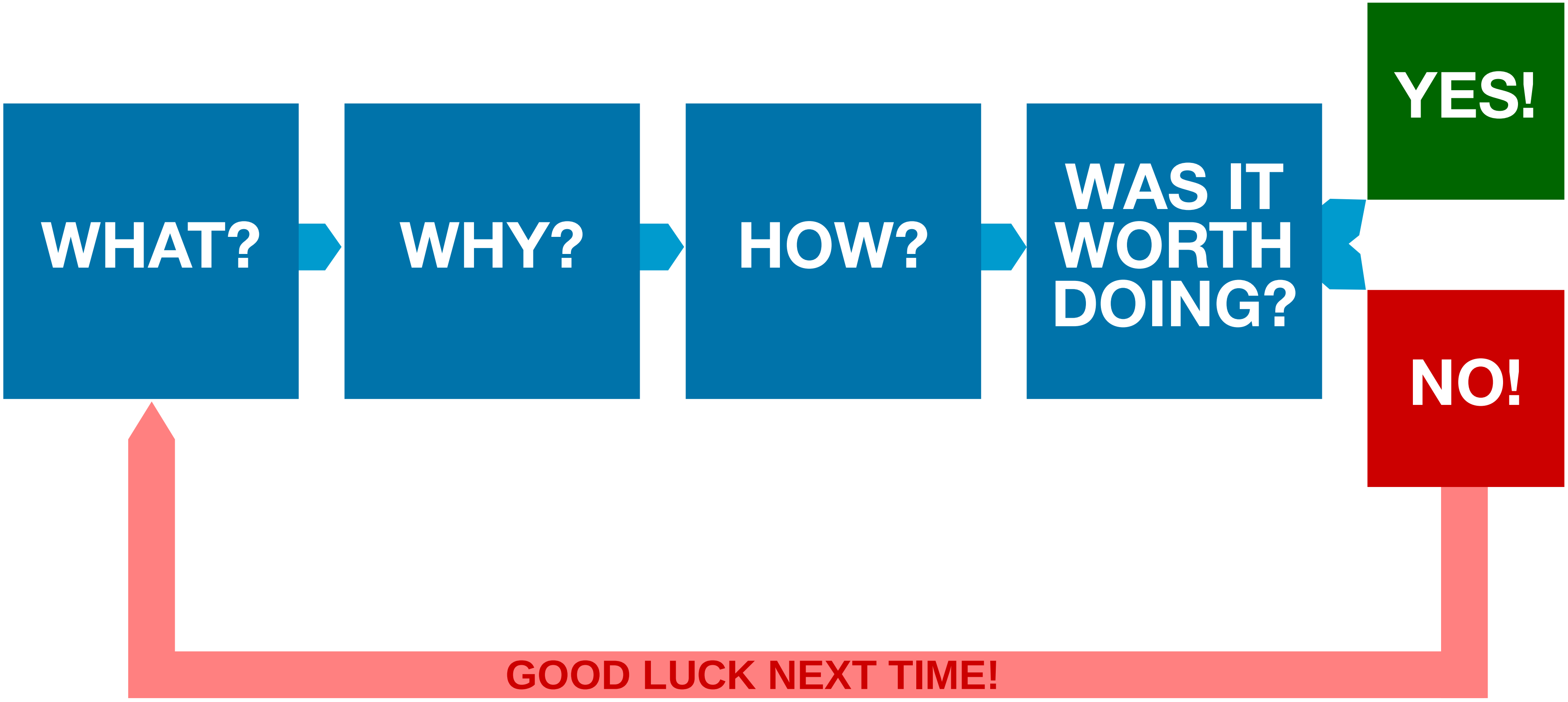
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YES!
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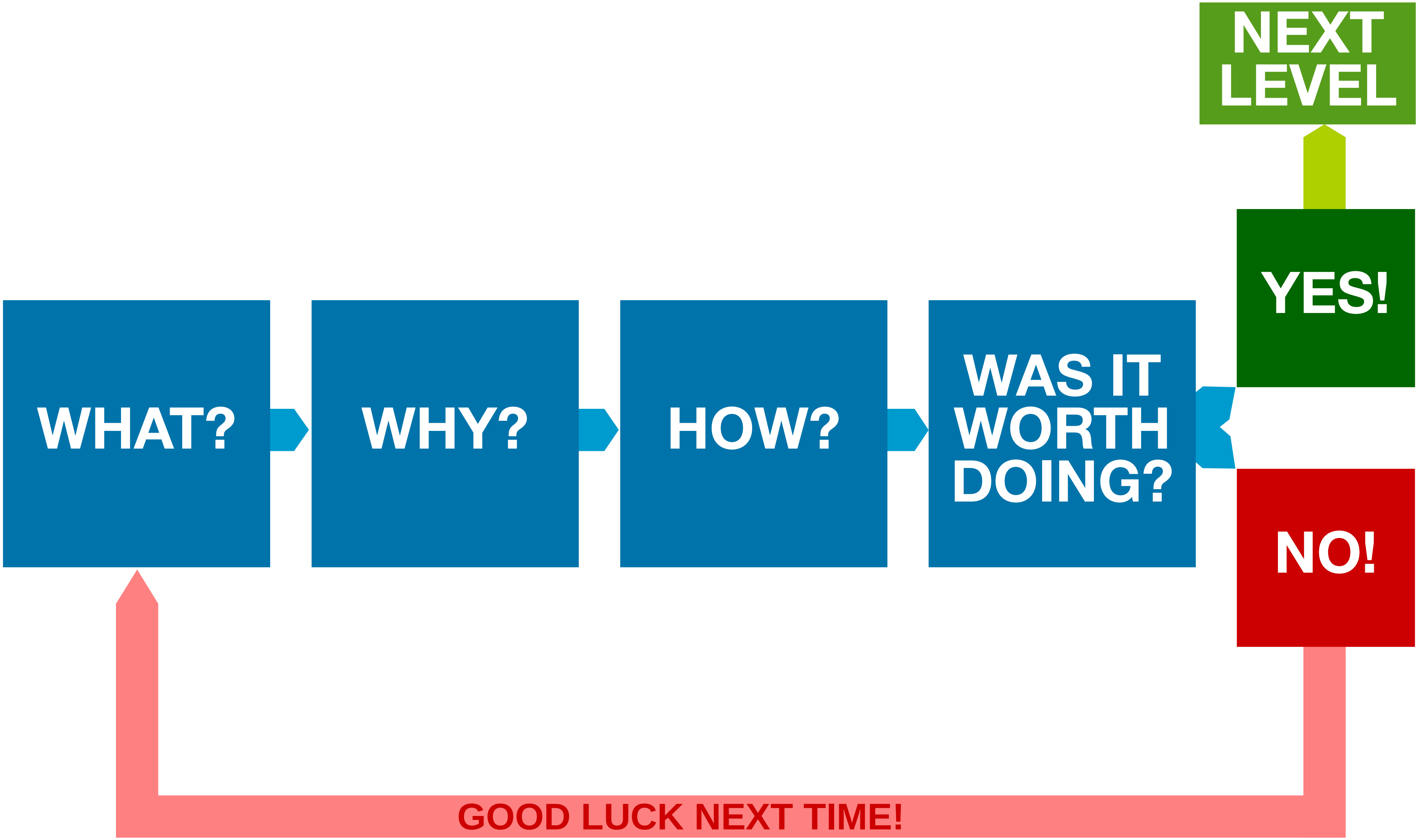
NEXT LEVEL
YES!
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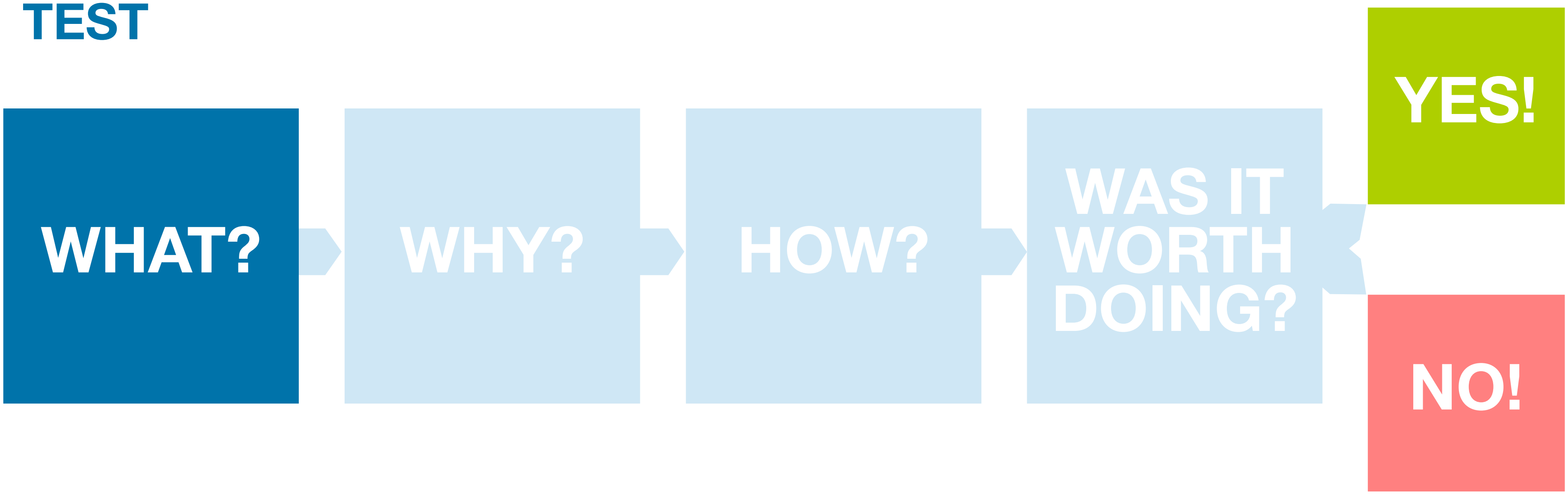
REQUIREMENTS FOR A NEW DIGITIZER FOR FAST NEUTRON SPECTROMETRY IN HIGH-INTENSITY MIXED n/γ FIELDS

