Thermal neutron detector principles, front end electronics and signal processing

ILL SCI group

Patrick Van Esch

Thermal Neutron Detection

- Thermal neutrons
  - Have almost no kinetic energy
  - Are neutral

  => They are essentially « invisible »

- In order to detect them, we need a nuclear reaction with energy liberation

Thermal Neutron Detection

- Reaction n(He-3,p)H-3 + 0.77 MeV   (300 ppm)
- Reaction n(Li-6,alpha)H-3 + 4.79 MeV (7.8%)
- Reaction n(B-10,alpha)Li-7 (+ gamma) + 2.79 MeV (20%)
- Reaction n(U-235,fission) + ~100 MeV (0.7%)
- Reaction n(Gd-157,Gd) e- 0.182 MeV (15.7%)

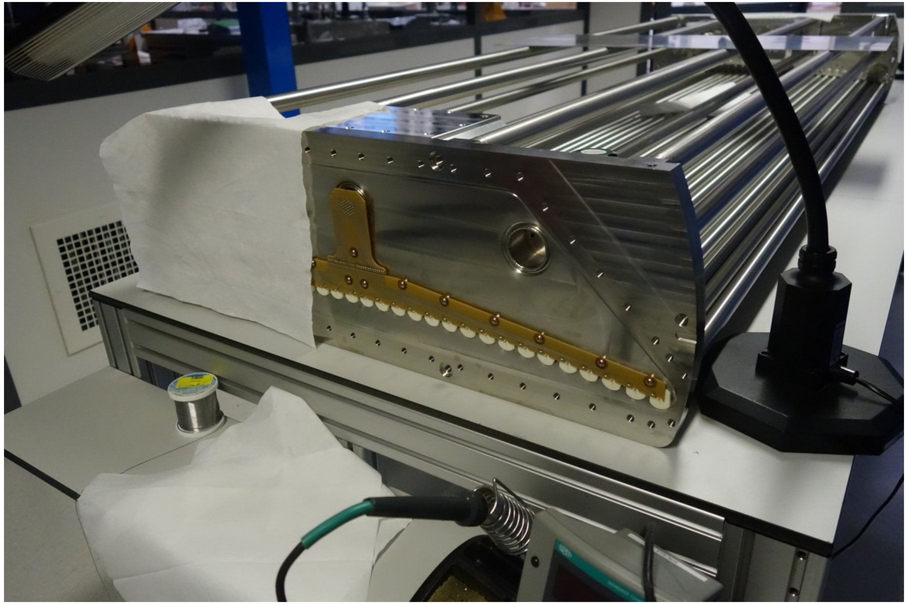
Thermal Neutron Detection

- Heavy ions after conversion (except Gd-157)
  - Ionisation in gas (track ~mm)
  - Excitation in scintillator (track ~micrometer)
  - Injection from layer or bulk in semiconductor
- Detecting secondary signal (charge or light)

