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The Ionization-Chamber-Beammonitor I-BM for thermal and cold neutron beams

Christian J. Schmidt, 12.12.2016, CDT GmbH Heidelberg

The Ionization-Chamber-Beammonitor I-BM is a beam monitor for thermal neutrons thought as a extremely robust beam monitoring solution for extreme environments of radiation exposure and thus very limited accessibility. The device, the front-end chamber itself, needs no servicing over its lifetime. It is composed as an entirely passive device without exposed gain stage or requirements concerning operation gas or other consumables. The beam monitor is designed as an ionization chamber with ambient air as gas filling and a natural Boron coating to give it sensitivity to thermal neutrons. In the environment of application the device is, apart from neutrons, typically exposed to very high gamma dose rates. To increase the devices specificity, it is designed as an ionization chamber pair with a measurement cell and a reference cell, the former being coated with a neutron converter, the latter being uncoated and serving as a gamma dose reference in a difference measurement.

Thermal beam neutrons entering the ionization chamber will be captured by the neutron converter with a probability that depends upon the capture cross section as well as the overall thickness of the converter layer that is coated onto the ionization chamber´s electrodes. Upon neutron capture the Boron converter undergoes a nuclear reaction and disintegrates into ^{6}Li and an alpha particle, releasing a considerable amount of energy. If the converter layer is thinner than the track length of these fragments, they will enter the gaseous layer between the chamber´s electrodes and release their energy as electron-ion pairs, which can be detected. When a gaseous detector is operated with air as gas filling, practically all free electrons attach to Oxygen, Water molecules and hydrates, giving the charges an effective heavy weight and collision cross section. Their mobility of electrons is thus reduced by several orders of magnitude to values typical for ions and ionic molecules (~ 1,5 cm^2/(Vs))[1]. This effect reduces the signal rise time roughly to the time it takes for such a molecule to traverse half the ionization chamber´s gap under the applied drift field. For the drift gap of 2,2 mm and a biasing voltage of 2kV, signal rise times of 8µs and below are achieved. The ionization chamber is thus designed to resolve intensity modulations on these time scales such as they are projected for ESS neutron beam choppers.

The ionization chamber is read-out by means of a noise optimized current sensing transimpedance amplifier (TIA) that may be allocated far from the ionization chamber itself in an area that is easier accessible and not exposed to such high radiation levels. The TIA output is then digitized at a sampling rate of up to 800kHz, giving a beam-intensity monitoring signal. To optimize the signal noise level the TIA´s bandwidth is limited to about 125kHz, where 44kHz is the bandwidth needed to resolve a Gaussian pulse of 10µs duration (FWHM) (a Gaussian has a time bandwidth product of 0,44).

Difference measurement with reference cell

At the targeted and intended location of application of very high radiation levels, gamma irradiation fields could, by ionization, cause false signals in the ionization chamber. For this reason the I-BM is realized as a difference measurement between a neutron-sensitive ionization chamber and a neutron-insensitive ionization

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First Differential Mobility Analysis (DMA) Measurements of Air Ions Produced
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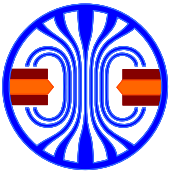2 *RAMEM S.A., Sambara 33, 28027 Madrid, Spain*

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chamber, operated sandwiching the common high voltage electrode. The neutron signal is fed to the inverting input of the TIA whereas the signal on the reference cell is fed to the non-inverting input as depicted in Figure 1. Both current signals are fed through the same impedance so that any signal generated identical (common mode) in both chambers is nulled. Only differential signals, which in this case are the neutron signals, generate a signal at the output of the TIA. The scheme simultaneously gives complete insensitivity to noise on the HV-supply, as this by symmetry appears as common mode on the amplifier´s input as well.
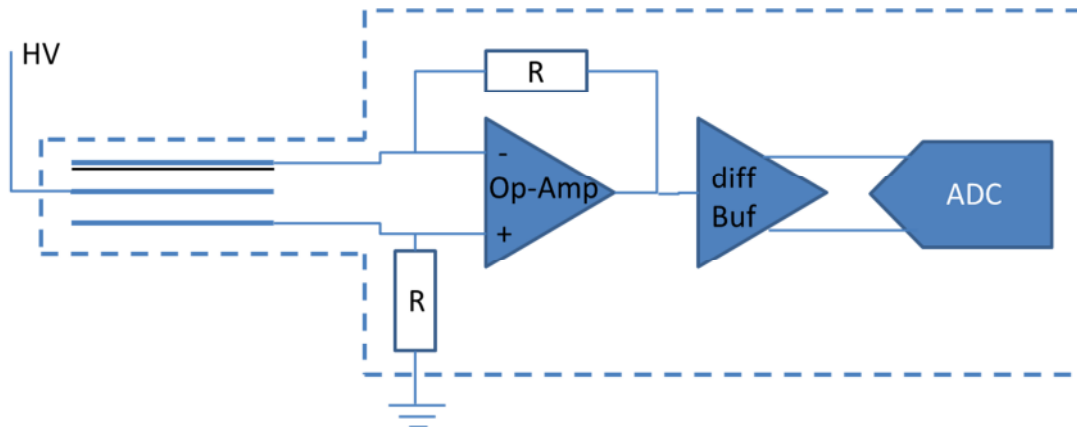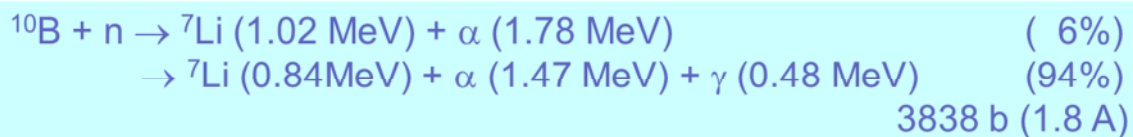