PURCHASE

TEST



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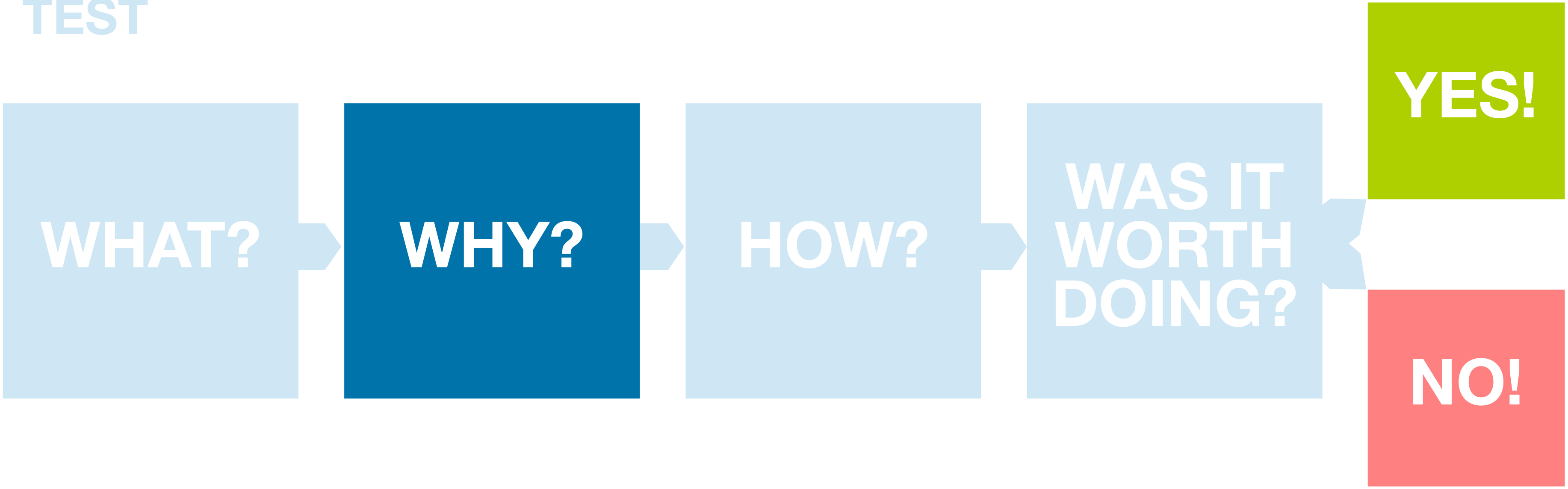

INCREASE QUALITY AND PRECISION OF MEASUREMENT

IMPLEMENT INNOVATIVE IDEAS & ADVANCED TECHNOLOGIES

REQUIREMENTS FOR A NEW DIGITIZER FOR FAST NEUTRON SPECTROMETRY IN HIGH-INTENSITY MIXED n/γ FIELDS

PURCHASE

TEST

WHAT? → WHY? → **HOW?** → WAS IT WORTH DOING? → YES! / NO!

PERFORMANCE TESTS IN PTB NEUTRON FIELDS

INCREASE QUALITY AND PRECISION OF MEASUREMENT

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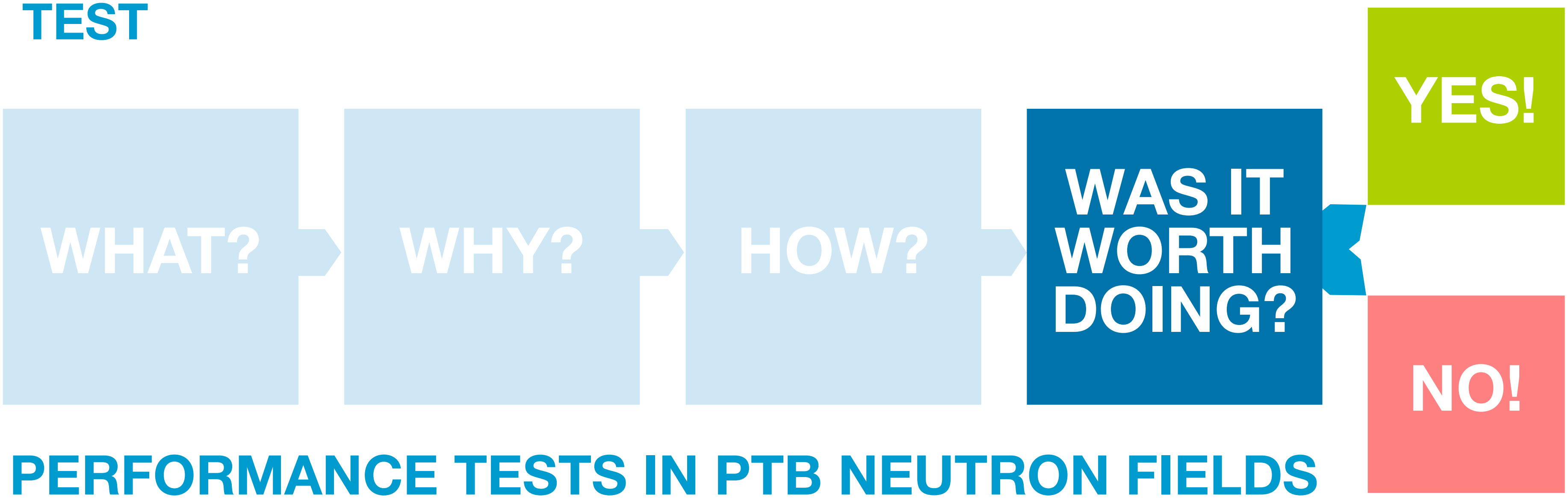

PERFORMANCE TESTS IN PTB NEUTRON FIELDS

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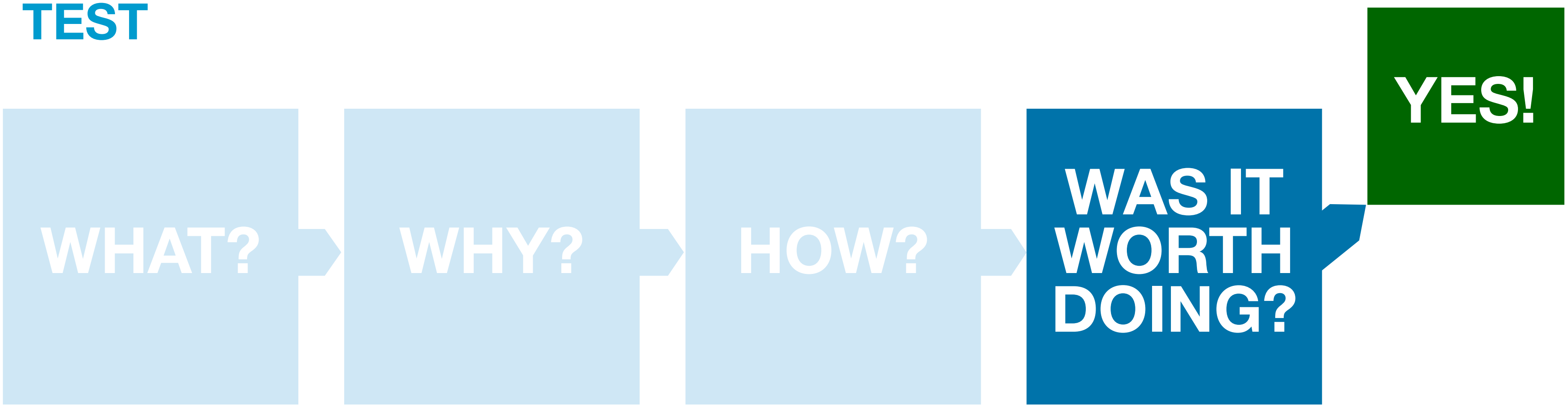


PERFORMANCE TESTS IN PTB NEUTRON FIELDS

INCREASE QUALITY AND PRECISION OF MEASUREMENT

IMPLEMENT INNOVATIVE IDEAS & ADVANCED TECHNOLOGIES

High-intensity fast neutron fields

- **Neutron fusion diagnostics**
- **Spectrometry of spallation neutron fields**

High-intensity fields I

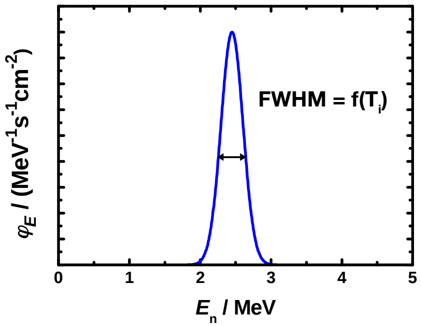
- **Neutron fusion diagnostics**

  based on fast neutron spectrometry due to the relation between the shape of neutron spectrum and plasma temperature

- Extreme environmental conditions (radiation, temperature, magnetic field)

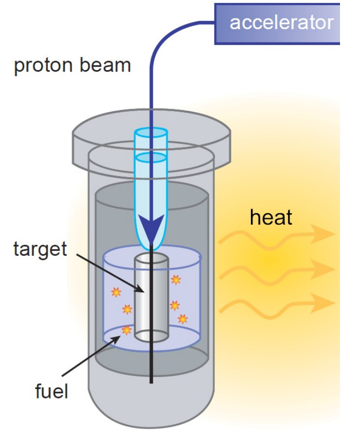
- Development of the Compact Neutron Spectrometer at PTB within the Joint European Torus (JET) Enhancement Project

- ITER under construction

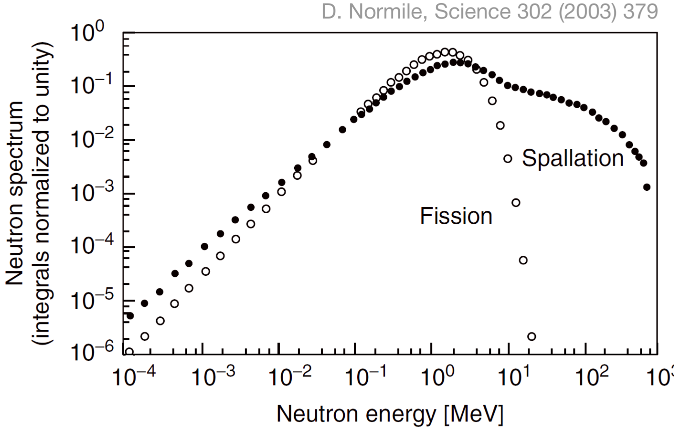


High-intensity fields II

- **Spectrometry of high energy neutrons is essential for characterization of intense spallation neutron fields**
- **Neutron energy of interest up to some GeV**
- **Utilization of ^{232}Th and ^{238}U in ADS and GEN IV fast nuclear reactors**
- **Transmutation of spent nuclear fuel**
- **Challenge for neutron dosimetry at research spallation neutron sources (SNS, ESS, MYRRHA)**
- **PTB contribution to EU projects**



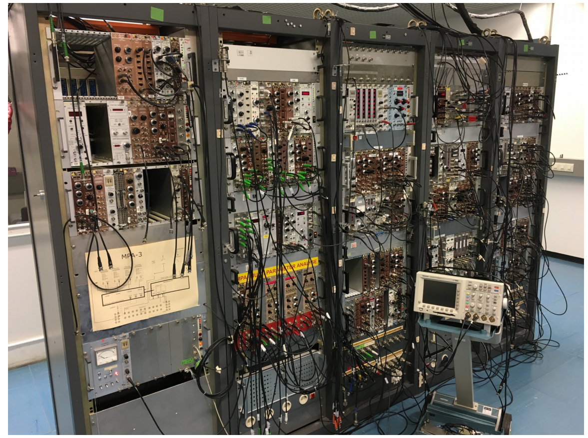
D. Normile, Science 302 (2003) 379



D. Filges and F. Goldenbaum, Handbook of Spallation Research, WILEY-VCH Verlag, 2009

Developments in Nuclear Electronics

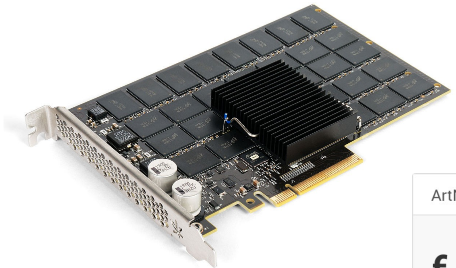
- In **HIGH COUNT RATE APPLICATIONS**, analog modules cannot compete with the digital signal processing systems
- Recent developments in computer hardware have helped initiate progress in many areas of physics research