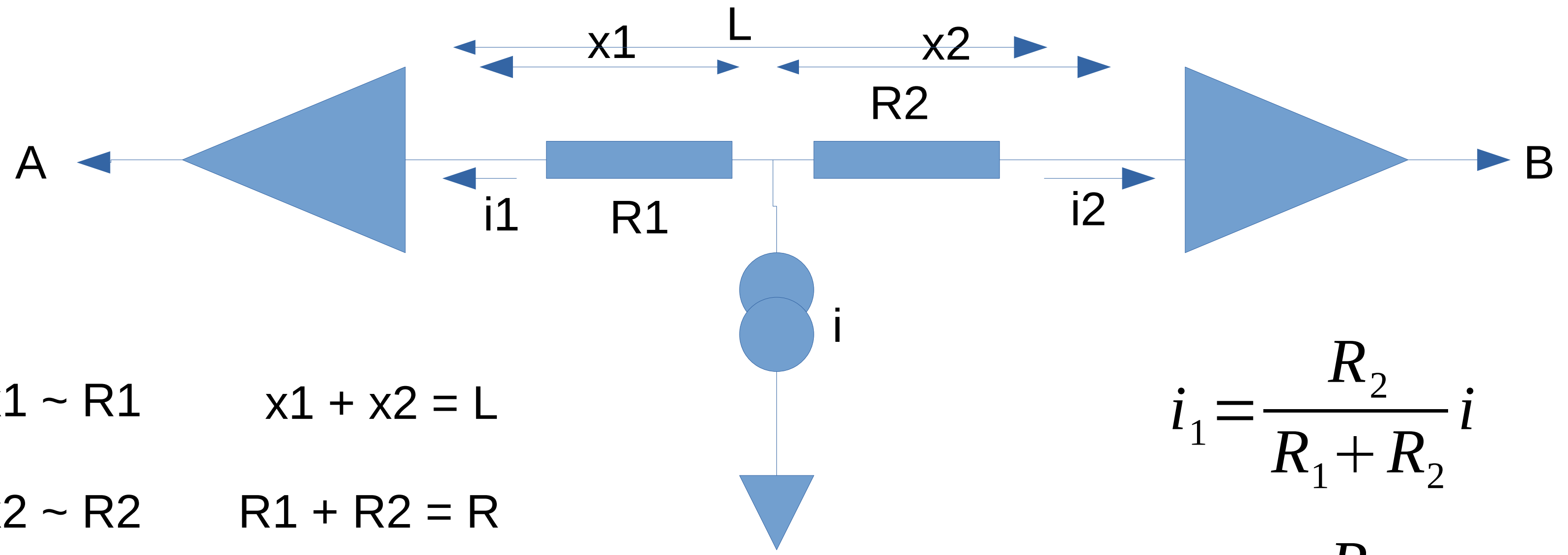
Thermal Neutron Detection 2

- Neutron beams usually have low flux density
  - Need for relatively wide beams and large samples
  - Angular resolution needs large distances
- Neutron detectors usually are
  - Big in size
  - Do not need very fine spatial resolution
- But there are exceptions…

Thermal Neutron Detection 3



Charge division : principle



x1 ~ R1 x1 + x2 = L

x2 ~ R2 R1 + R2 = R

$$i_1 = \frac{R_2}{R_1 + R_2} i$$

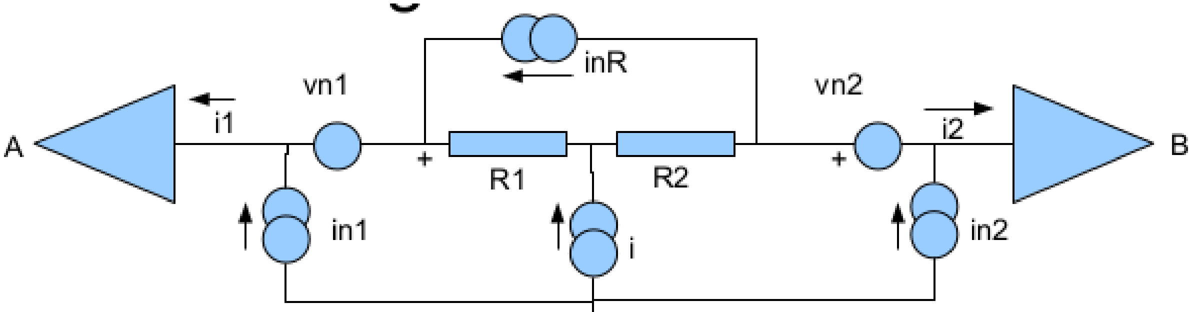
$$i_2 = \frac{R_1}{R_1 + R_2} i$$

A ~ i1

B ~ i2

$$\frac{x_2 - x_1}{L} = \frac{A - B}{A + B}$$

Charge division : theoretical noise



$$i_1 = i_{n1} + \frac{v_{n2} - v_{n1}}{R_1 + R_2} + i_{nR} + \frac{R_2}{R_1 + R_2} i$$