Figure 1: Schematic presentation of the ionization beam monitor I-BM. The symmetric parallel plate ionization chamber pair on the left is fed with a biasing voltage on its central electrode. One chamber has an internal coating with neutron sensitive ^{10}B converter material, the other one is left uncoated. Neutron signals appear as differential signals, whereas Gamma signals together with noise on the HV supply are common mode and thus annihilated. The device is read-out by a noise optimized TIA, limited in bandwidth to about 125 kHz and thus optimally adapted to the fastest signals of ~ 10µsec duration that are projected for ESS. Between the ionization chamber and the electronic readout a shielded cable of up to 10m length may be inserted.

Lifetime of the converter coating at ESS

For the I-BM, ^{10}B as part of natural Boron is employed as neutron converter. Upon neutron capture, Boron undergoes the following nuclear reaction:

$$^{10}B + n \rightarrow {}^{7}Li\ (1.02\ MeV) + \alpha\ (1.78\ MeV) \qquad\qquad (\ 6\%)$$
$$\rightarrow {}^{7}Li\ (0.84 MeV) + \alpha\ (1.47\ MeV) + \gamma\ (0.48\ MeV) \qquad (94\%)$$
$$3838\ b\ (1.8\ A)$$

The neutron capture cross section of σ = 3838 Barn implies that the probability for a Boron nucleus to capture a neutron and disintegrate in the neutron beam of capture flux Φ_C is $P = \sigma\ \Phi_C$. For ESS with $\Phi_{C\_average}$ up to 5 x10^9 n/(cm^2 s) for the unchopped macro pulses with typical beam divergence (see below), this probability amounts to 2 x 10^{-11} s^{-1} . In other words, a Boron atom and thus the monitor´s coating will have a lifetime in such a beam of 5 x 10^{10} sec ~1600 years. But even for an allocation of the ionization chamber at a position covering much larger divergence the lifetime is still well acceptable.
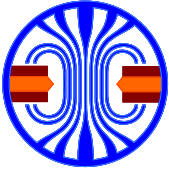
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Signal formation

Upon neutron capture the boron nucleus disintegrates into the two fragments stated above. The energy released is carried by the alpha and Li ions which are released back to back. As the converter is attached to a substrate and since only the fragments released into the detector gas can be detected, the energy deposit in the detector is a line spectrum of 4 lines with an energy of up to 1,78 MeV. These energetic ions generate electron ion pairs in the detector gas where they lose about 34eV/ion-pair generated in air. The range of these ions in air is several mm. With the ionization chambers gap of 2mm, most of the ions will deposit their kinetic energy only partially into the counting gas before they hit the inactive material of the opposing electrode. For any geometry of ionization chamber depth and coating thickness, an average energy deposit and thus charge deposit per neutron may be determined. For the example configuration of 1,2 µm coating thickness and (2,2 +/- 0,1) mm chamber depth, this average Energy deposit was computed to amount to (521 +/- 11) keV which is equivalent to a total charge deposit (positive and negative together) per converted neutron of $Q_o = 30.600$ e. The corresponding signal energy spectra are depicted in Figure 2.
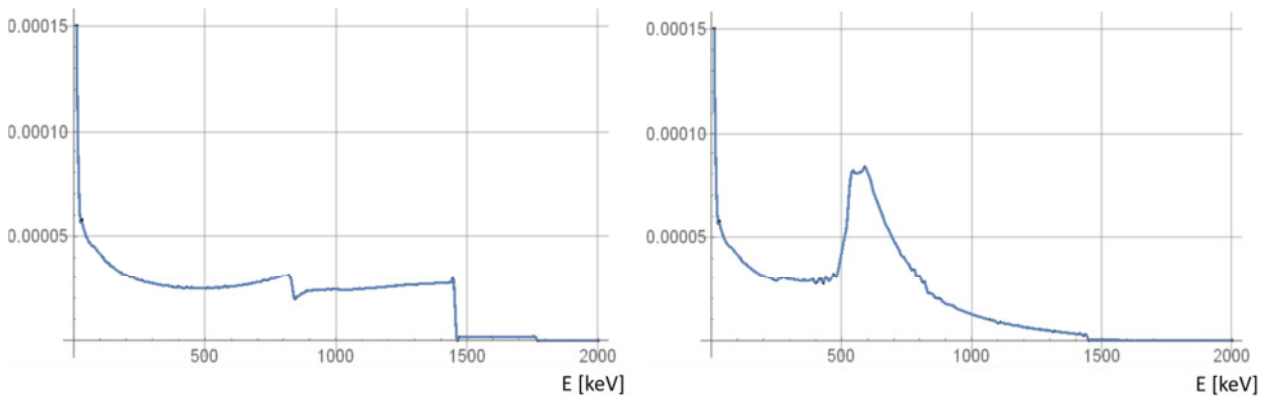

Figure 2 Computed pulse height spectra of neutrons detected in a gas detector with a 1,2 µm thick $^{10}B_4C$ converter. For very thin converter layers the energy spectrum is a line spectrum. For thick layers, it washes out to a continuous spectrum as the secondary particles lose energy in the passive converter layer on their way from point of conversion into the counting gas (left). This spectrum is further distorted if the depth of counting gas is limited to below the range of secondary ions in the counting gas. For a chamber depth of 2,2 mm the resulting pulse height spectrum is depicted on the right.

