Novel scintillator screens for fast neutron detection with improved efficiency

B. Walfort[1,*], M. Morgano[2], R. Zboray[2], C. Grünzweig[2]
[1] RC Tritec AG, Speicherstrasse 60a, 9053 Teufen, Switzerland
[2]NIAG, Laboratory for neutron scattering and imaging, Paul Scherrer Institut, Switzerland

Neutron imaging in short

Neutron imaging:

It was shown in the past years that Neutron Imaging (NI) has become a powerful, competitive and promising method for material research, many industrial applications and a tool for different branches in university related studies. One main reason for the progress is given by the development and application of dedicated digital neutron imaging devices in combination with scintillator screens as the backbone of the detector system. Therefore it is obvious that the performance of the scintillator screen directly influence the performance of a NI beamline.

Thermal / Cold Neutrons:

The scintillation mechanism for thermal or cold neutrons is a two step mechanism: First a core reaction with ions of high capture cross section ($^{155/157}$Gd, ^{6}Li or ^{10}B) to create a secondary radiation took place, which was followed by the excitation of a luminous material. Typically separated systems with ^{6}LiF / ZnS as absorber / fluorescence pigment or a single component system like Gd_2O_2S:Tb with Gd as the absorbing ion integrated in the fluorescent pigment are used.

Fast Neutrons

For imaging with fast neutrons a polypropylen plate filled with a ZnS-phosphor is used. The scintillation is also a two step process. First neutrons interact with the hydrogen atoms of the polypropylene plate to build up recoiled protons. Those excite the ZnS to give the corresponding detectable light (a fluorescence emission (blue to orange-red) in the optimal range of the detection system can be selected).

Light output

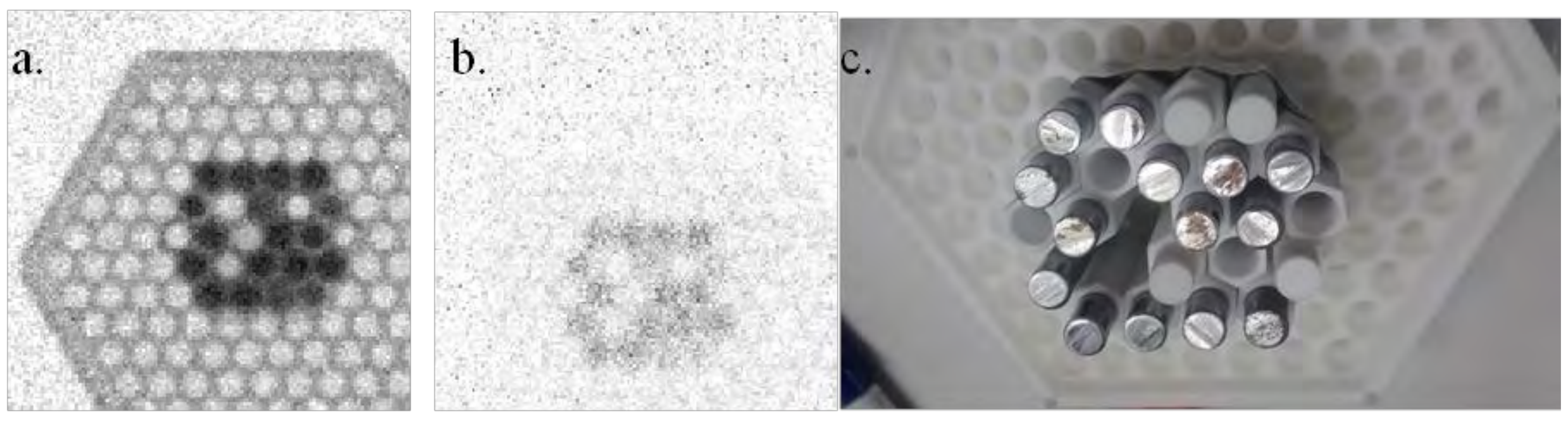
Using the ANDOR camera the FOV was ~15cm x 15cm at a pixel size of 150.75 µm. We compared the counting efficiency of the two converter screens which are shown in the table below. The imaging count rates are given in number of electrons per second, created on the CCD chip per mm^2 image area. Note that the BC400 screen is used with a mirror in front of it (looking from the beam), which reflects the light leaving into the other direction back to the camera. This essentially doubles the light collection efficiency, while it can have some adverse effect on the spatial resolution.