$$i_2 = i_{n2} - \frac{v_{n2} - v_{n1}}{R_1 + R_2} - i_{nR} + \frac{R_1}{R_1 + R_2} i$$

$$i_1 - i_2 = i_{n1} - i_{n2} + 2\frac{v_{n2} - v_{n1}}{R_1 + R_2} + 2 i_{nR} + \frac{R_2 - R_1}{R_1 + R_2} i$$

$$i_1 + i_2 = i_{n1} + i_{n2} + i$$

$$S_{min} = S_i + S_i + \frac{4}{R^2}(S_v + S_v) + 4 S_R = 2 S_i + \frac{8 S_v}{R^2} + \frac{16 k T}{R}$$

$$S_{plus} = 2 S_i$$

Charge division : theoretical spatial resolution

$$\delta_{rms} D = \sqrt{\int_{f=0}^{\infty} |H|^2 S_{min}\, df}$$

$$\delta_{rms} S = \sqrt{\int_{f=0}^{\infty} |H|^2 S_{plus}\, df}$$

$$p = \frac{D}{S}$$ Relative position from -1 to 1.

$$x = \frac{p}{2} L$$ Physical position

$$dp = \frac{dD}{S} - \frac{D}{S}\frac{dS}{S} = \frac{1}{S}(dD - p\, dS)$$

$$\delta_{rms}\, p = \frac{1}{S}\sqrt{(\delta_{rms} D)^2 + p^2(\delta_{rms} S)^2}$$

$$\delta_{rms}\, x = \frac{L}{2S}\sqrt{(\delta_{rms} D)^2 + p^2(\delta_{rms} S)^2}$$

Position resolution (1 sigma)

Time scaling and amplifier gain

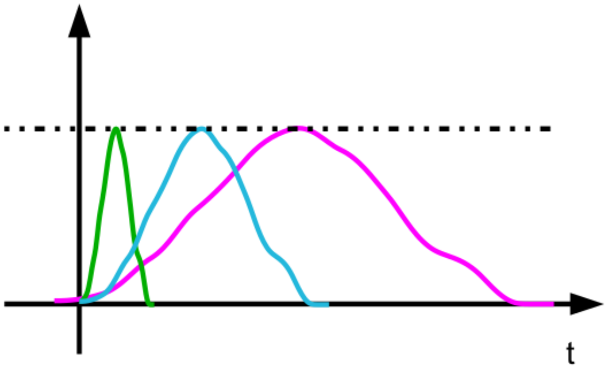
A « unit charge » will generate an impulse response of which the height is the « gain » of the amplifier chain.

Scaling the time axis (k times faster), but keeping the gain (maximum value):

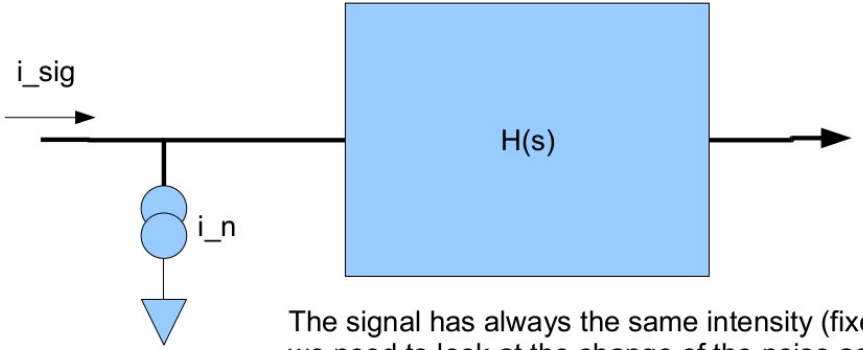
$$h(t) \rightarrow h'(t) = h(kt)$$

$$H(s) = \int_0^\infty h(t) e^{-st} dt$$

$$H(s) \rightarrow H'(s) = \frac{1}{|k|} H\left(\frac{s}{k}\right)$$



Time scaling and S/N ratio



The signal has always the same intensity (fixed gain)
we need to look at the change of the noise as a function of time scale.
Noise = RMS value of noise (to be compared with peak signal)

