A pixelised detector for thermal neutrons

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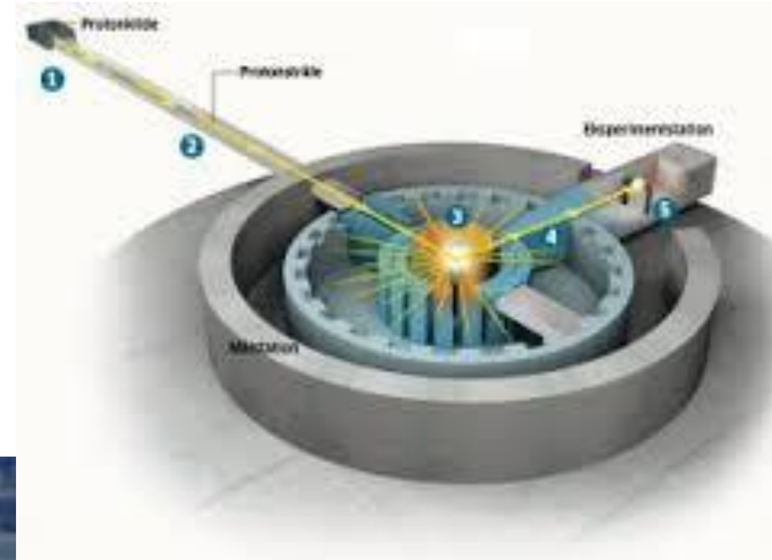
ATTRACT

Neutron beam: European Spallation Source ESS (2022)



A new generation of (thermal) neutron detectors is required:

- 2D spatial resolution
- time resolution
- efficiency
- discrimination against gammas
- rate capability
- (neutron) radiation hard

➔ granularity: pixellation, pixelisation

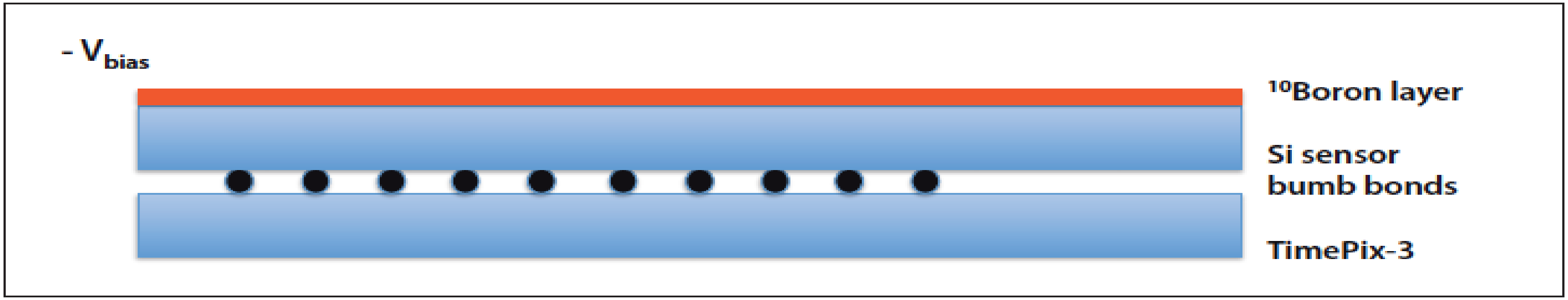
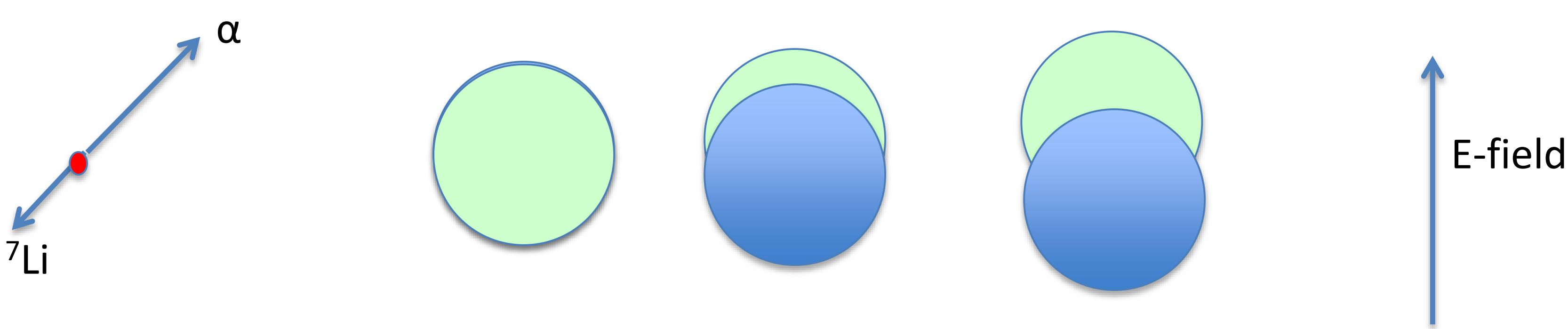