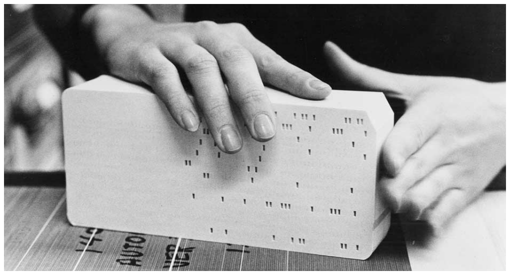


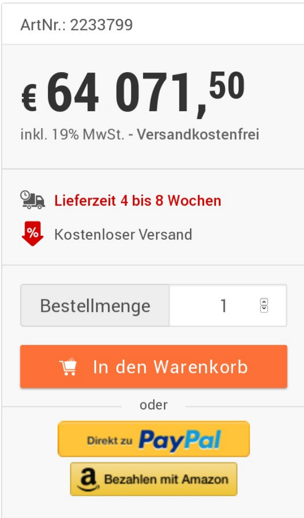
ANALOG MODULES	DIGITAL SYSTEMS
✓ Easy replacement/repair of individual modules in case of failure	✗ Minor malfunction of any component can cause failure of the whole system
✓ Considerable knowledge and experience of an experimenter are required and can be learnt	✗ “black box”

Fast Nuclear Electronics

- **FAST DIGITAL ELECTRONICS MUST PROVIDE:**
  1) Continuous collection of maximum amount of information from a detector
  2) No internal memory limit
  3) High-speed data transfer
  4) Optimal data compression (minimal data storage)
  5) High sampling rate
  6) High resolution
  7) Universality
  8) Cost-effectiveness



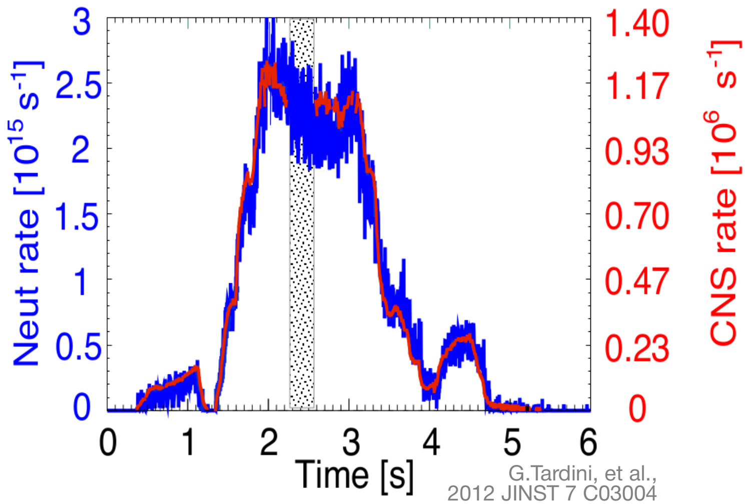


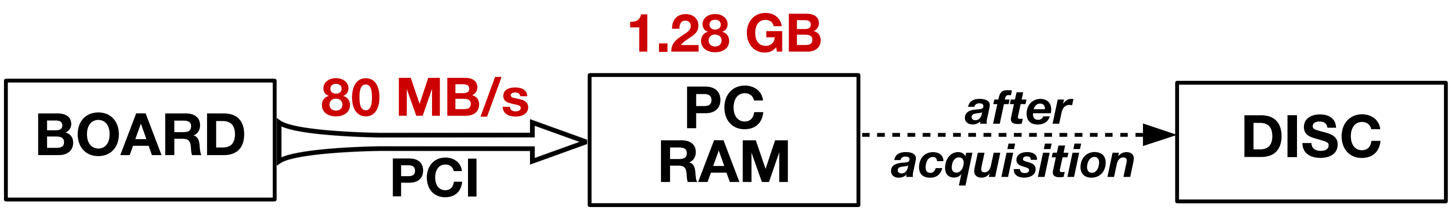


PTB: From Analog to Digital Systems

- **Analog modules used for decades**
- **Digital Pulse Shape Discrimination system ENEA Frascati FUS-ING 07-010 in use since 2006:**
  - **14-bit resolution**
  - **200 MS/s sampling rate**
  - **PCI bus 80 MB/s**
  - **1.28 GB RAM**
  - **Dynamic window**

$$Y_{sat} = \frac{80\ MB/s}{2\ B/sample * 50\ samples/pulse} = \underline{0.8\ Mpulse/s}$$





- **Developed especially for acquisitions in n/γ mixed fields**

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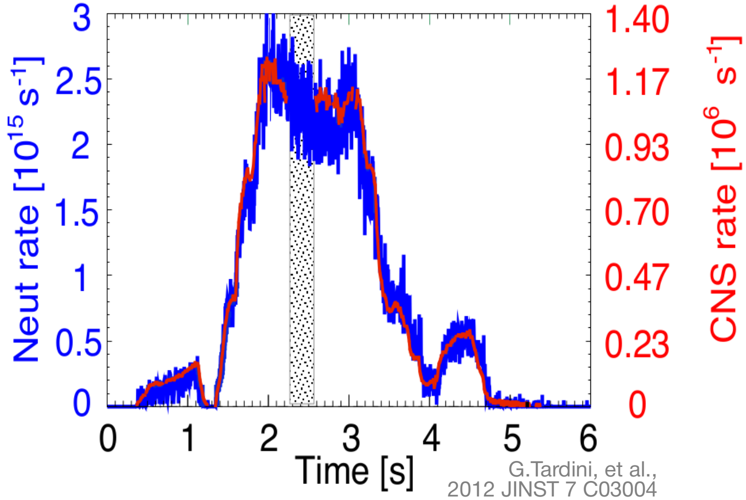
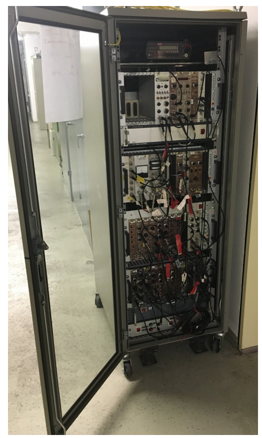
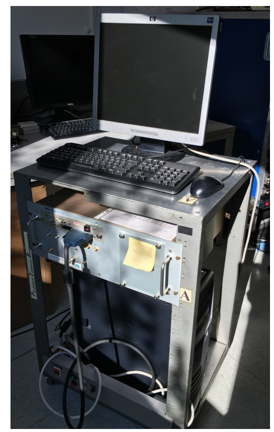


G.Tardini, et al., 2012 JINST 7 C03004

QUALITY	NIM	ENEA
Continuous & fast collection	✗	✗
No memory limit	✓	✗
Optimal data compression	✗	✓
High sampling rate	✗	✗
High resolution	✓	✓





A New Digitizer

- **Requirements for a new digitizer for measurements with fast radiation detectors introduced by A. Zimbal**
- **Currently, no commercially available product with:**
    - **Resolution ≥ 14 bit**
    - **Sampling rate ≥ 500 MS/s**
    - **Minimum 2 independent DC input channels**
    - **Variable gain input (1÷3 Vpp) with over-voltage protection**
    - **Dynamic and fixed window length modes**
    - **Zero dead time**
    - **User-friendly Graphical User Interface (GUI)**
    - **Field-Programmable Gate Array (FPGA)**
- **Digitizer developed by Signal Processing Devices AB Sweden (SP Devices) in 2015**

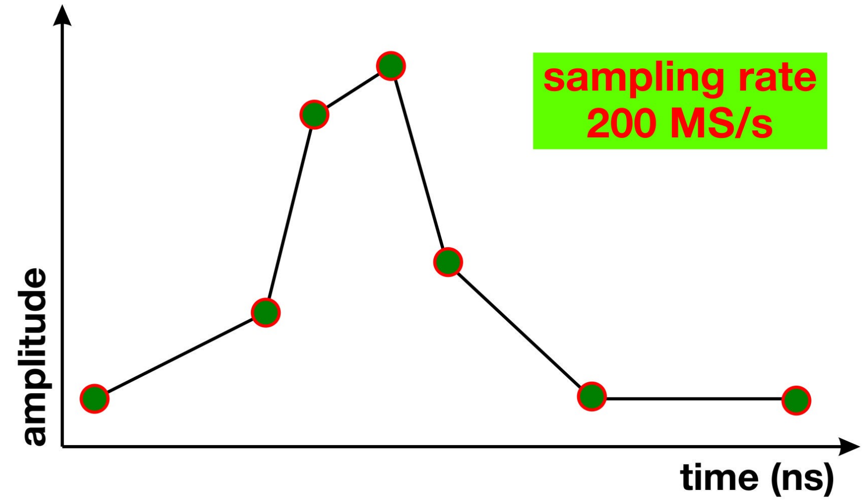
Characteristics of ADQ14

- **SP Devices ADQ14-4C-DC-VG waveform digitizer provides:**

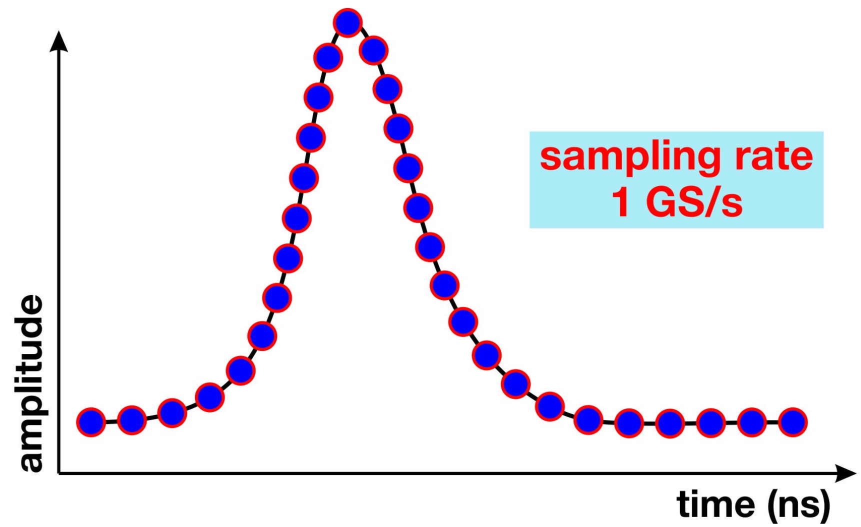
  - **4 channels running each at 1 GS/s**
  - **14-bit resolution**
  - **Variable gain input 0.3 ÷ 5.0 Vpp**
  - **Fixed and dynamic record length modes**
  - **Digital baseline stabilizer and moving average filter**
  - **Transfer rate from digitizer to PC RAM 3.2 GB/s**
  - **Intel PCIe SSD 800 GB (Write 1.9 GB/s, Read 2.8 GB/s)**
  - **Data-driven acquisition: FirmWare Pulse Detection**
  - **Header (time stamp, window length) and data files**