For a beam monitor, most of the neutrons will traverse the device undetected. Only a small fraction is being converted with a detection efficiency ε_n. With the prototype device presented here, the $^{10}B_4C$ converter coating was chosen comparatively thick with 1,2 µm, additionally both electrode surfaces of the chamber were coated, giving an overall detection efficiency of 3,8% for thermal neutrons. Detection efficiency for this configuration was computed and is depicted in Figure 3. A monitor device for operation at a facility like ESS would be adapted to the available flux and be equipped with a detection efficiency of about 10^{-4} to 10^{-3}, the goal being a broad dynamic range for beam intensities that can be covered with an adequate signal height.

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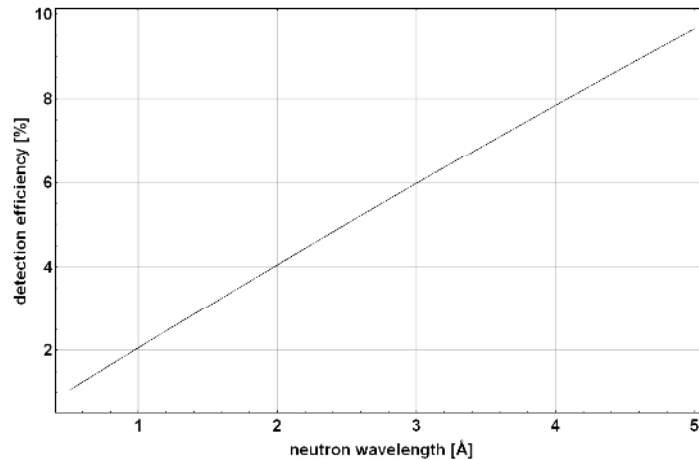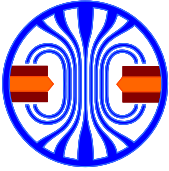Handy: +49 (0)151 613 658 20
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Figure 3 Computed detection efficiency of the beam monitor configuration with 1,2µm thick $^{10}B_4C$ converter coatings on both electrodes.

With these numbers at hand, the neutron capture flux Φ_C through the ionization chamber (at vertical incidence) can be computed to:

$$\Phi_C = \frac{I_{monitor}}{Q_o\, \varepsilon_n} = 5,4 * 10^{15}\frac{1}{s}\ I_{monitor}[A] = 9 * 10^8 \frac{1}{s}\ U_{out\_TIA}[V]$$

This holds true for dry air as detector gas. With humidity present, the effective signal height is somewhat compromised. The following plot gives a calibration factor for operation in humid[2] air.
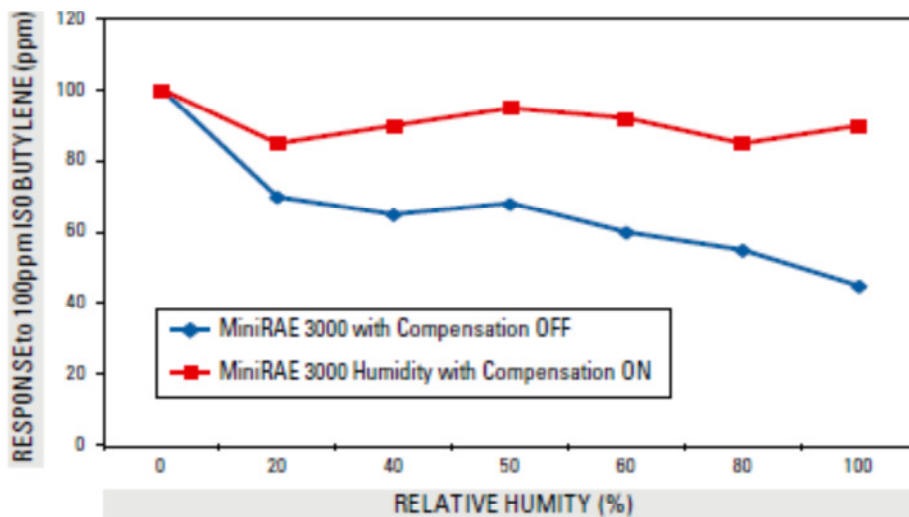

FIGURE 3.2.7(a). Effect of humidity PID response

Figure 4 The effect of humidity on detector response for detectors where electrons and ions are drifted through air. Here a Honeywell PID was studied, which however relies upon a very similar detection and charge collection mechanism as the I-BM. For typical environmental conditions of relative humidity between 40 and 60 per cent, the signal, that is the output current, is degraded to about $\beta_{humidity} \sim 2/3$ as an effect of humidity.