Imaging detector counting rates for different converter screens and detector setups at closed experimental shutter

Camera:	ANDOR	ANDOR	ANDOR	TS14
Converter screen:	ZnS+PP	BC400+mirror	BC400	BC400+mirror
Count rate total [e-/s/mm^2]	27.11	21.88	14.00	17.85
Count rate direct beam [e-/s/mm^2]	21.42	15.01	9.60	12.25
Count rate direct beam neutron [e-/s/mm^2]	19.06	13.36	8.54	10.90

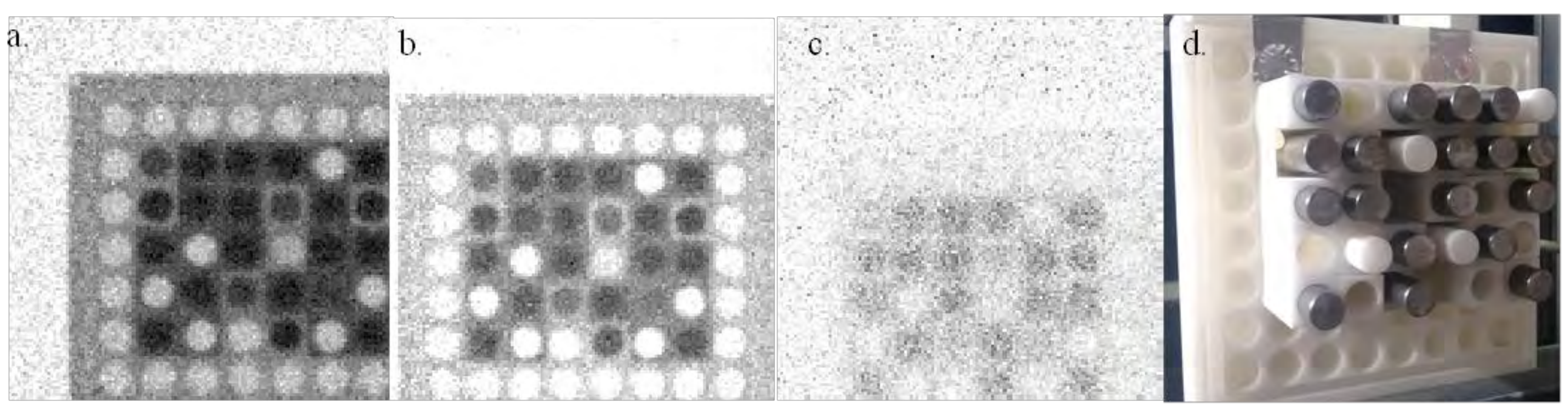
Image Quality

We have made radiographic images of different objects. The first is a mock up, which is simulating in some rough way a nuclear fuel bundle with a hexagonal lattice geometry (VVER). It consist of a 3D printed, polyamide (PA) 12, holder with holes into which steel pins, simulating the fuel pins, can be placed. Around the pins, hollow, hexagonal outer shaped, PA12 elements can be placed simulating the coolant water around the pins. The images below are showing the normalized intensity behind. The total exposure time was 3 x 120 s.



Radiographic image of a hexagonal fuel assembly mockup using the ZnS converter (a), the BC400 converter (b) and a photo of it (c). 8x8 pixel binning have been applied on the images

The next object imaged is a similar mock up as above featuring a rectangular lattice geometry. As above, the arrangement is the same, but the pin diameter is only 12 mm and the lattice pitch is 16.2 mm. The total exposure time was again 3x120 s.