Sampling rate

- **ENEA Frascati**
  FUS-ING 07-010
  200 MS/s

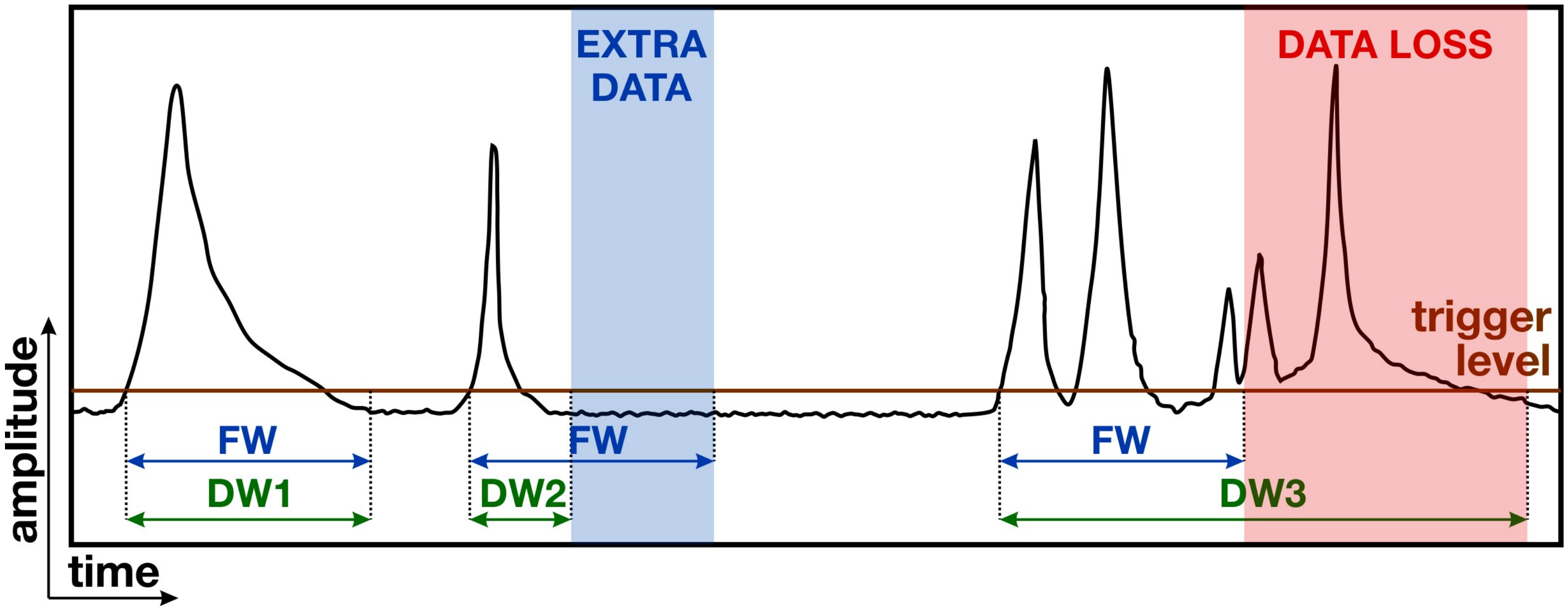


- **SP Devices**
  ADQ14-4C-DC-VG
  1 GS/s



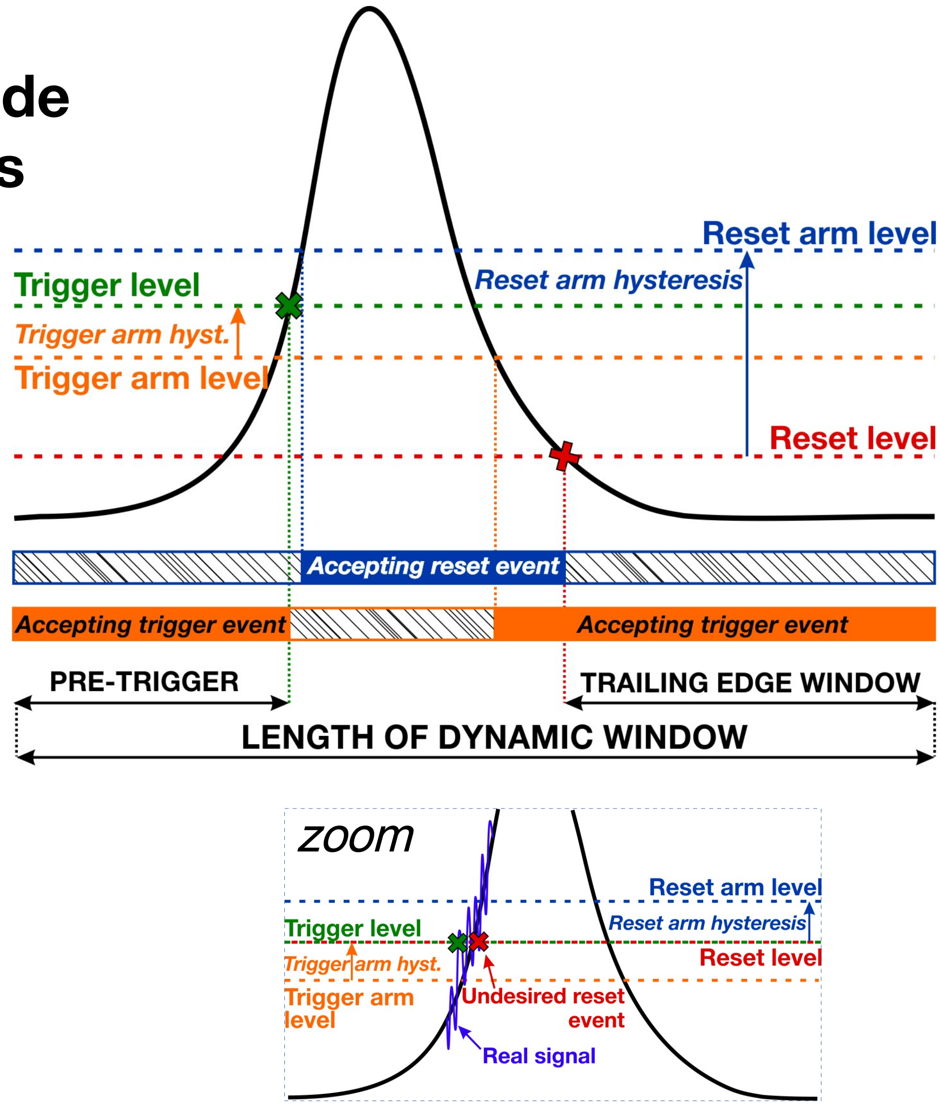
Dynamic vs. Fixed Record Length

- **Optimization of data collection by:**
  1) **Minimizing record length** when pulses of different lengths occur
     Neutrons, gammas, LED
  2) **Extending record length** when pulses arrive closely one to the other: loss-less data collection
     High count rate conditions, bursts, pile-up analysis required

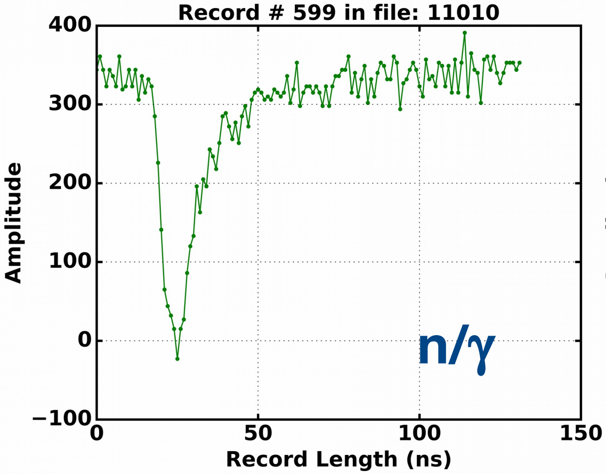


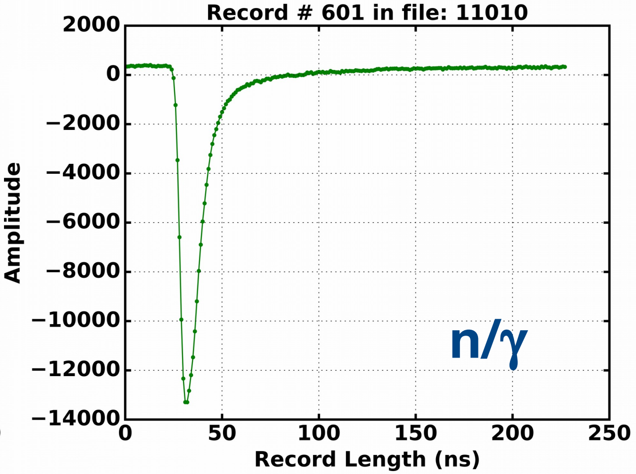
Arming Principle

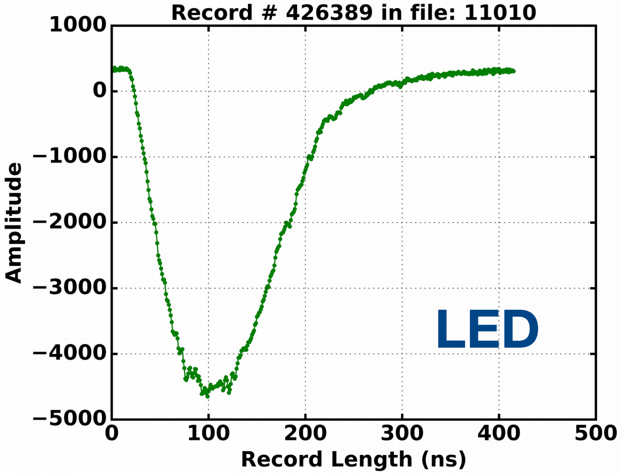
- **Dynamic record length mode controlled by a set of levels and arm hystereses:**
  - **Trigger level**
  - **Reset level**
  - **Trigger arm hysteresis**
  - **Reset arm hysteresis**
- **Each record contains user-specified:**
  - **Pre-trigger**
  - **Trailing edge window accepting trigger events**