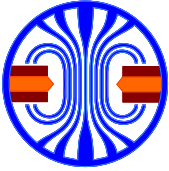[2] Technical Note TN-163 RAE Systems by Honeywell 877-723-2878 raesystems.com

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For this typical case of operation in humid air with a correction factor $\beta_{hum} = 2/3$ to the measured current, the neutron capture flux is:

$$\Phi_C = \frac{I_{monitor}}{Q_o\,\varepsilon_n\,\beta_{humidity}}$$

$$= 5{,}4 * 10^{15}\,\frac{1}{s}\frac{I_{monitor}[A]}{\beta_{humidity}} \sim 8 * 10^{15}\,\frac{1}{s}\,I_{monitor}[A] \sim 1{,}3 * 10^9\,\frac{1}{s}\,U_{out_{TIA-R=3MOhm}}[V]$$

The uncertainty in calibration introduced through the uncertainty in changing environmental conditions amounts to about +/- 7,5% over typical environmental conditions in relative humidity, atmospheric pressure and temperature, where the former clearly predominates. It is, apart from the signal rise time which is for operation in air radically slowed down by three orders of magnitude, the price that is payed for device robustness. However, even the shortest pulse durations envisioned for installations like ESS can be resolved with this device. Further, the calibration factors related to environmental conditions show time constants in the order of hours or days, which are not in the realm of what these devices are intended to monitor and serve for.

Conversely, assuming the peak capture flux projected for ESS as described below at a value of $\Phi_{C\_peak} \sim 10^{11}$n/(cm^2 s), the ionization chamber realized and described herein would generate a current of 15µA or an output signal of 90V with a 1 cm^2 beam, about an order of magnitude higher than the dynamic range. Consequently, an ESS dedicated device should be equipped with one boron layer only of about 100nm thickness and of natural isotopic mixture. Further adaptation may be realized by modification of the feedback resistance R.

Noise

The noise performance of the transimpedance amplifier TIA is optimized through the choice of input amplifier, feedback resistor, input capacitance (sensor and cable) and compensation capacitance. In effect, the amplifier output noise is constant at constant bandwidth, where bandwidth is determined by the RC of the feedback resistor and the compensation capacitor which again is directly proportional to the input capacitance. If a long operating cable is needed to allocate the active electronics in a safe place, thus introducing a large input capacitance to the electronics, then a large compensation capacitance is needed to secure stability. In order to maintain a certain bandwidth that may be needed to locally detect a pulsed neutron beam, the feedback resistance R_f needs to be adapted. In final conclusion, the signal to noise ratio at constant bandwidth is proportional to the feedback resistance R_f.
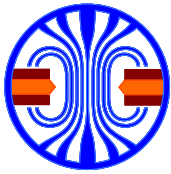
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Realization

A first realization of the Ionization-Chamber-Beam-Monitor I-BM is depicted in Figure 6. The device was built with an aperture of 70mm for evaluation purposes. The ionization chamber itself can be adapted in size to the particular application. It consists of Aluminum electrodes and ceramic or FR-4 based insulators. Each device contains two ionization chambers formed by a central HV electrode sandwiched between two current collecting electrodes and 2,2mm wide detector gaps. One of the ionization chambers is coated with isotopically enriched $^{10}B_4C$. The other ionization chamber is insensitive to neutrons as it has no coating. It serves as reference chamber to gain complete insensitivity to gamma-irradiation induced current signals. Insensitivity is achieved through complete symmetry. The ionization chambers are mounted in a housing that has shielding functions as well. It may be adapted to the particular application.
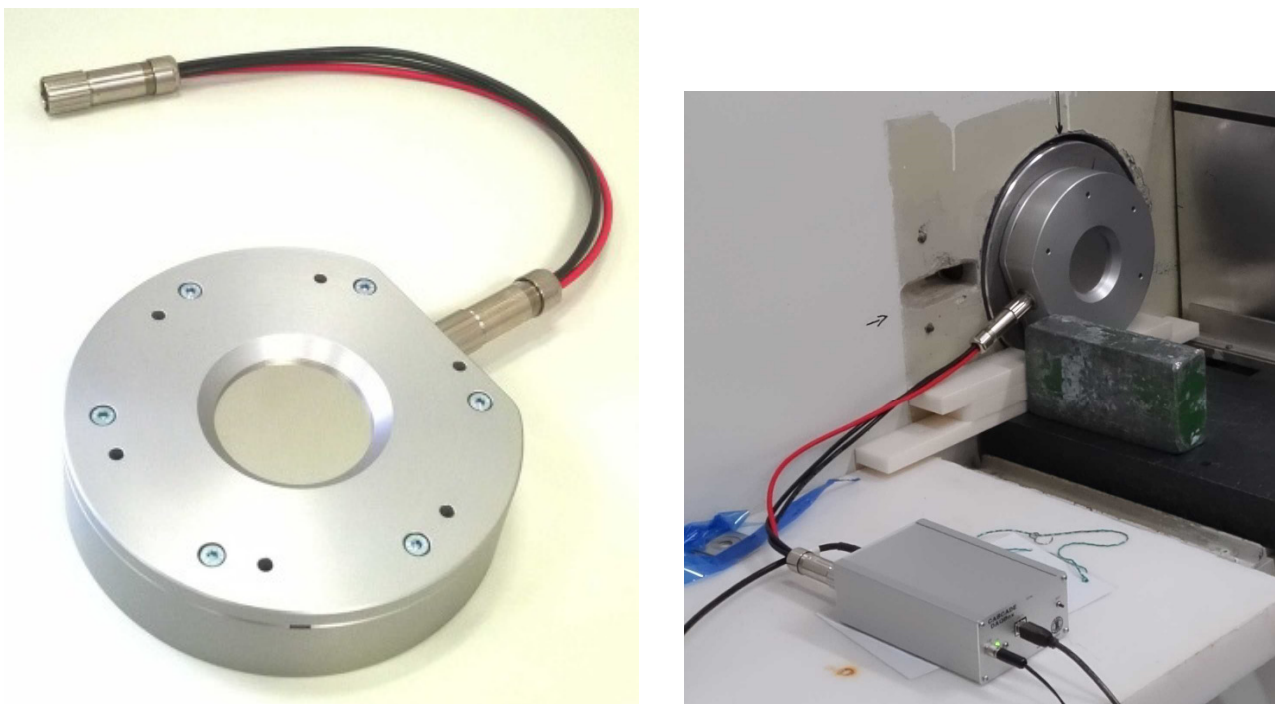