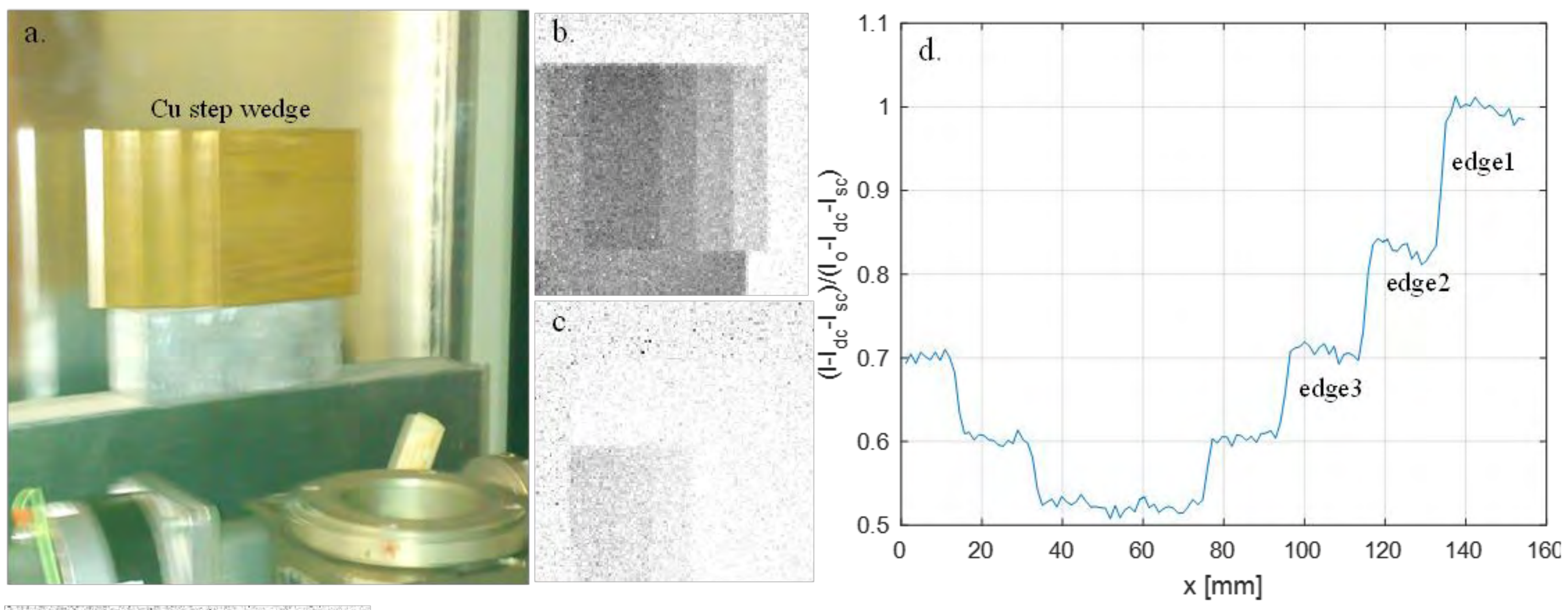
Radiographic images of a rectangular fuel assembly mockup, which is placed far (~45cm) from the detector using the ZnS converter (a), placed directly in front of the detector and using the ZnS screen (b), placed far (~45cm) from the detector using the BC400 converter (c) and a photo of it (d). 8x8 pixel binning have been applied.