Dynamic Record Length in Real Life







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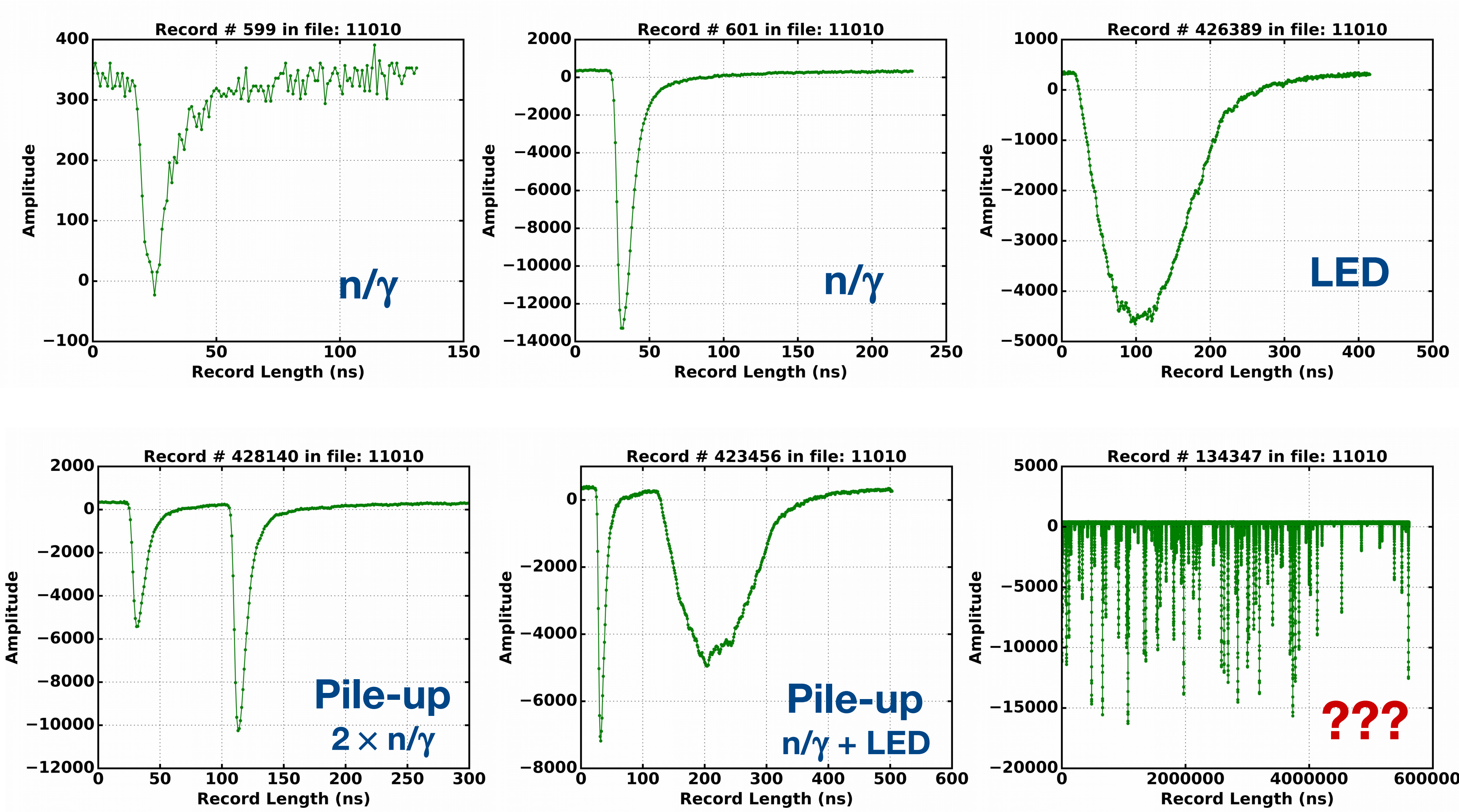
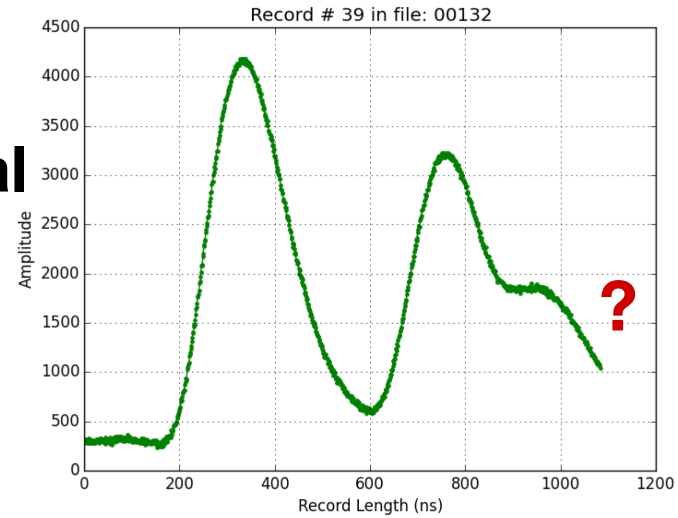
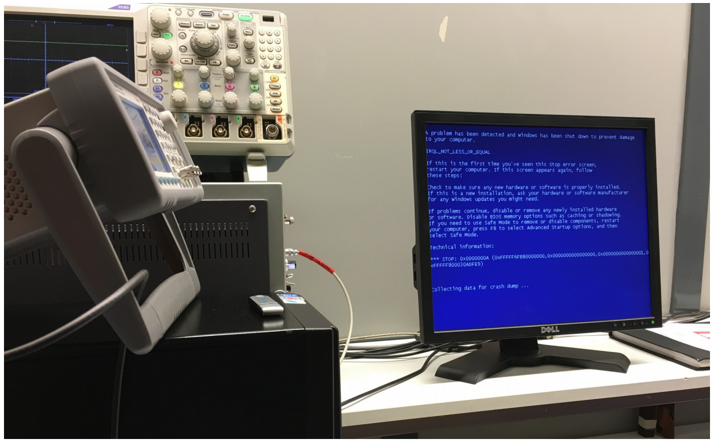


Commissioning Troubles

- Initially very limited options in GUI
- Magic formulas required for optimal acquisition settings
- Improper function of arming
- Unstable mode of data collection
- Memory management errors
- Half of maximum gain available
- Coincidence option did not work
- All bugs successively removed



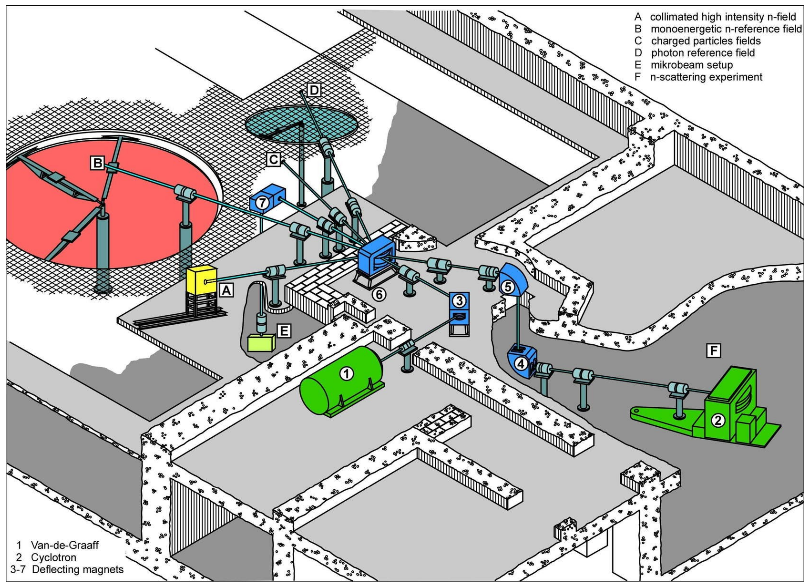


PTB Ion Accelerator Facility

- **PTB Department of Neutron Radiation operates:**
  - **Cyclotron: $E_{p,max}$= 19 MeV, $E_{d,max}$= 14 MeV**
  - **Van de Graaf (3.75 MV, *in decommissioning*)**
  - **Tandetron (2 MV, from 2017) $E_{p,d,max}$= 4 MeV, I_{max}= 50 μA**

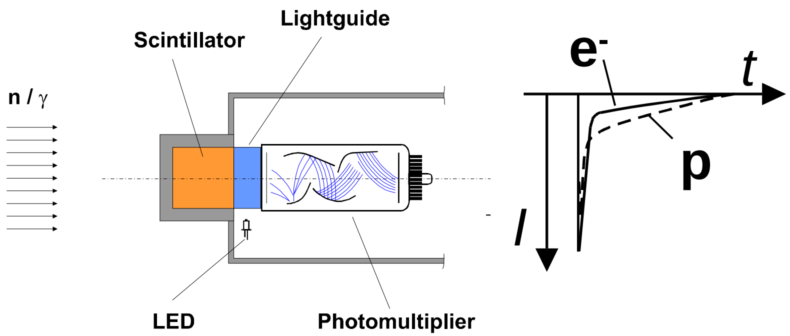
and provides standard reference neutron fields:

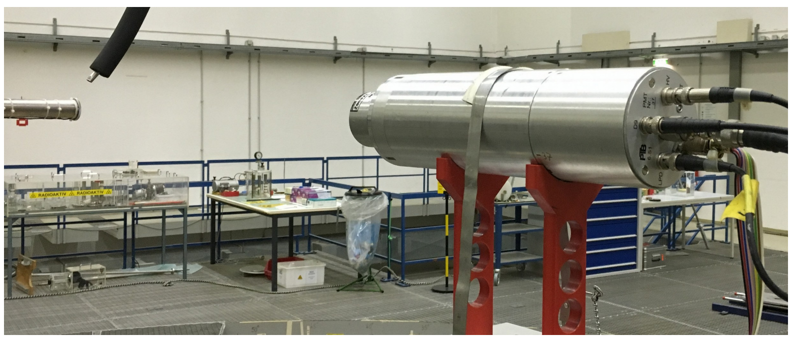
- **Monoenergetic E_n = 24 keV ÷ 19 MeV**
- **Collimated high-intensity beams with a broad energy distribution ≤ 17 MeV**
- **High-energy gamma radiation (7 MeV)**
- **Low backscatter background**
- **Achievable time resolution of 1 ns, TOF**
- **Micro-ion beam for radiobiological investigations on cells**

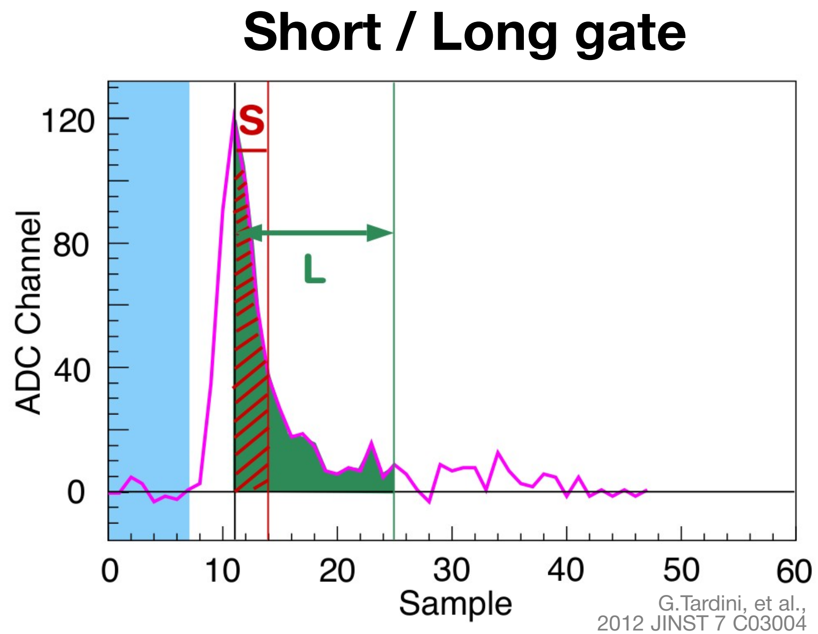


Scintillation Detectors

- **Liquid scintillation detector NE213 / BC501A, 2''× 2''**
- **PMT gain stabilization with an integrated pulsed LED**
- **n/γ discrimination based on different response of the detector to recoil protons and Compton electrons**







Diamond Detectors

- **single crystal Chemical Vapor Deposition diamond detectors (scCVD)**
- **Neutron spectrometry in range 2 MeV < E_n < 50 MeV**
- **Elastic and inelastic neutron collisions with carbon nuclei**
- **Not very sensitive to γ radiation**
- **Fast response, good resolution**
- **Small size (5 × 5 × 0.5) mm³**
- **High radiation hardness**
- **Charge trapping and imperfect electrode/diamond interface influence stable operation**