Figure 5: Left: Ionization Beam Monitor I-BM in its housing. Right: I-BM on the thermal neutron beam at the TRIGA Reactor Mainz (Johannes Gutenberg Universität, Institute for Nuclear Chemistry). The device is read-out through an adopted DAQ-Box that contains the transimpedance amplifier circuitry, ADC and DAQ electronics with USB-link.

Performance Tests

The device was tested at the TRIGA reactor in Mainz. With the similar configuration of two converter coatings of identical thickness, the conversion rate was determined in a multi-wire proportional chamber prior to the experiments with the I-BM. The beam on the thermal column of the TRIGA reactor showed a signal rate of 15,4kHz with the wire chamber at the maximum CW operating power of 100kW. With each converted neutron generating 30600 e charges, 2/3 of which are detected in humid atmosphere , this amounts to a CW current of about 50 pA, just about the targeted noise related detection limit. The TRIGA reactor may however be pulsed as well. A single pulse, where the reactor´s control rods are being shot out of the core, has a peak power of 250MW, 2500 times higher than the highest CW power. Such reactor pulses were detected with the I-BM, one of which is depicted in Figure. 7.
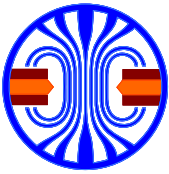
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The overall measured amplitude of the pulse was 766mV. The full integrated energy of the reactor pulse was determined by the operators to 9,86 MWs, corresponding to the area of the pulse. This calibration then results in a measured peak reactor power in the pulse of 246 MW, a factor of 2460 higher than ordinary CW operation. At a CW power of 100kW, a CW detection rate of 15,4kHz was determined as stated before. Consequently, a current of 2460 x 50pA = 123 nA must have been detected in the peak, corresponding to 743mV, giving an impedance U_{out}/I_{in} = 6,0 MΩ, very well in accordance with the TIA feedback resistance of 3,0 MΩ together with the additional voltage gain of 2 of the subsequent buffer to the ADC of the electronics employed.
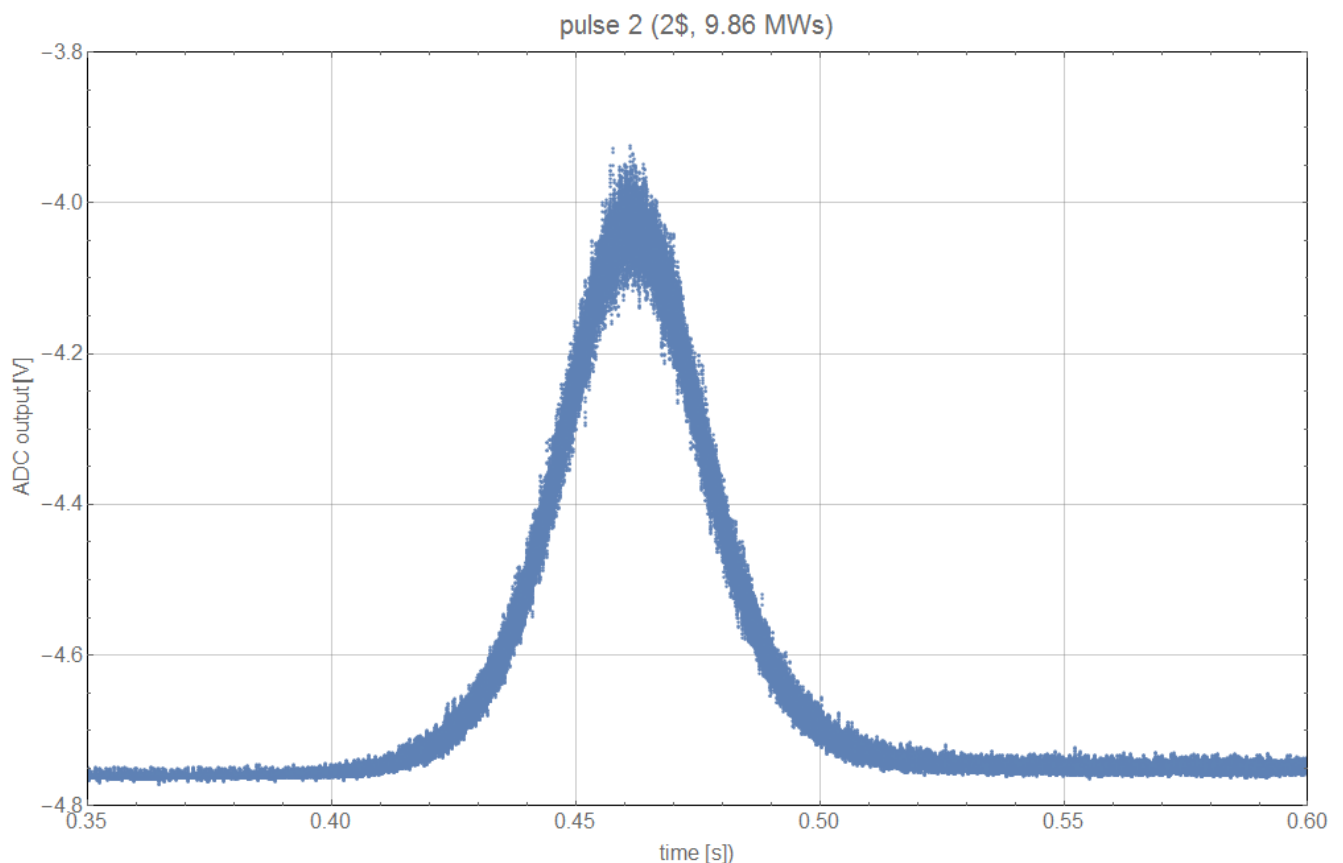