$$N_1 = \sqrt{\int_{f=0}^{\infty} |H(j 2\pi f)|^2 S(f)\,df}$$

$$N_2 = \frac{1}{k}\sqrt{\int_{f=0}^{\infty} \left|H\left(j 2\pi \frac{f}{k}\right)\right|^2 S(f)\,df}$$

$$= \frac{1}{\sqrt{k}}\sqrt{\int_{u=0}^{\infty} |H(j 2\pi u)|^2 S(k u)\,du}$$

f/k = u

Time scaling : S/N ratio (2)

- When k times faster, S/N ratio sqrt(k) times better
- Smallest band width lowest noise
- Shortest pulse in time lowest dead time
- => Gaussian shape
  - Is the mathematical curve with narrowest time domain and frequency domain extension

Analogue gaussian shaping

- Laplace transfer function: $e^{\frac{s^2}{4}}\sqrt{\pi}$
- Series development of inverse squared:

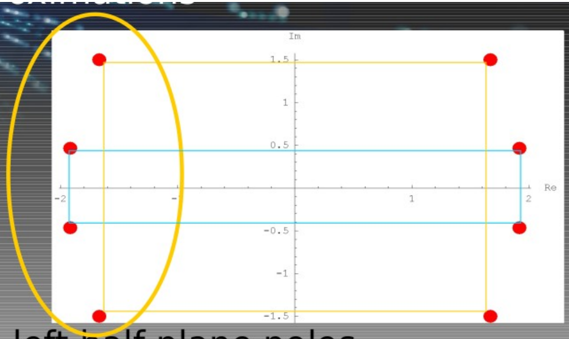
$$\frac{1}{\frac{e^{-\frac{s^2}{2}}}{\pi}} :\to \frac{1}{\frac{1}{\pi} - \frac{s^2}{2\,\pi} + \frac{s^4}{8\,\pi} - \frac{s^6}{48\,\pi} + \frac{s^8}{384\,\pi} + O[s]^9}$$

- poles:

$s \to -1.6703 + 1.4996\, i$
$s \to 1.6703 - 1.4996\, i$
$s \to -1.6703 - 1.4996\, i$
$s \to 1.6703 + 1.4996\, i$
$s \to -1.91677 - 0.463789\, i$
$s \to 1.91677 + 0.463789\, i$
$s \to -1.91677 + 0.463789\, i$
$s \to 1.91677 - 0.463789\, i$

Left Half Plane Poles

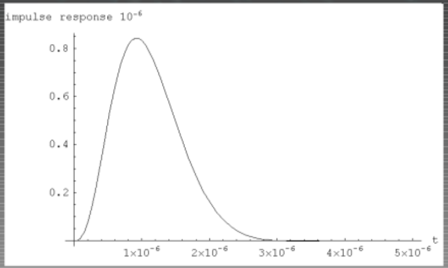
- Poles in s-plane

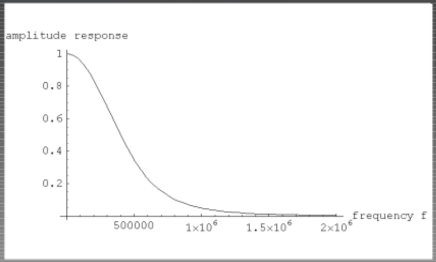


- We keep (stable) left half plane poles
- l $\frac{1}{0.56419 + 0.930182\, s + 0.62575\, s^2 + 0.206552\, s^3 + 0.0287912\, s^4}$

$$3.85699\, e^{-1.91677\, t}\, \mathrm{Cos}[0.463789\, t] - 3.85699\, e^{-1.6703\, t}\, \mathrm{Cos}[1.4996\, t] + 35.3354\, e^{-1.91677\, t}\, \mathrm{Sin}[0.463789\, t] - 10.2945\, e^{-1.6703\, t}\, \mathrm{Sin}[1.4996\, t]$$