Experimental Campaign I

- **Main purposes of test measurements:**
  - **Test performance of the new digital board in mixed neutron and γ-ray fields**
  - **Connect the digitizer to different types of neutron spectrometers (diamond, scintillation)**
  - **Test both the fixed and dynamic record length modes**
  - **Determine optimal settings of the adjustable parameters in the firmware pulse detection GUI**
  - **Compare performance of the new board with the already available ENEA digital pulse shape discrimination system**

DIAMOND DETECTOR	SCINTILLATION DETECTOR

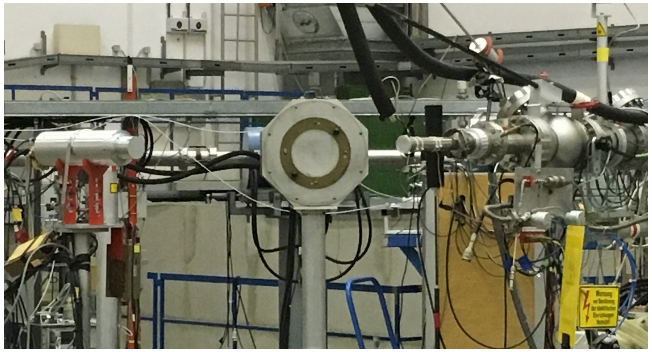
Experimental Campaign II

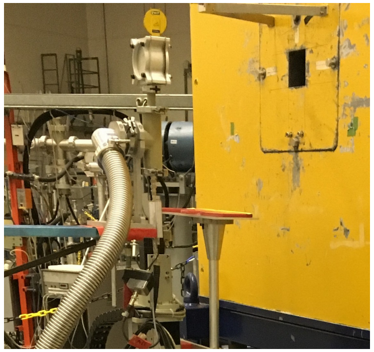
DIAMOND DETECTOR:

- High-intensity neutron field with a broad energy distribution up to 17 MeV
- Test the count-rate capability and dead time of the new digitizer
- Test performance with different preamplifiers
- Test the arming mechanism with positive input signals

SCINTILLATION DETECTOR:

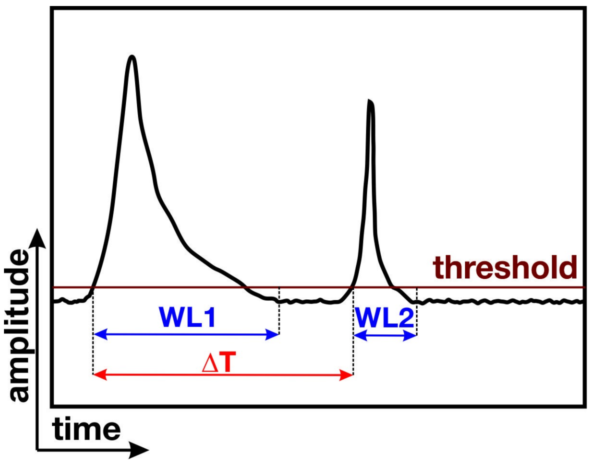
- Monoenergetic field of 14 MeV neutrons
- Find out optimal settings for n/γ discrimination (Figure of Merit - FOM)
- HV bias: 1462, 1630, and 1690 V
- Custom build shaping amplifiers (passband DC – 15 MHz, Gain 1.2 & 4.0)
- Test the arming mechanism with negative input signal
- Pulse height spectrum resolution test

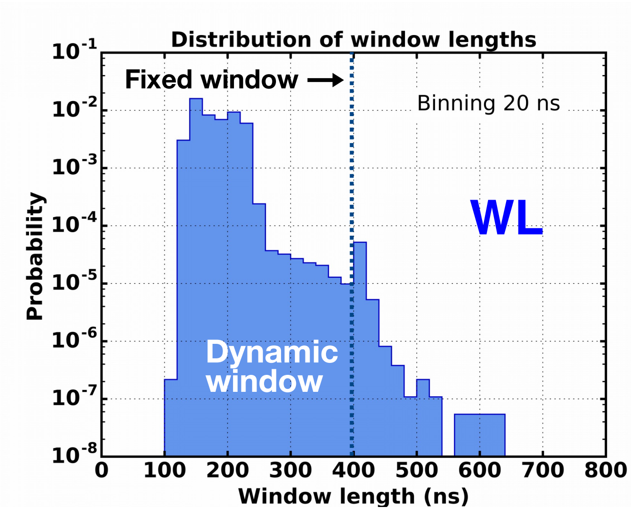


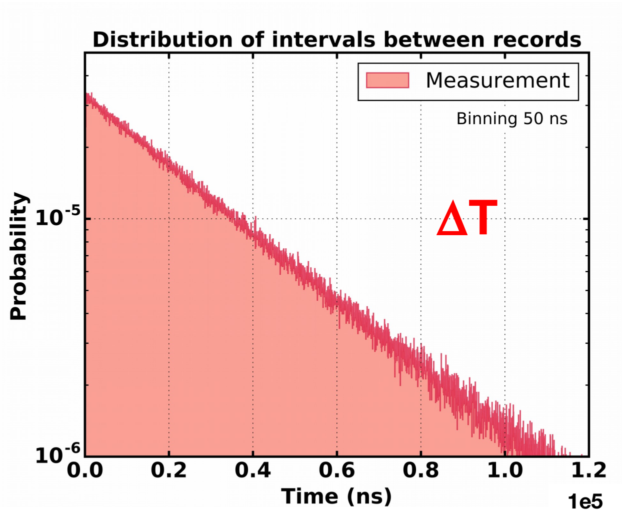


Count Rate Capability I

- **Test of digitizer's dead time at high count rate (9×10^4 cps)**
- **Distribution of intervals between successive events:**
  - **Random process characterized by a constant probability of occurrence per unit time (Poisson random process)**







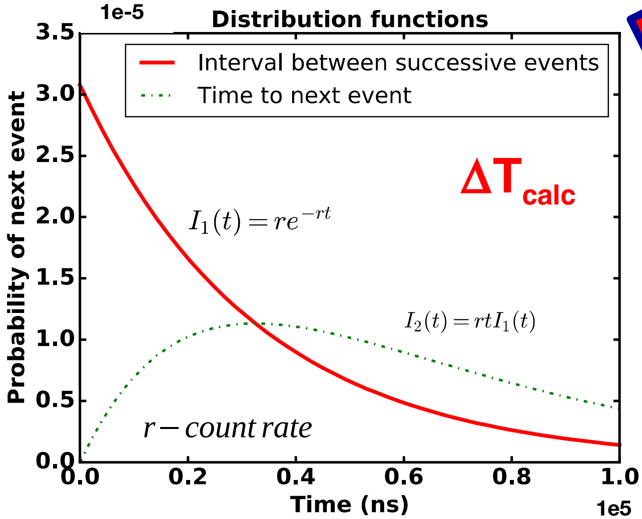
  - **Application of Monte Carlo methods:** ***(comes on the next slide)***

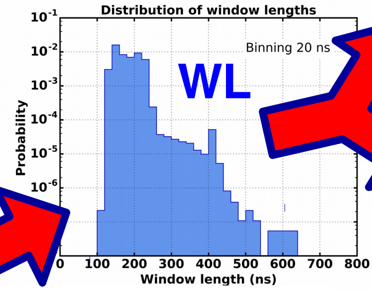
Count Rate Capability II

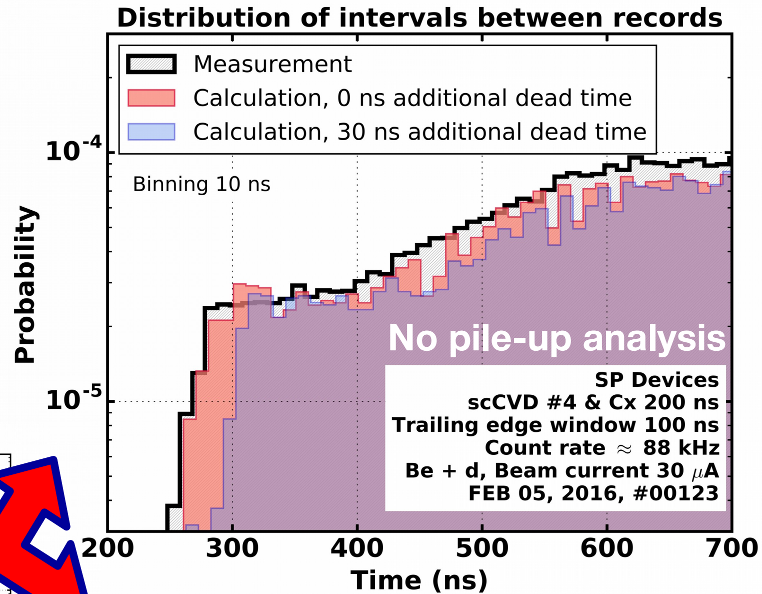
- Random selection of
  - Interval between records (ΔT_{calc})
  - Window length (WL)

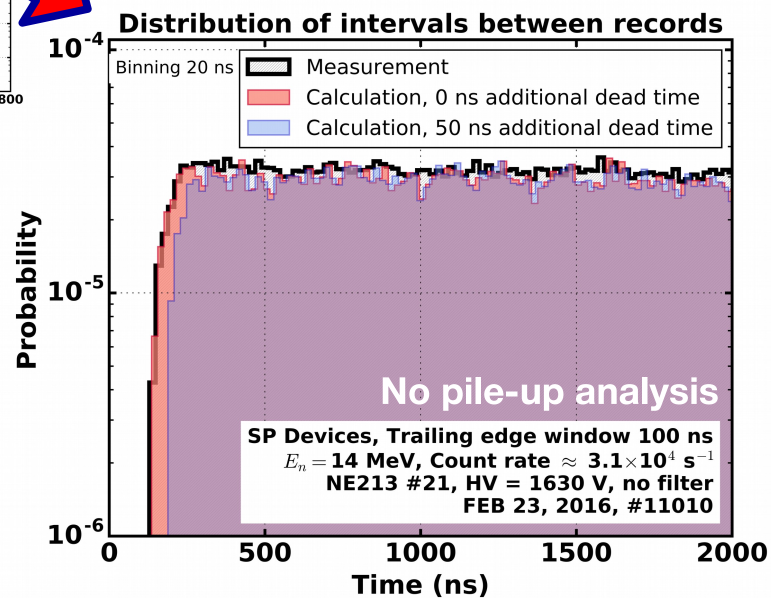
  if (ΔT_{calc}) > (WL):

  fill histogram









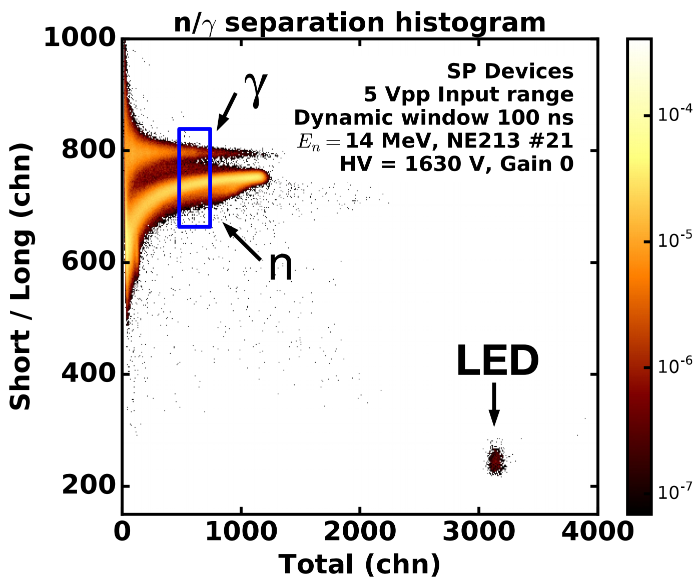
- Digitizer shows no dead time in the order of ~ 10 ns or higher