Figure 6: One of two pulses of the TRIGA reactor measured with the prototype I-BM. The reactor operators determined a full pulse power of 9,86 MWs. Taking the full pulse energy for calibration, the pulse peak power as measured with the I-BM device amounted to 246 MW. The width of the pulse was measured to be 34,1ms FWHM. Both results are consistent with the reactor´s specifications. The current was sampled at 702kHz sampling rate, the signal is offset at -4,75V to fully exploit the dynamic range of the electronics for the unipolar signal. Some pick-up oscillations were revealed in this measurement and allowed to improve the shielding as well as the internal powering scheme of the electronics.

The TIA output voltage signal was recorded with an 18bit ADC at 702kHz sampling rate. Such high sampling rate was chosen to avoid spurious high frequency noise to fold back into the bandwidth of the signal and the monitor itself, targeted at around 125kHz.

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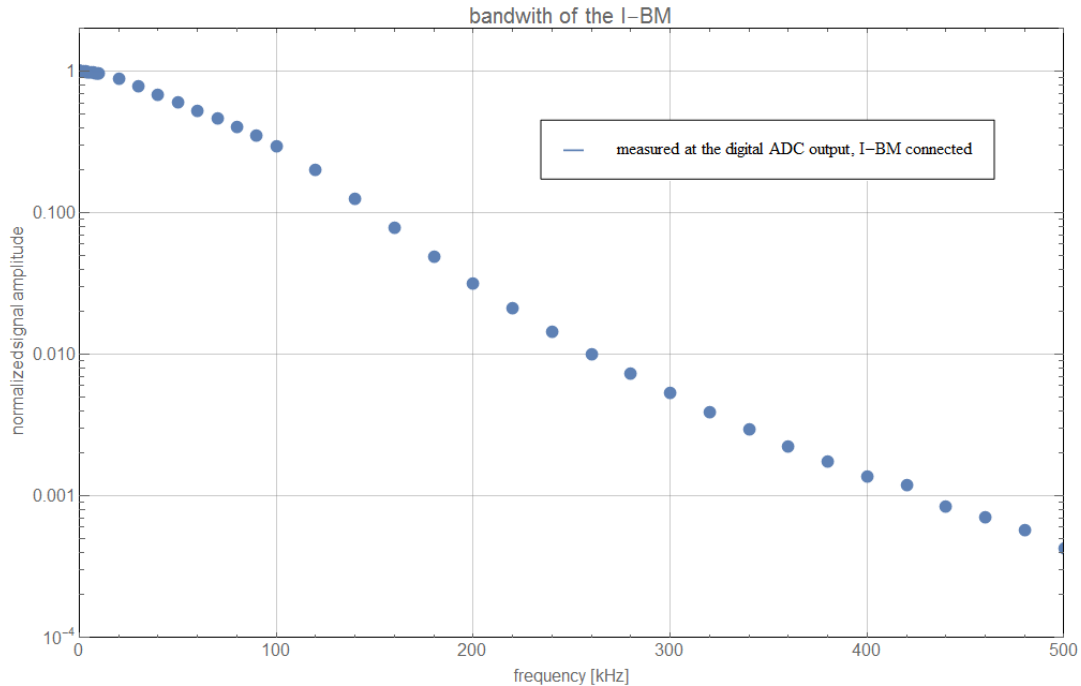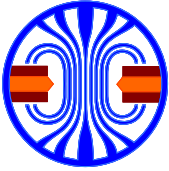Handy: +49 (0)151 613 658 20
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Figure 7: Study of the bandwidth of the I-BM transimpedance amplifier electronics with the concrete setting of 1,5 pF compensation and 3MΩ feedback resistance. Even with the beam-monitor capacitance connected to the input of the amplifier, a 46kHz bandwidth is achieved. Higher bandwidth may be achieved with lower transimpedance R_f. The rapid drop of the transfer-function beyond 100kHz is due to the Sullen-Key 3-Pole Filter employed and tuned to 125kHz bandwidth.

During these tests, it became apparent that the setup tested showed some pick-up signals of discrete frequencies, which could be abolished through an improved shielding of the device as well as through changes in the powering scheme of the electronics.

The overall integrated output continuous noise voltage amounts to $\Delta U = 272\mu V$ RMS, quite well in accordance with the projected noise level for the particular choice in input capacitance and feedback resistance. The corresponding input noise is $\Delta I = 45pA$. The ADC binning amounts to $76\mu V$. Thus, in principle, the feedback resistance of the TIA could be reduced down from 3 MΩ by a factor of 3 to 1MΩ. With such a feedback resistance the noise level is about matched to the ADC binning, so that the dynamic range is maximized to full 18 bits. Also the bandwidth can then be increased by an equivalent factor of 3 to beyond 100kHz.