Analogue gaussian shaping 2

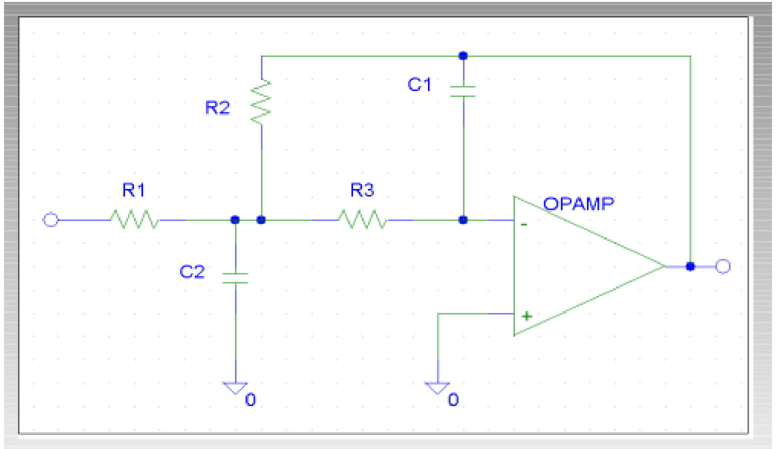




$$\frac{9.74091\times 10^{25}}{(1.1234\times 10^{13} + 4.98807\times 10^{6}\, s + s^2)\,(8.67091\times 10^{12} + 5.7241\times 10^{6}\, s + s^2)}$$