Figure 1. The TimePix-3 pixel chip with a bumb-bonded Si sensor covered with a 1μm thick layer of pure Boron, possibly enriched ^{10}B. Instead of pure B, BN or B_4C could be applied, having practical advantages.

$$^{10}B + n \rightarrow {}^{7}Li + \alpha + \gamma_{0.48MeV}$$



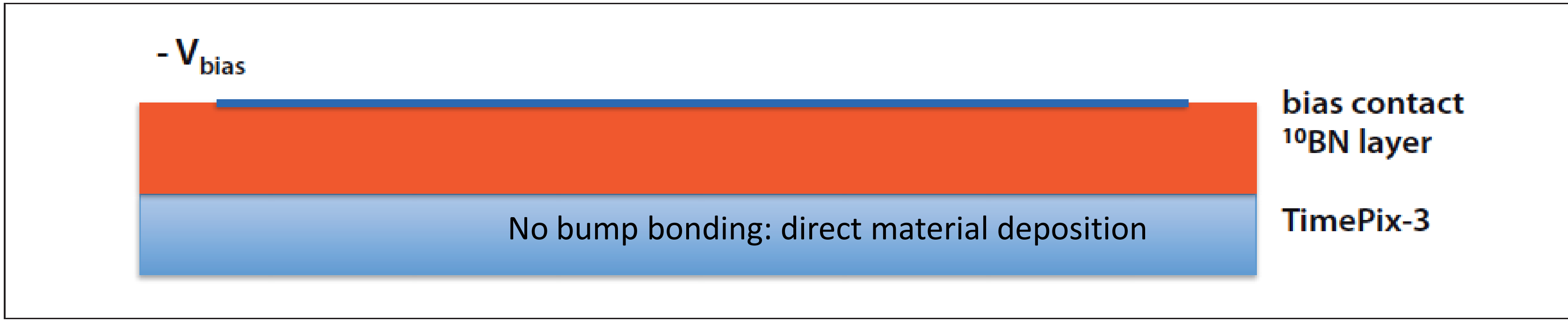
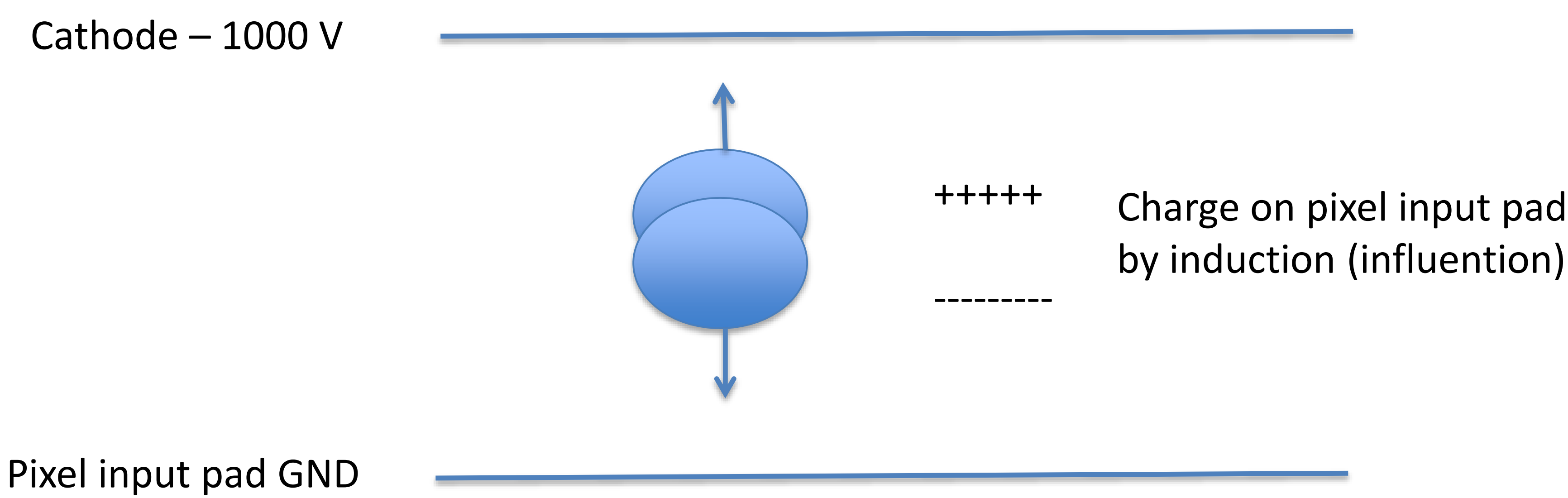