The signal rise-time performance of about 10µs could not be shown in these tests due to a lack in sufficiently fast neutron beam intensity variations. Such tests could be performed on a chopped beam with a fast chopper such as projected for the instrument POWTEX or future ESS instruments. The bandwidth measurement shown above proves timing performance consistent with electronics.

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Figure 8: Measured pulse responses with a 10µs rectangular electronic pulse stimulus and 45 kHz bandwidth (upper), as well as 135 kHz bandwidth (lower). Both pulses have the same FWHM of 10µs. With one give sensor and cable setup the bandwidth was adapted through the choice of feedback resistor R_f (3MΩ and 1MΩ).

Targeting 100kHz bandwidth, the following steps and conclusions need to be taken:

1. For stability, $C_{Det} < 263\ C_f$ otherwise, oscillation will occur
   (the factor depends upon the amplifier device)
2. $R_f = 2\pi\ C_f\ Bw$, where Bw is the targeted bandwidth
3. The output noise of the TIA is roughly constant at constant bandwidth, so refered to the input we find:
4. $S/N \sim R_f$

Thus, for a concrete application with concrete cable capacitance between sensor and electronics, the electronics needs to be adapted in terms of compensation and bandwidth. Noise and S/N then result from these parameters. These issues are application specifics that need no change during operation.

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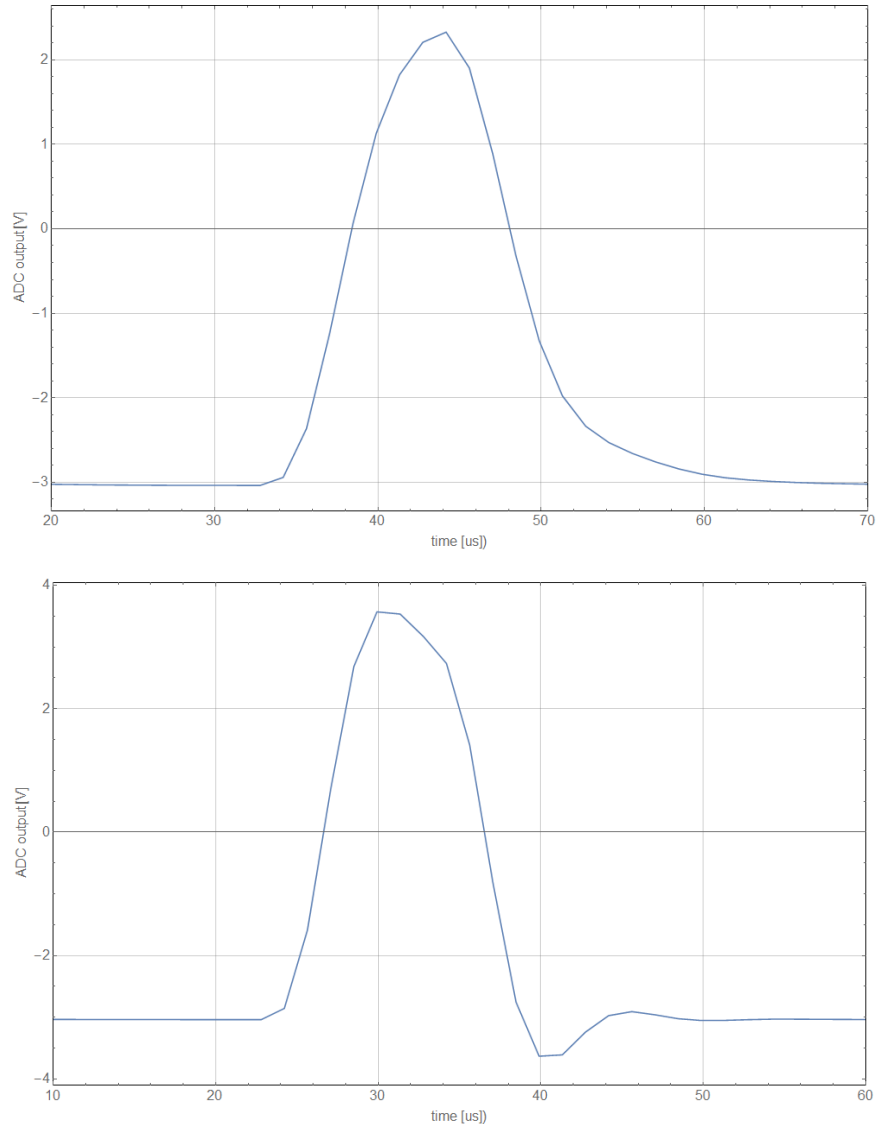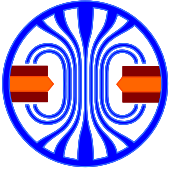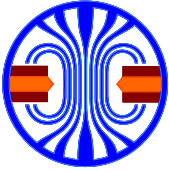Dr. Martin Klein,
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The projected ESS pulse beam intensity