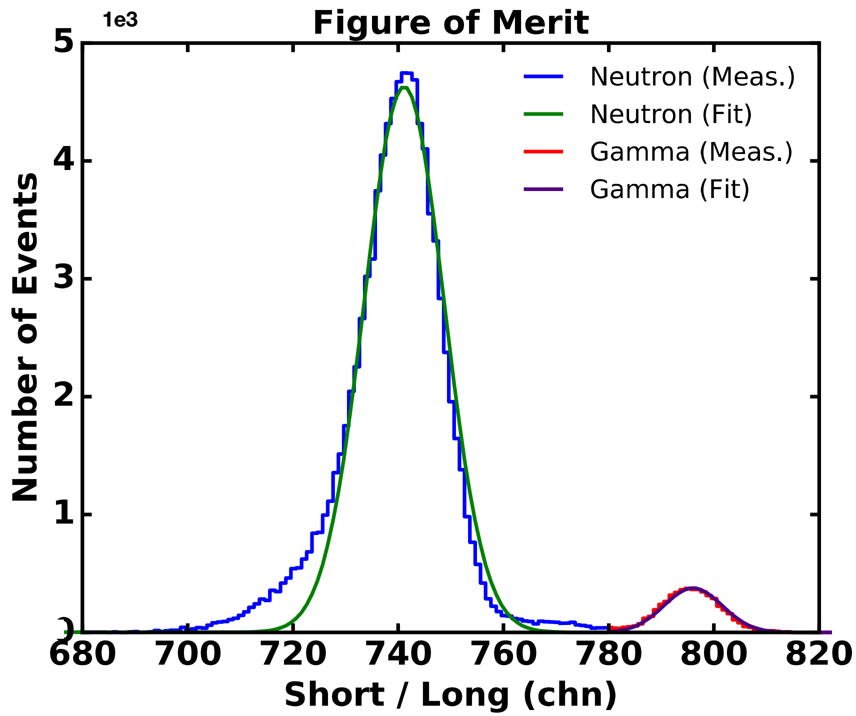
Neutron / Gamma-Ray Discrimination

- **Fundamental n/γ discrimination quality: Figure of Merit (FOM)**

$$FOM = \frac{S}{FWHM_{gamma} + FWHM_{neutron}}$$

S: *separation between peaks*
σ: *standard deviation*
$FWHM \approx 2.36\,\sigma$





Neutron / Gamma-Ray Discrimination

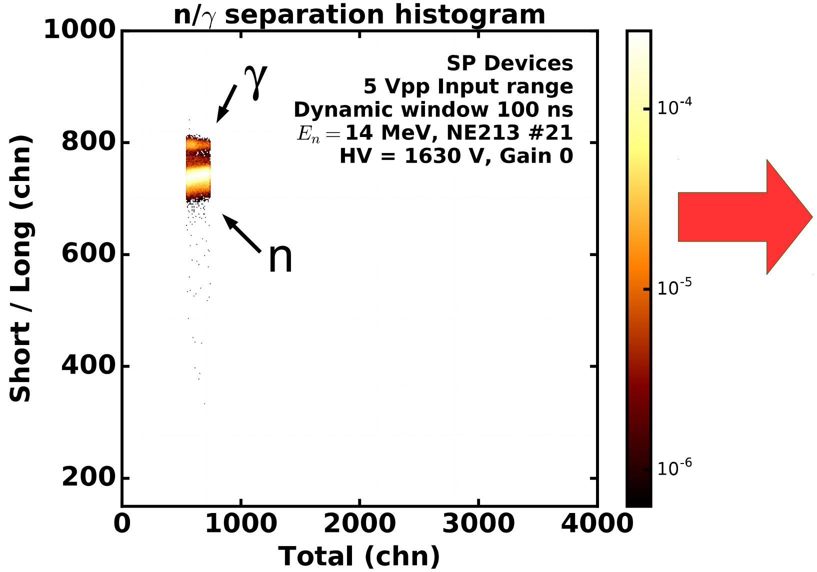
- **Fundamental n/γ discrimination quality: Figure of Merit (FOM)**

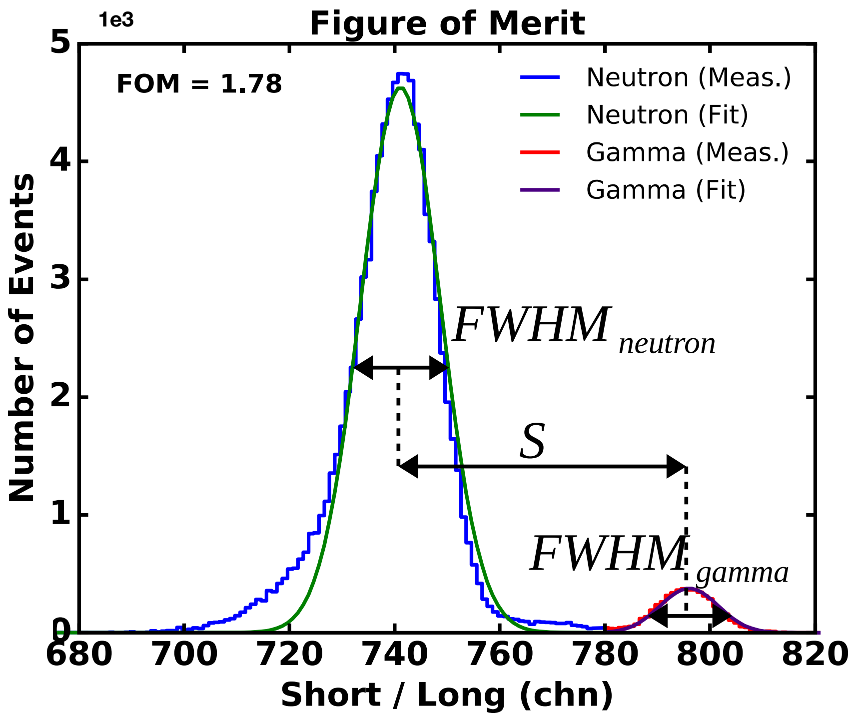
$$FOM = \frac{S}{FWHM_{gamma} + FWHM_{neutron}}$$

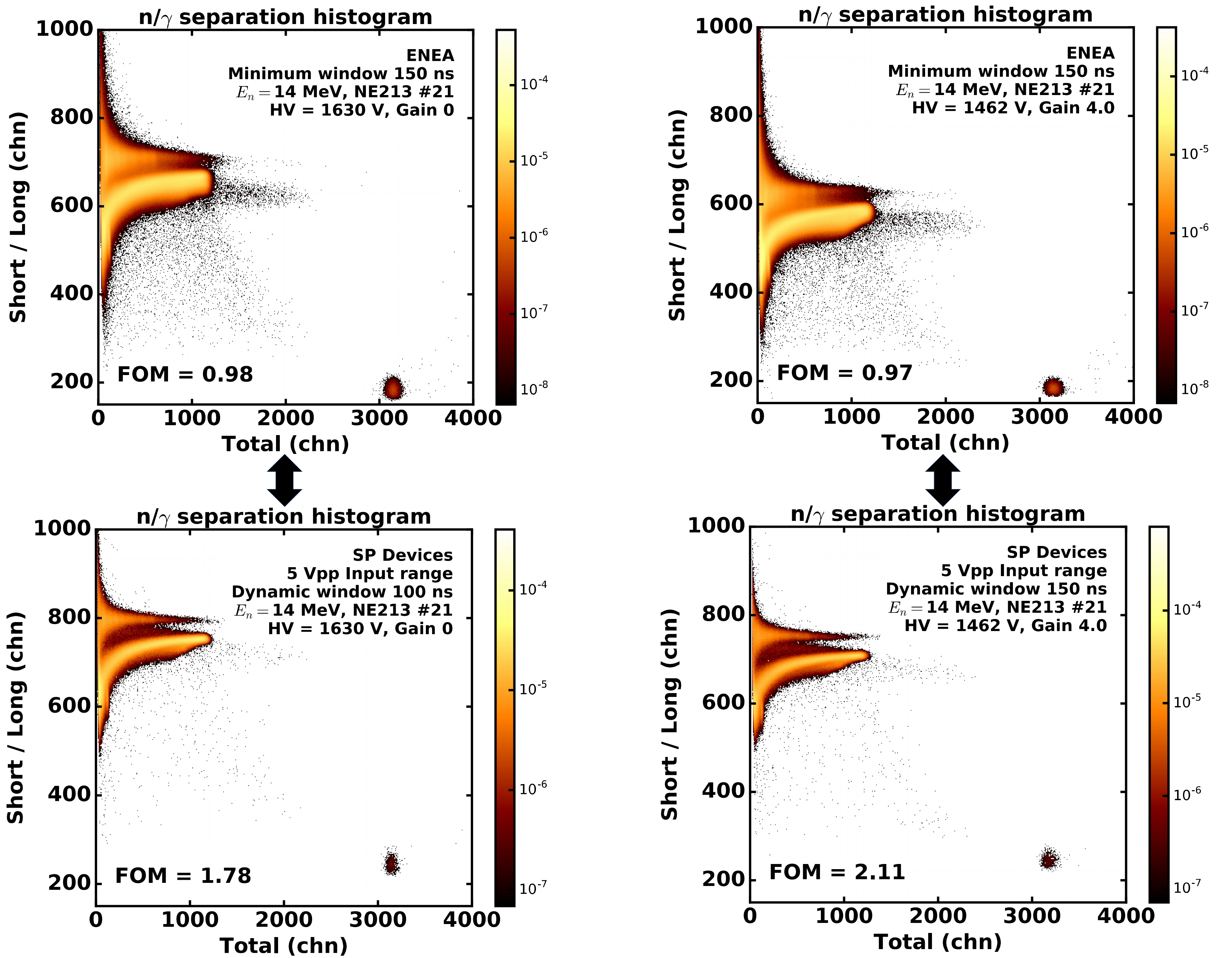
S : *separation between peaks*
σ : *standard deviation*
$FWHM \approx 2.36\,\sigma$

- **For well separated Gaussian distributions:** $S > 3(\sigma_{gamma} + \sigma_{neutron})$

$$FOM \geq \frac{3(\sigma_{gamma} + \sigma_{neutron})}{2.36(\sigma_{gamma} + \sigma_{neutron})} \approx 1.27$$







n/γ separation histogram
ENEA
Minimum window 150 ns
$E_n =$ 14 MeV, NE213 #21
HV = 1630 V, Gain 0
FOM = 0.98
Short / Long (chn)
Total (chn)
n/γ separation histogram
ENEA
Minimum window 150 ns
$E_n =$ 14 MeV, NE213 #21
HV = 1462 V, Gain 4.0
FOM = 0.97
Short / Long (chn)
Total (chn)
n/γ separation histogram
SP Devices
5 Vpp Input range
Dynamic window 100 ns
$E_n =$ 14 MeV, NE213 #21
HV = 1630 V, Gain 0
FOM = 1.78
Short / Long (chn)
Total (chn)
n/γ separation histogram
SP Devices
5 Vpp Input range
Dynamic window 150 ns
$E_n =$ 14 MeV, NE213 #21
HV = 1462 V, Gain 4.0
FOM = 2.11
Short / Long (chn)
Total (chn)