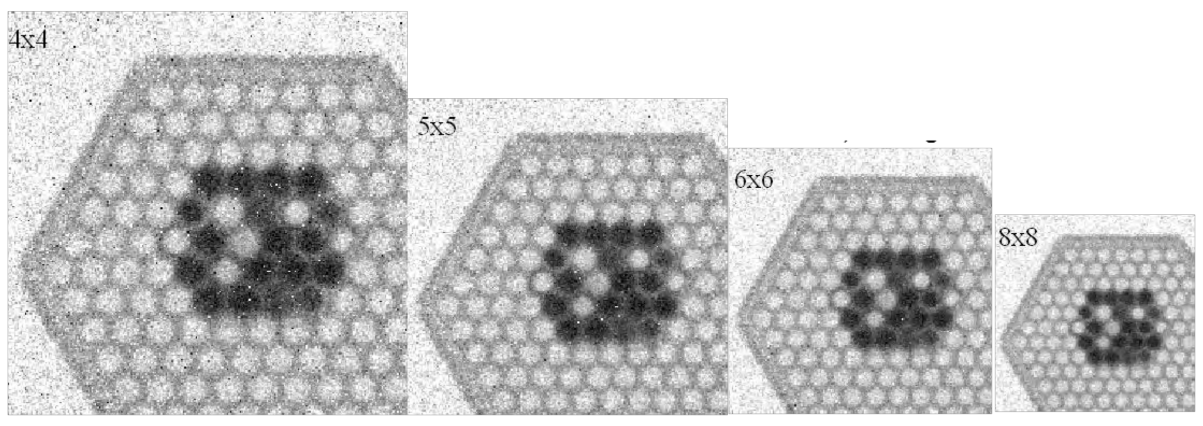
Resolution

The image resolution is estimated based on the image of a copper step wedge object placed right in front of the detector. Exposure time was 3x120 s. The step wedge profile is obtained from the ZnS image by averaging it vertically over the height of the step wedge. The edge responses, indicated by edge 1 to 3 on the figure, are fitted by a logistic (Fermi) function as:

$$ESF(x) = \beta_1 + \beta_2 / (1 + \exp[-\beta_3 (\beta_4 - x)])$$

The FWHM of the line spread function (LSF), the derivative of the ESF, is used here as a measurement for the spatial resolution and is obtained as $3.53/\beta_3$. The values are listed in the table below. The trend of worsening resolution by increasing the bin size is clear from the figures. Note that the step sizes gradually decrease with increasing material thickness to be penetrated. This is clearly due to the influence of sample scatter and beam hardening, though the latter does not play such an important role for fast neutrons as for thermal ones.





The influence of pixel binning on the resolution

Binning [pixs]	4x4	5x5	6x6	8x8
Pixel size [mm]	0.603	0.754	0.905	1.206
Res. Edge1 [mm]	1.4±0.22	1.54±0.17	1.63±0.21	1.53±0.89
Res. Edge2 [mm]	1.54±0.29	1.35±0.39	1.33±0.69	1.49±0.71
Res. Edge3 [mm]	1.69±0.22	1.46±0.42	1.63±0.61	1.92±0.61

Standard scintillation screens for neutron imaging with cold or thermal neutrons (0.12 – 100 meV):

Base material	Emission	Dimension	Thickness	Comment
^{6}LiF / ZnS:Cu (ratio 1 / 2)	530 nm (green)	up to 400 x 400 mm	50 up to 400 µm	High light output and high resolution
^{6}LiF / ZnS:Ag (ratio 1 / 2)	450 nm (blue)	up to 400 x 400 mm	50 up to 400 µm	High light output and high resolution
Gd_2O_2S:Tb	447 / 549 nm (blue-green)	up to 100 x 150 mm	10 up to 40 µm	Very high resolution
Gd_2O_2S:Tb / ^{6}LiF (20%)	447 / 549 nm (blue-green)	up to 100 x 150 mm	10 up to 50 µm	Very high resolution with enhanced intensity

Standard scintillation screens for neutron imaging with fast neutrons (>0.8 MeV):

Base material	Emission	Dimension	Thickness	Comment
PP / ZnS:Cu (30%)	530 nm (green)	up to 450 x 450 mm	2 - 5 mm	Very high light output and good resolution
PP / ZnS:Ag (30%)	450 nm (blue)	up to 450 x 450 mm	2 - 5 mm	Very high light output and good resolution

RC Tritec AG, Speicherstrasse 60a, CH-9053 Teufen; www.rctritec.com; +41 71 335 73 73; sales@rctritec.com