First section

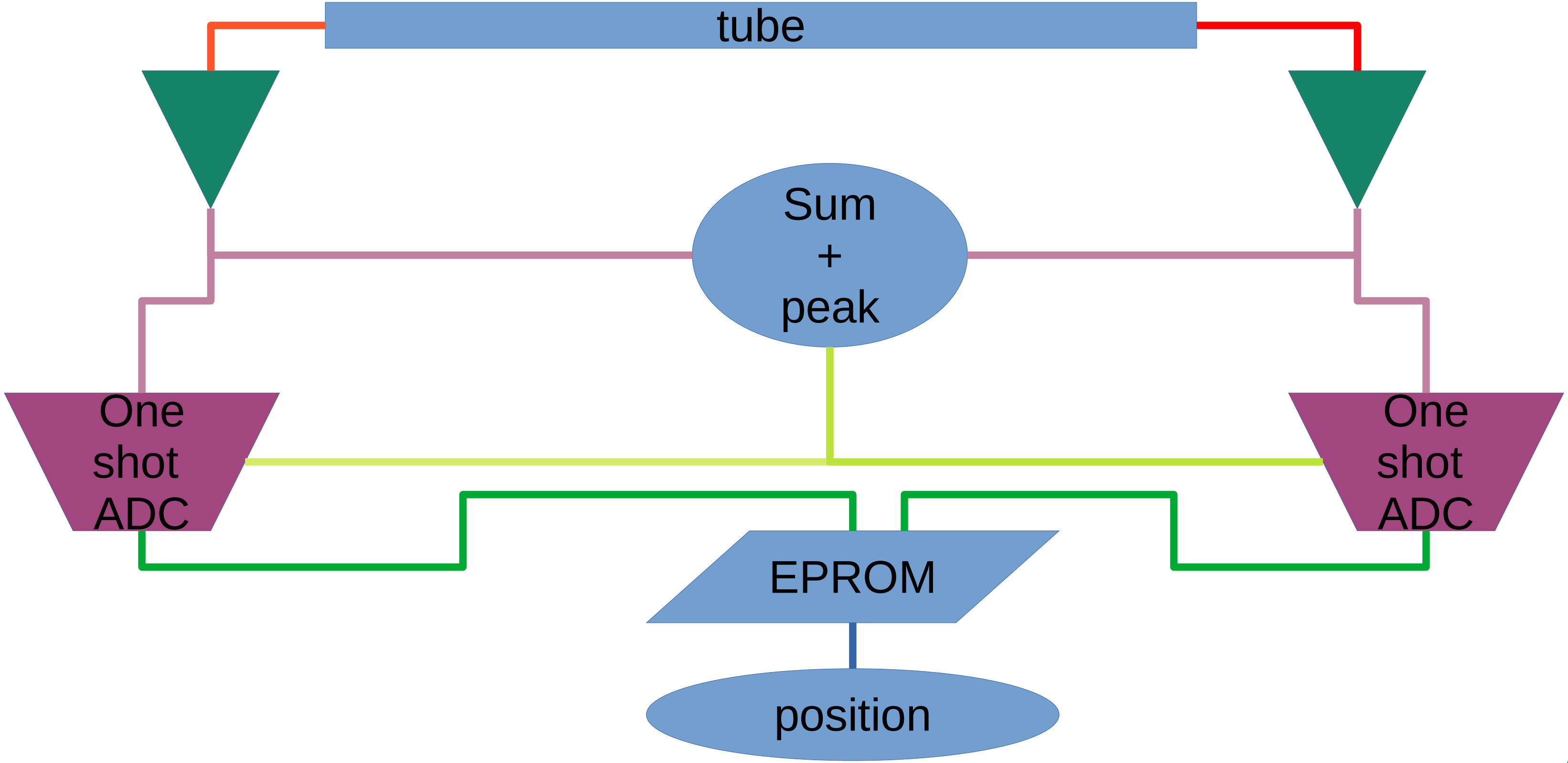
Second section



$$\frac{K\,C}{s^2 + B\,s + C}$$

$$\begin{pmatrix} R_1 \to -\frac{B+\sqrt{\frac{4\,C\,(-1+K)\,C_1+B^2\,C_2}{C_2}}}{2\,C\,K\,C_1} & R_1 \to \frac{-B+\sqrt{\frac{4\,C\,(-1+K)\,C_1+B^2\,C_2}{C_2}}}{2\,C\,K\,C_1} \\ R_3 \to \frac{2}{B\,C_2+\sqrt{C_2\,(4\,C\,(-1+K)\,C_1+B^2\,C_2)}} & R_3 \to \frac{2}{B\,C_2-\sqrt{C_2\,(4\,C\,(-1+K)\,C_1+B^2\,C_2)}} \\ R_2 \to \frac{B+\sqrt{\frac{4\,C\,(-1+K)\,C_1+B^2\,C_2}{C_2}}}{2\,C\,C_1} & R_2 \to \frac{B-\sqrt{\frac{4\,C\,(-1+K)\,C_1+B^2\,C_2}{C_2}}}{2\,C\,C_1} \end{pmatrix}$$

Overall semi-analogue readout structure



Digital implementation

- CAEN digitizer board V1740 (2007 creation)
  - 64 12-bit ADC channels @ 62.5 MHz
  - Altera Cyclone III FPGA (1 FPGA per 16 channels)
    - We asked CAEN to upgrade the Cyclone to the biggest pin-pin compatible FPGA that could be integrated in the board
    - EP3C40F484
      - 39600 LE / 126 multipliers / 126 M9K memory blocks
- Agreement to open up firmware for pulse processing

Digital implementation 2

- Very limited ressources to
  - Implement base line correction
  - Implement pole-zero correction
  - Implement 2 sections of Gaussian filter
  - Implement linear position calibration
- Hence
  - Use IIR implementations
  - « outsource » divisions

