Pile-up discrimination algorithms for the HOLMES experiment

E. Ferri[1], B. Alpert[2], D. Bennett[2], M. Faverzani[1], J. Fowler[2], A. Giachero[1], J. Hays-Wehle[2], M. Maino[1], A. Puiu[1], A. Nucciotti[1], J. Ullom[2]

[1]University of Milano-Bicocca & INFN Milano-Bicocca, Milano, Italy
[2]NIST, Boulder, CO, USA

ERC
Advanced Grant 2013
GA n. 340321
PI: S. Ragazzi, HI:INFN

The HOLMES experiment is a new large scale experiment for the electron neutrino mass determination by means of the electron capture (EC) decay of 163Ho. In such experiment, random coincidence events are one of the main sources of background which impairs the ability to identify the effect of a non-vanishing neutrino mass. In order to resolve these spurious events, detectors characterized by a fast response are needed as well as pile-up recognition algorithms. For that reason, we have developed a code for testing the discrimination efficiency of various algorithms in recognizing pile up events in dependence of the time separation between two pulses. The tests are performed on simulated realistic TES signals and noise. Indeed, the pulse profile is obtained by solving the two coupled differential equations which describe the response of the TES according to the Irwin-Hilton model. To these pulses, a noise waveform which takes into account all the noise sources regularly present in a real TES is added. The amplitude of the generated pulses are distributed as the 163Ho calorimetric spectrum. Furthermore, the rise time of these pulses has been chosen taking into account the constraints given by both the bandwidth of the microwave multiplexing read out with a flux ramp demodulation and the bandwidth of the ADC boards currently available for ROACH2. Among the different rejection techniques evaluated, the Wiener Filter technique, a digital filter to gain time resolution, has shown an excellent pile-up rejection efficiency. The obtained time resolution closely matches the baseline specifications of the HOLMES experiment.