Summary of Results

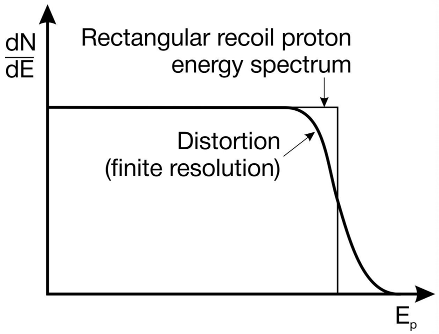
Comparison of the new digitizer with ENEA system performance

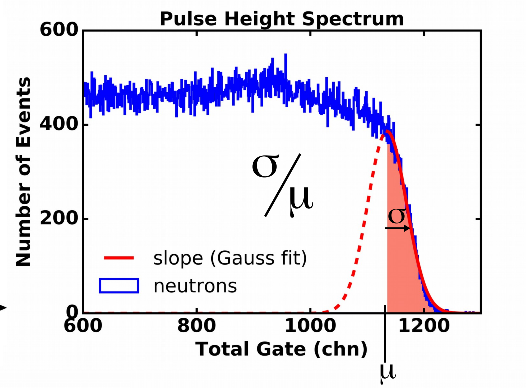
HV BIAS (V)	1462		1630		1690		
GAIN	FOM	Pile-up (%)	FOM	Pile-up (%)	FOM	Pile-up (%)	WL
0			0.98(3)	0.85			D
	1.21(2)	2.88	1.86(2)	3.30	1.98(2)	4.65	F500
		-		0.86		-	D100
1.2			1.07(5)	0.75	1.23(4)	1.41	D
	1.34(2)	2.54	2.10(2)	2.97	2.24(1)	4.53	F500
		-		1.60		1.97	D150
4	0.97(3)	1.26					D
	2.11(1)	3.66					F500
		1.55					D150

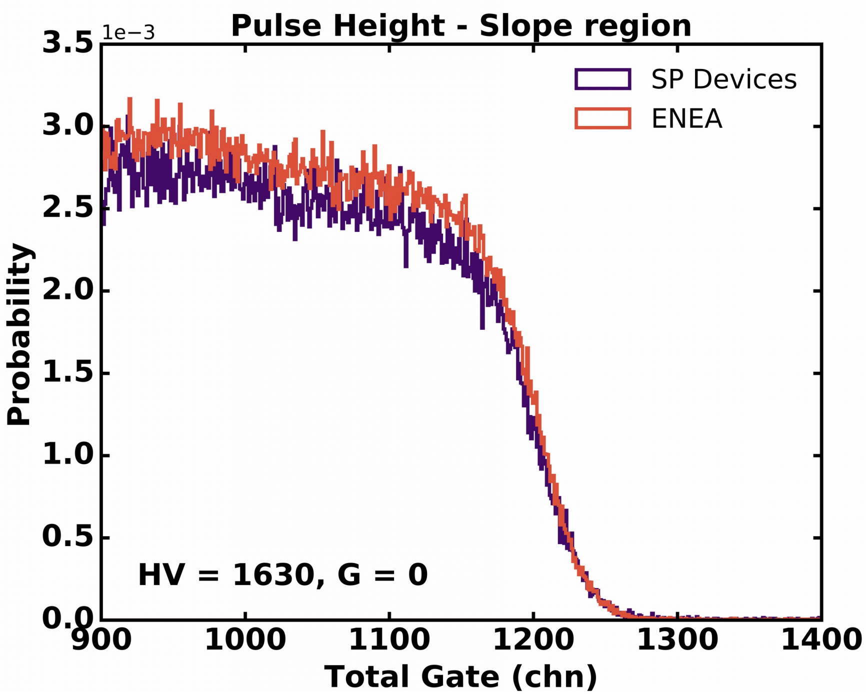
Maximal figure of merit (FOM): SP Devices, HV = 1690 V, Gain = 1.2

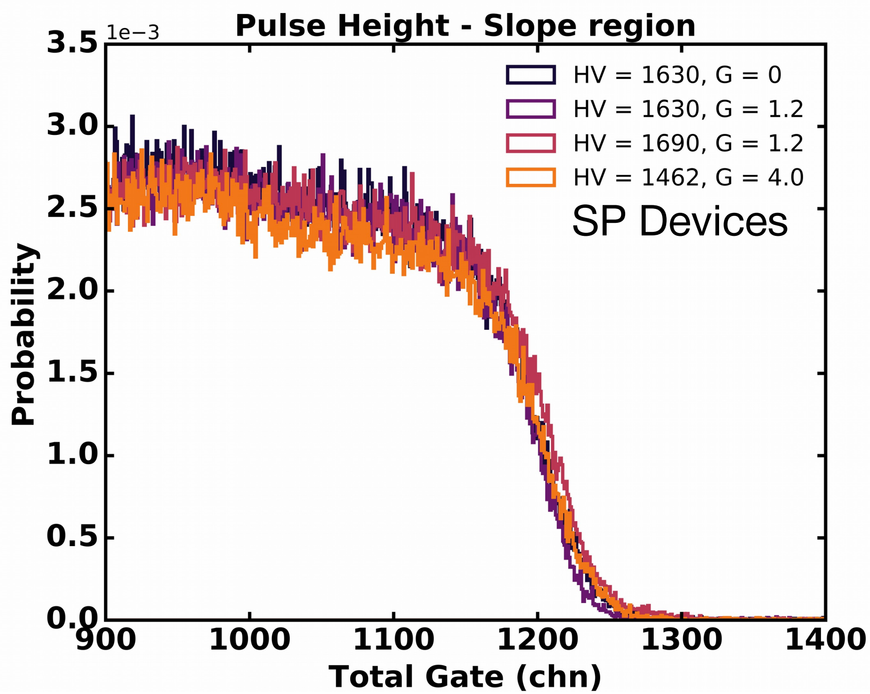
PHS Slope Resolution

- **Recoil proton energy spectrum can be distorted through:**
  - **(a) Nonuniform light collection**
  - **(b) Photoelectron statistics**
  - **(c) Other sources of noise**









Conclusion

- Performance of the new digitizer was tested in various experimental conditions and a positive impression has been left despite some problems during commissioning
- Quality of measurements - considering especially FOM, acquisition time, amount and speed of data storage - has increased substantially with the new digitizer
- Optimal configuration with scintillation detector has been found
- No significant dead time observed
- Plans for future:
    - Implementation of the pile-up analysis
    - Perform further tests (coincidence mode, TOF)

Thank you for your attention

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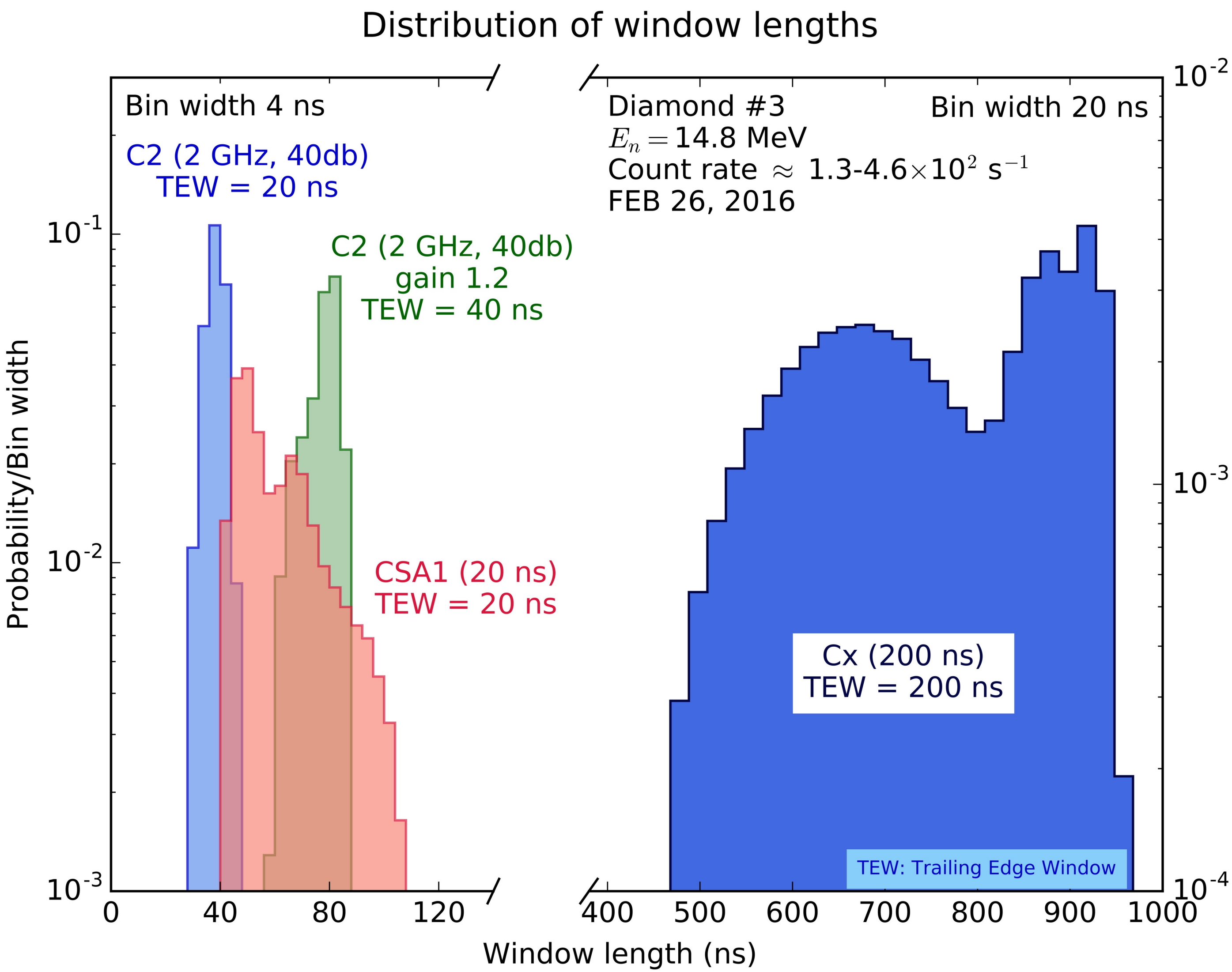

Distribution of window lengths
Bin width 4 ns
C2 (2 GHz, 40db)
TEW = 20 ns
C2 (2 GHz, 40db)
gain 1.2
TEW = 40 ns
CSA1 (20 ns)
TEW = 20 ns
Diamond #3
$E_n = 14.8$ MeV
Count rate $\approx$ 1.3-4.6$\times10^2$ s^{-1}
FEB 26, 2016
Bin width 20 ns
Cx (200 ns)
TEW = 200 ns
TEW: Trailing Edge Window
Probability/Bin width
Window length (ns)
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-3}
10^{-4}
0
40
80
120
400
500
600
700
800
900
1000