The beam brilliance as projected for the ESS long pulse is depicted in Figure 8. The quantity plotted is the source brightness $d^2\Phi/(d\lambda\ d\Omega)$. The quantity measured with a gray detector ($\varepsilon \ll 1$) is however the capture flux Φ_C. The capture flux measures the neutron flux weighted by the wavelength-proportional efficiency for the detection. $\Phi_C = \int(\lambda/1,8\text{Å})\ d^2\Phi/(d\lambda\ d\Omega)\ \Delta\Omega\ d\lambda$. The brightness given in Figure 8 corresponds to the supposedly highest value at 1,5Å. Assuming a thermalized Maxwell distribution, the width of the distribution is equal to the wavelength at its maximum. The integral can thus be approximated to $\Phi_C = \int(\lambda/1,8\text{Å})\ d^2\Phi/(d\lambda\ d\Omega)\ \Delta\Omega\ d\lambda \sim (\lambda^2/1,8A)\ d^2\Phi/(d\lambda\ d\Omega)\ \Delta\Omega$. The angular divergence of the beam is limited by the neutron guide acceptance to about 10^{-4}sr. In conclusion, the peak capture flux transported through the guides can be computed as:

$$\Phi_{C\_peak} = 10^{-4}(1,5^2/1,8)\ d^2\Phi/(d\lambda\ d\Omega) = 1,3 \times 10^{-4} \times 8 \times 10^{14}\ \text{n/(cm}^2\text{sec)} = 10^{11}\ \text{n/(cm}^2\text{sec)}$$

For the average capture flux, this value needs to be multiplied by the duty cycle of the neutron pulses, which for ESS will be 4% with the pulse length of 2,86ms and 14Hz repetition rate, so that

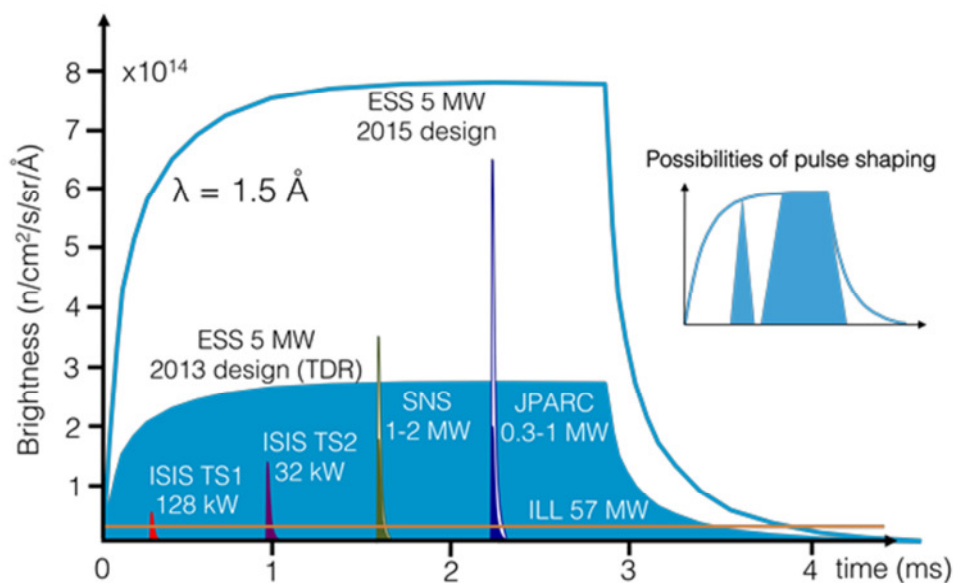$$\Phi_{C\_average} = 4 \times 10^9\ \text{n/(cm}^2\text{sec)}.$$

Figure 9 Projected ESS pulse structure as published[3]. The macro pulse has a duration of 2,86 ms and is repeated at 14 Hz, giving a macro pulse duty cycle of 4%.

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[3] https://europeanspallationsource.se/unique-capabilities-ess

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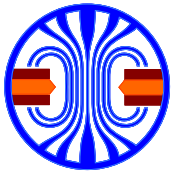Amtsgericht Mannheim: HRB 700496
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I-BM Specification Sheet

Detection principle	Ionization chamber with reference cell in difference measurement for gamma signal rejection, gain = 1	
Detector gas	ambient air	
Converter	2 x 1,2μm $^{10}B_4C$	
Chamber gap	2,2 mm	
Area	38,5 cm^2	Adaptable to needs
Minimal installation depth along beam	10 mm	Customized housing needed
Gamma sensitivity	Very low, achieved through differential measurement with identical reference chamber	
Signal	$$\Phi_C = 8 * 10^{15} \frac{1}{s} I_{monitor}[A]$$	Highest sensitivity (I_{mon}/Φ_C), adaptable within factor 25 towards less sensitivity, further adaptation through TIA sensitivity feasible
Noise	Depends on chamber and cable capacitance Cin. Cin = 20pF --> ΔI= 14 pA Cin = 170pF--> ΔI= 91 pA Cin = 2000pF --> ΔI= 1050 pA Cin / ΔI ~ 2 F/A	Adding cable length adds input capacitance. To maintain stability at 100kHz bandwidth the feedback Resistance needs to be reduced to cope with capacitance. The roughly constant output noise of the TIA translates to higher effective noise on input current and thus measured rate.
Dynamic range: Noise/max_Signal	1:2^{18} to 1:2^{17} 1:262000 to 1: 131000	Feasible after careful adaptation Noise floor level dependent upon precise configuration
Max Bandwidth	Up to 125 kHz (-3dB) limit through electronics filter,	Targeted to resolve 10μs neutron pulse, concrete application needs optimized
Maximum sampling rate	700kHz	
High Voltage	3 kV maximum	HV determines drift speed and thus signal rise time
Amplifier	Noise optimized transimpedance amplifier TIA	