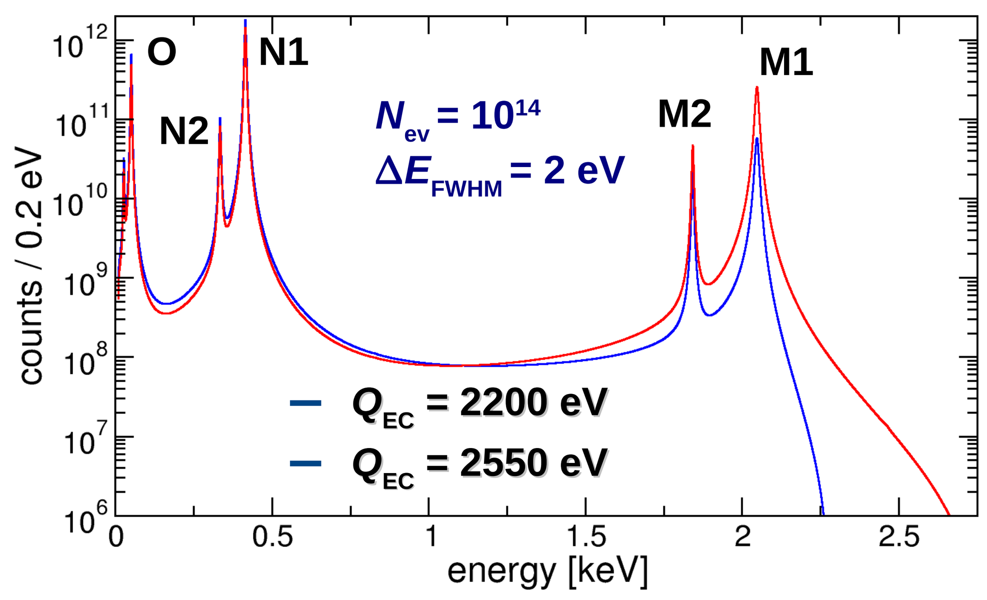
Holmium electron capture

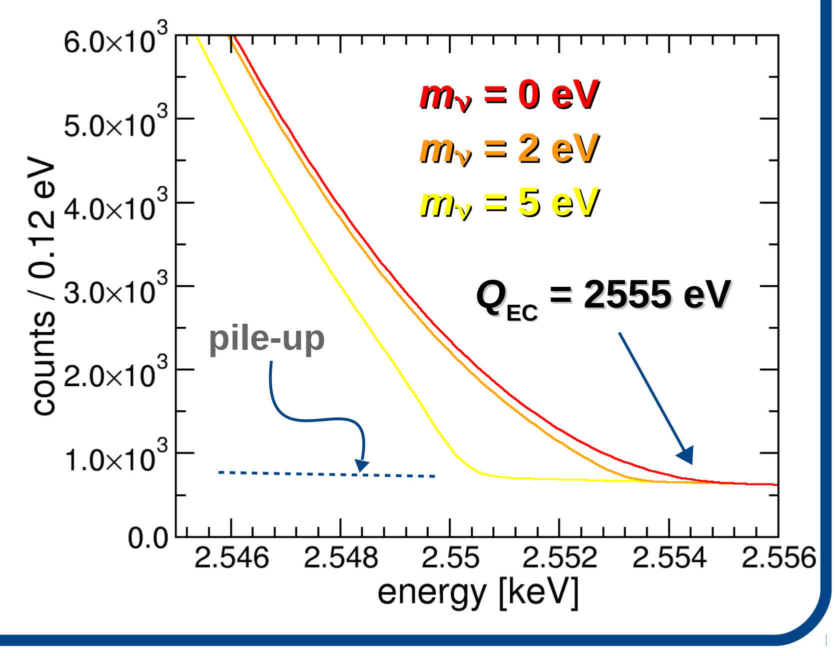
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

$Q_{EC} \approx 2.5$ keV → electron capture from shell ≥ M1

$$N_{EC}(E_{EC}) = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2}\times\sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

- calorimetry of Dy atomic de-excitations (mostly non-radiative)
  → rate at end-point and ν mass sensitivity depend on Q_{EC}
- Measured: Q_{EC} = 2200÷2800 eV. Recommended: Q_{EC} = 2555 eV
- $\tau_{1/2} \approx$ 4570 years: 2×10^{11} ^{163}Ho nuclei → 1 Bq