Digital implementation 3

IIR implementation via impulse invariance method:

$$H(s)=\frac{1}{s-s_0} \qquad h(t)=e^{s_0 t}$$

$$h_z(n)=e^{s_0 n T_s}=T_s h(nT_s)=T_s(e^{sT_s})^n$$

$$H_z(z)=\frac{T_s}{1-e^{s_0 T_s} z^{-1}}$$

$$H(s)=\sum_i \frac{A_i}{s-s_i} \quad \text{gives} \quad h(t)=\sum_i A_i e^{s_i t} \quad \text{so} \quad h_z(n)=T_s h(nT_s)=T_s \sum_i A_i e^{s_0 n T_s}$$

$$H_z(z)=T_s \sum_i \frac{A_i}{1-e^{s_i T_s} z^{-1}} \qquad s_i \rightarrow e^{s_i T_s}$$

Digital implementation 4

Our analogue (normalized with tau = 2 pi) Gaussian filter approximation:

$$H(s)=\frac{4.899}{4.899+11.42\,s+10.87\,s^2+5.073\,s^3+s^4}$$

Has 4 poles

-1.35536 +/- I 0.32795

-1.18108 +/- I 1.0604

$$\frac{1}{(1-a_1 z^{-1}+b_1 z^{-2})(1-a_2 z^{-1}+b_2 z^{-2})}$$

$$a_1=2e^{-1.355\,T}\cos(0.3279\,T)$$

$$b_1=e^{-2.711\,T}$$

$$a_2=2e^{-1.181\,T}\cos(1.0604\,T)$$

$$b_2=e^{-2.362\,T}$$

$$u[n]=i[n]+a_k u[n-1]-b_k u[n-2]$$

Digital implementation 5

Pole zero compensation:

$$H(s)=\frac{s+1/\tau_l}{s+1/\tau_s}=1+\frac{1/\tau_l-1/\tau_s}{s+1/\tau_s}$$

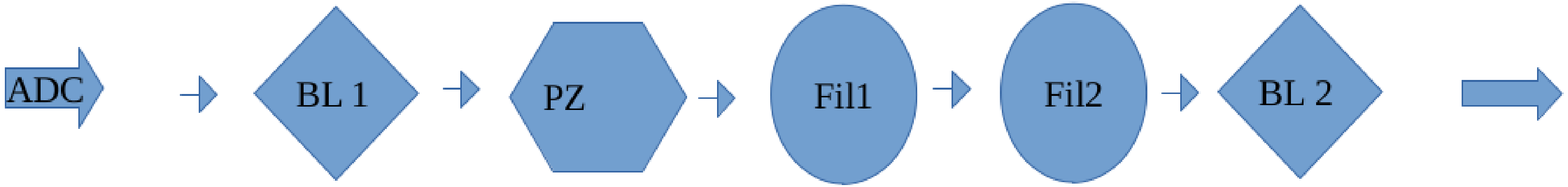
$$Z(z)=1+(T_s/\tau_l-T_s/\tau_s)\frac{1}{1-e^{-T_s/\tau_s}z^{-1}}$$

$$e^{-T_s/\tau_s}\approx 1-\frac{T_s}{\tau_s}$$

$$w[n]=i[n]+(1-\frac{T_s}{\tau_s})w[n-1] \quad \text{and}$$

$$u[n]=i[n]+(T_s/\tau_l-T_s/\tau_s)w[n]$$

Digital implementation of a channel



The channel signal treatment bloc consists of 5 elements:

1. A first baseline correction circuit, applied to the incoming signal
2. A pole-zero compensation circuit
3. A first second-order gaussian filter section
4. A second second-order gaussian filter section
5. A final baseline correction circuit

Deployment at the ILL

- D11, D22, D33
- Figaro, D17
- IN5, Panther, Sharp
- Wasp, IN12, D2B