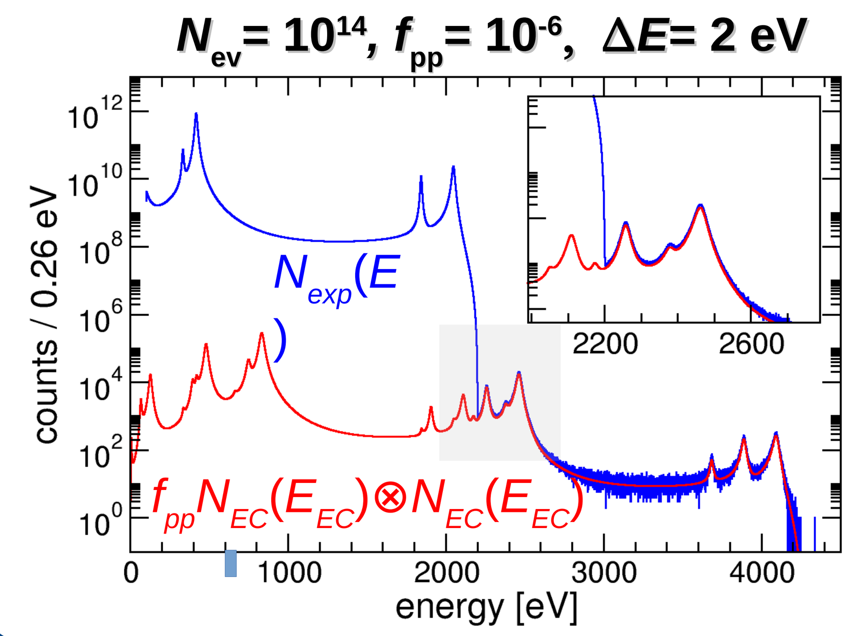


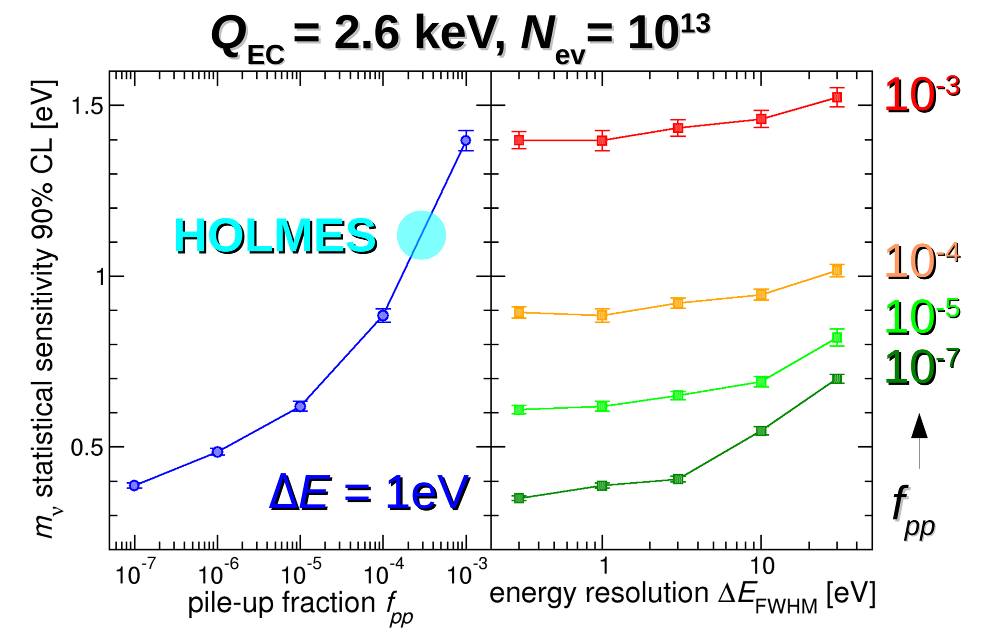
Statistical sensitivity $\Sigma(m_\nu)$ dependencies from MC simulations

- strong on statistics $N_{ev}=A_{EC}N_{det}t_M$: $\Sigma(m_\nu) \propto N_{ev}^{1/4}$
- strong on rise time pile-up (probability $f_{pp} \approx A_{EC}\tau_R$)
- weak on energy resolution ΔE

t_M measuring time
N_{det} number of detectors
A_{EC} EC activity per detector
τ_R time resolution (≈rise time)

A. Nucciotti, Eur. Phys. J. C (2014) 74:3161





HOLMES

Neutrino mass measurement with a m_ν statistical sensitivity as low as 0.4 eV

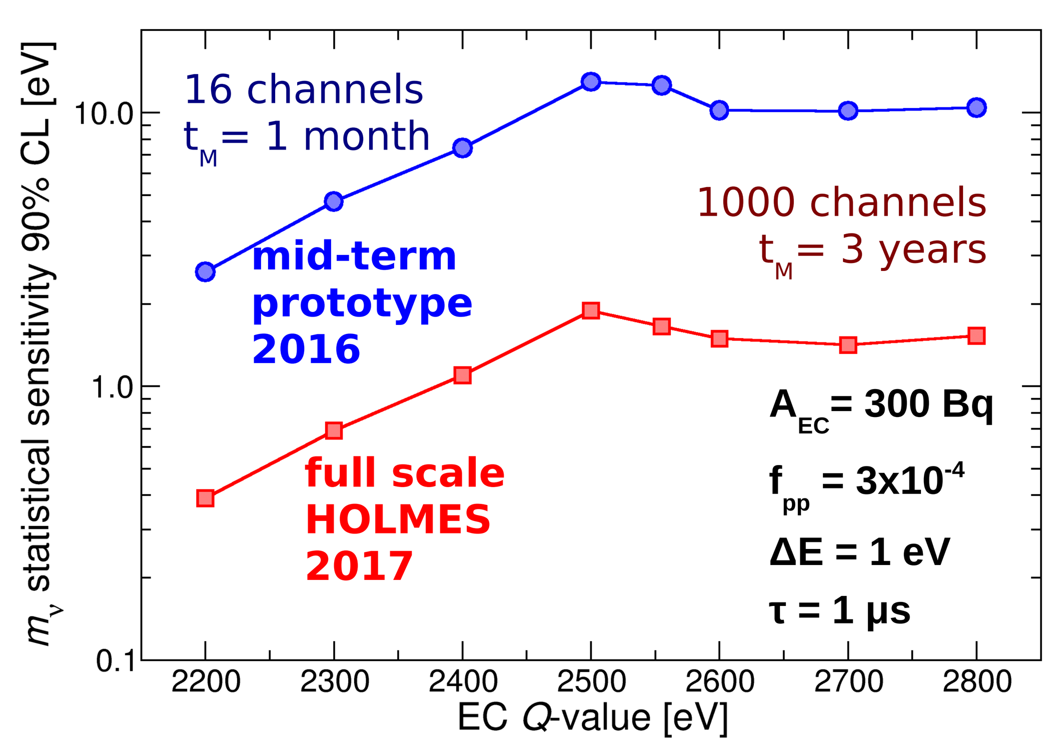
Detectors: Transition Edge Sensor (TES) with ^{163}Ho implanted in Bi/Au absorbers

Activity:
6.5×10^{13} nuclei per detector
→ 300 dec/s

Performances:
$\Delta E \approx$ 1 eV and $\tau_R \approx$ 1 μs

16 channel demonstrator

Final configuration:
1000 channel array
- 6.5×10^{16} ^{163}Ho nuclei
- 3×10^{13} events in 3 y

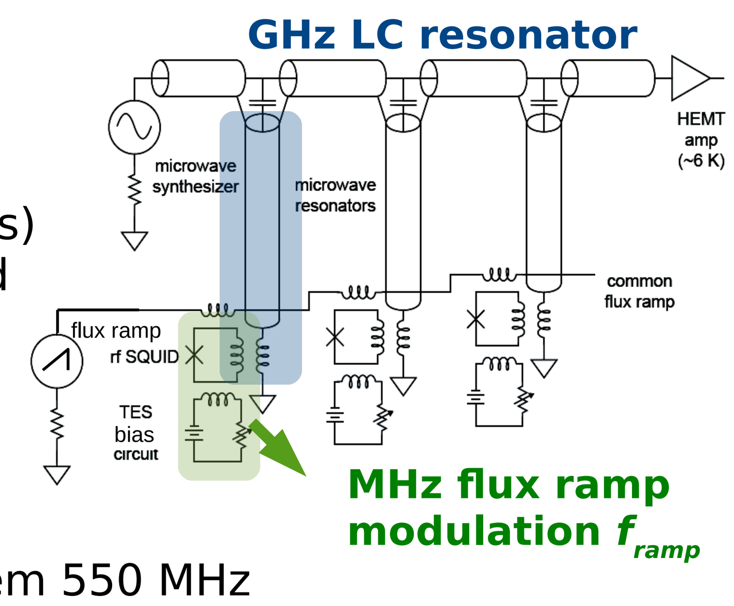


B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

Detailed information on HOLMES: A. Nucciotti's Talk

Rf-SQUID read out with microwave multiplexing

- DC biased TES
- SQUID coupled with TES and a resonator circuit
- rf-SQUID read out with flux ramp demodulation (common flux line inductively coupled to all SQUIDs)
- Signal reconstructed by homodyne detection and demodulation



Bandwidth Budget:

- Effective sampling rate is set by the ramp – f_r
- Available ADC bandwidth f_{ADC} with ROACH2 system 550 MHz
- τ_{rise} is the rise time 10-90 of a TES signal
- Mux factor: $n_{mux} = 0.02\,\tau_{rise} f_{ADC}$ ⇒ τ_{rise} = 5 μs → $n_{mux} \approx 50$

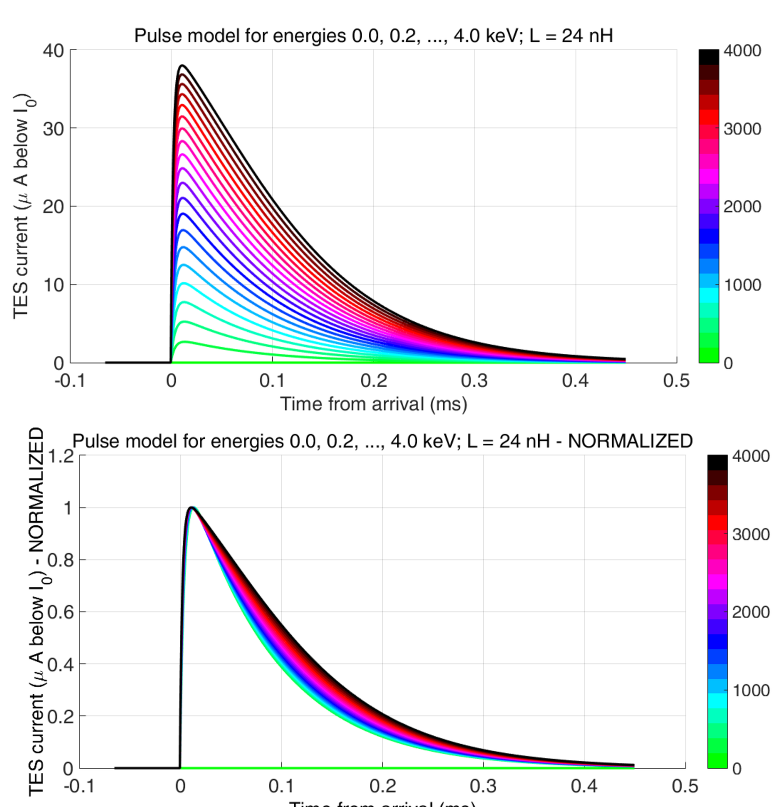
see A. Puiu's Poster

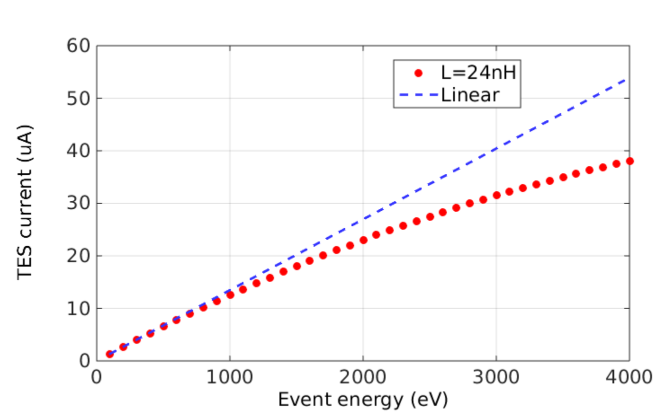
Simulations of TES response

Pulse profile: obtained by solving the two coupled differential equations (Irwin-Hilton model).
→ fourth order Runge-Kutta method (RK4)
→ the non-linearity behaviour is automatically taken into account

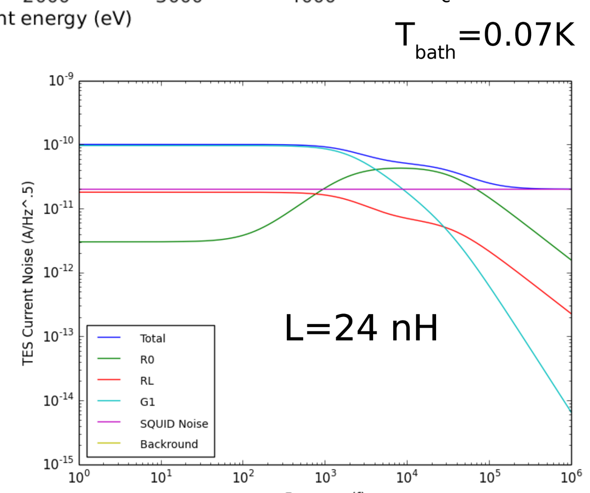
$$C\frac{dT}{dt} = -P_{bath} + P_j + \delta(t-t_0)E$$

$$L\frac{dI}{dt} = V + IR_L - IR(T,I)$$





TES parameters
n=3.25
C = 0.5 pJ/K
G = 0.4 nW/K
R_L=0.3 mΩ
R_N=10 mΩ
R_0=2 mΩ
L=24,48 nH
α_I=200, β_I=2.0
T_c=0.1K
T_{bath}=0.07K



Noise profile: thermodynamic fluctuations of its state variables (I,T) + Johnson noise of shunt resistance R_L and SQUID amplifier noise (Irwin-Hilton model).
→ double roll off from the separate roll-off of the Johnson noise and thermal fluctuation noise

Pile-up discrimination

Simulation of sets of pile-up events with random time distances.

Events:
- ^{163}Ho spectrum (Q=2.5 keV) energy distribution
- $E_1+E_2 \in$ [2.4 keV, 2.6 keV]
- delay of the pile up events from 0 to 8μs
- the arrival time does not match with the sampling

ADC:
- 12 bit in a dynamic range 0-40 μA
- sample frequency of 1-2 MHz
- record length 512 or 1024 points (1/8 for pre-trigger)

Effective time resolution
- for subsequent (Δt) events with energy E_1 and E_2: time resolution $\tau_R = \tau_R(E_1, E_2)$

$$N_{pp}(E) = A_{EC}\int_0^\infty \tau_R(E,\epsilon)N_{EC}(\epsilon)N_{EC}(E-\epsilon)\,d\epsilon$$

- the fraction of pile up events $f_{pp} = A_{EC}\tau_R$

$$f_{pp} = A_{EC}T\left[1-\int_0^T \frac{dx}{T}\eta(x)\right] \qquad \tau_r = T\left[1-\int_0^T \frac{dx}{T}\eta(x)\right]$$

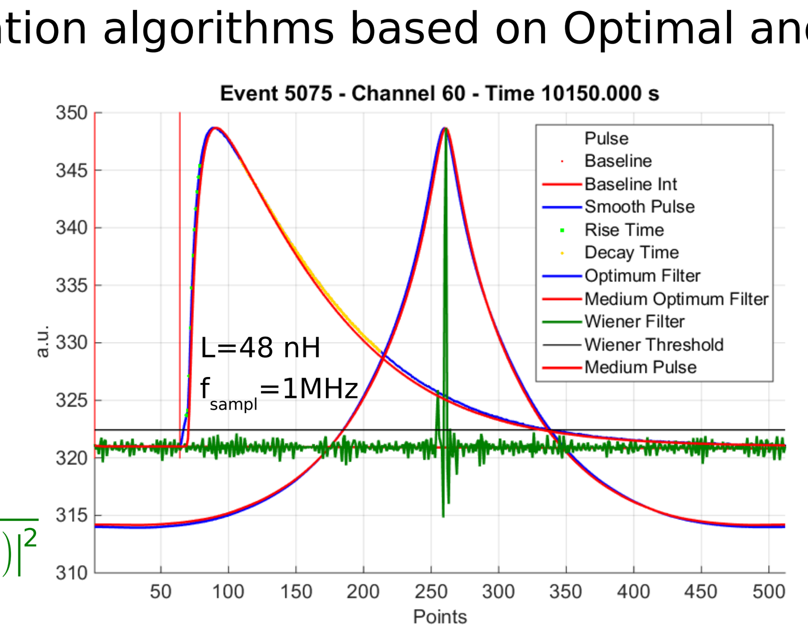
η(x): rejection efficiency (0-1)
T: the time arrival
τ_R: is an effective time resolution

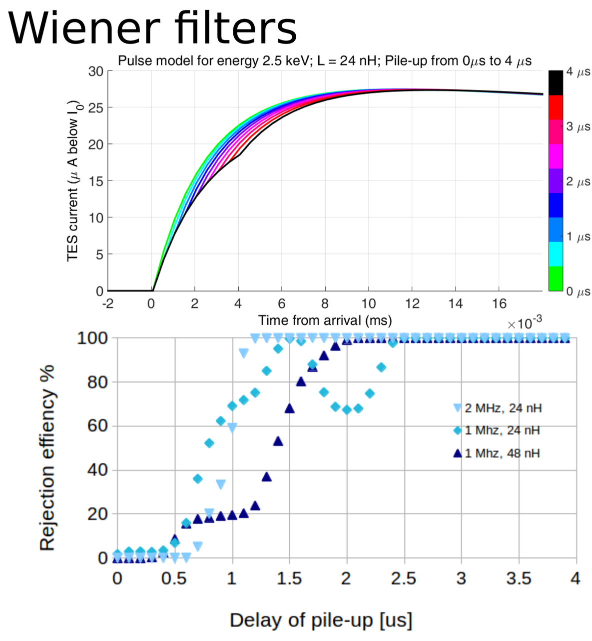
- pile-up discrimination algorithms based on Optimal and Wiener filters

signal $S(\omega)$
noise $N(\omega)$

$$H_{OF}(\omega) \propto \frac{S^*(\omega)}{N(\omega)}$$

$$H_{WF}(\omega) \propto \frac{S^*(\omega)}{|S(\omega)|^2+|N(\omega)|^2}$$





L	τ_{rise}	f_{sampl}	reclen	OF test: τ_{eff}	WF test: τ_{eff}	ΔE @ 2047 eV
[nH]	[μs]	[MHz]	[sample]	[μs]	[μs]	[eV]
24	2.3	2	1024	1.0	0.9	1.7
24	2.3	1	512	1.8	1.0	3.0
48	4.5	1	512	4.2	1.3	2.1