Figure 3. The TimePix-3 pixel chip covered with a 120 μm layer of ^{10}BoronNitride. The BN layer is covered with a thin conductor put at a bias potential.

- Layer of absorber/convertor material is directly deposeted onto pixel chip
- The layer is covered with a contact layer: bias e-field
- Enough charge is influenced on pixel input pad to activate circuitry
- Si pixel chip is shielded for neutron radiation by absorption/conversion layer



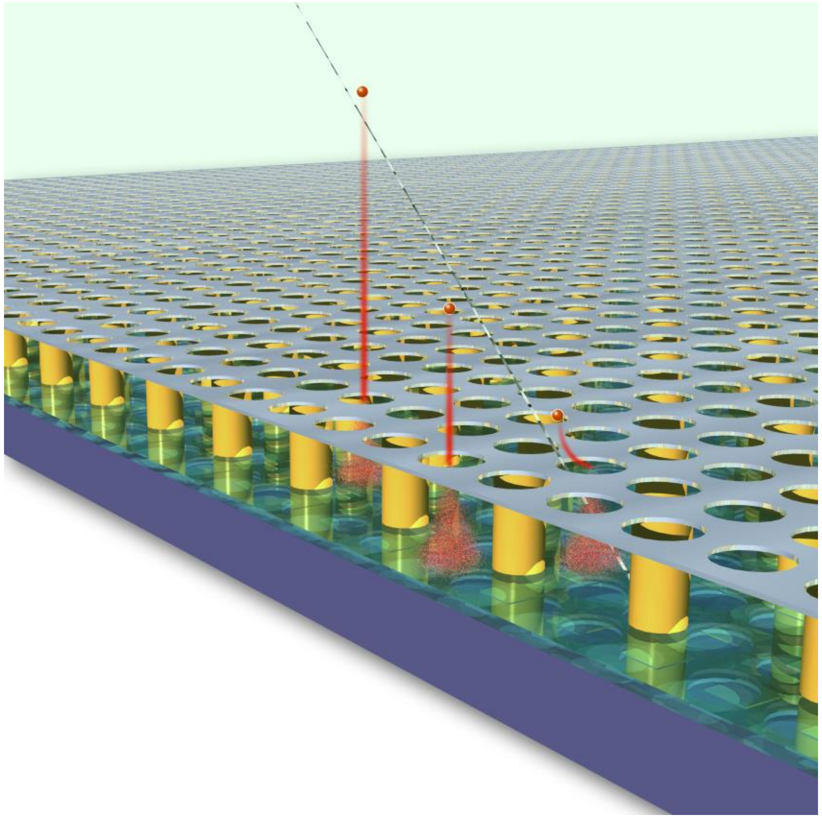
A new ^{10}B-based material with specific 'conduction' properties:

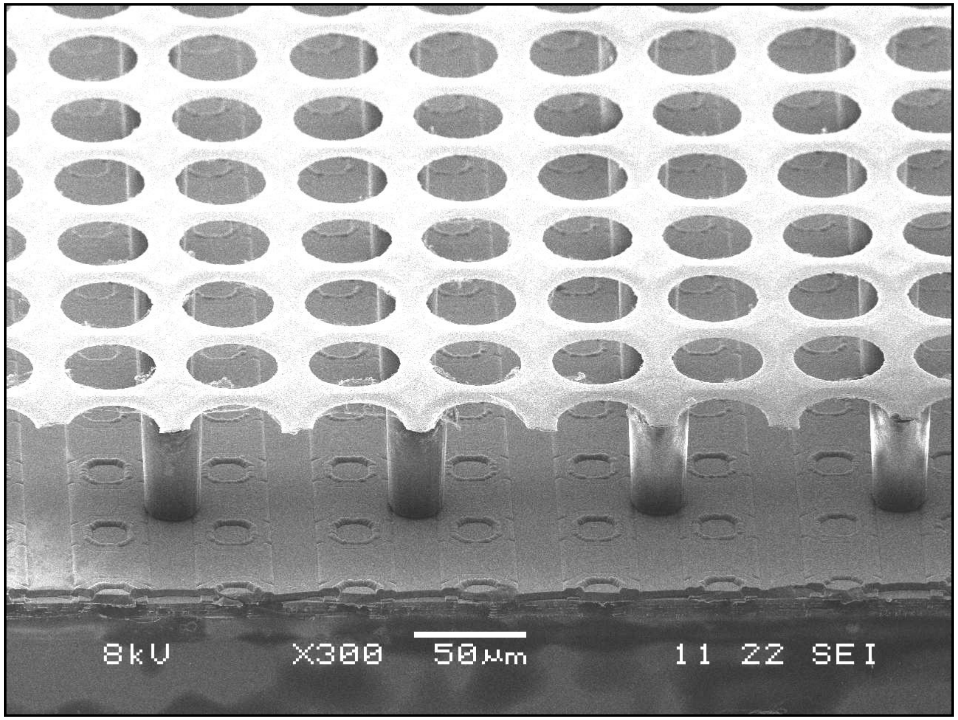
- high resistivity to avoid large bias current (source of noise)
- high level of ionisation per absorbed MeV
- sufficient e-/hole mobility
- sufficient e-/hole lifetime
- deposition of ~ 100 µm layer possible

New material in Micro Electronic Mechanical System MEMS technology
from GridPix and MEMBrane projects:

GridPix (gaseous proportional detector)

amorphous Hydrogen Si aSi_iH
Si-rich Si Nitride Si_iN_j

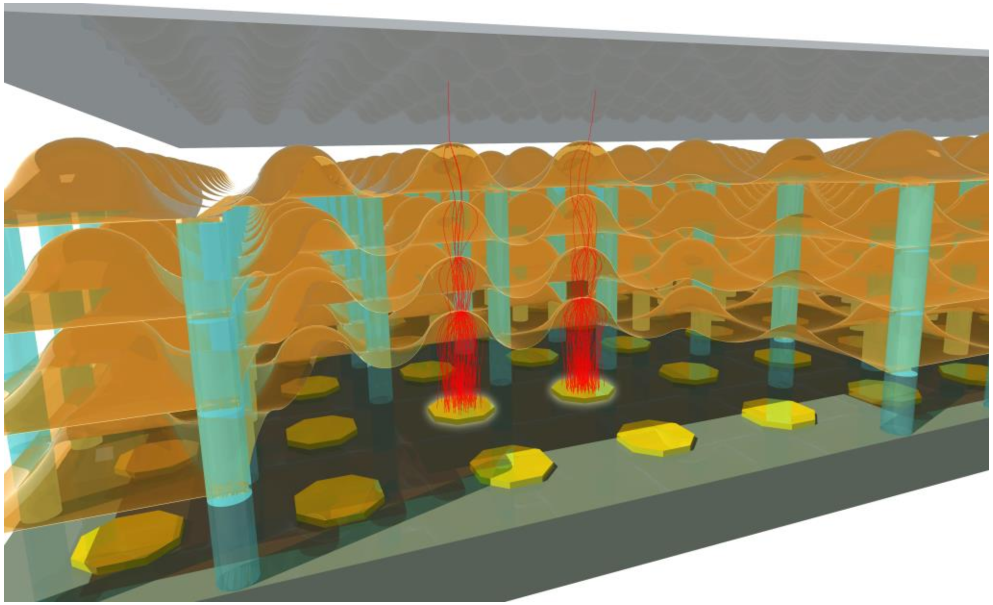


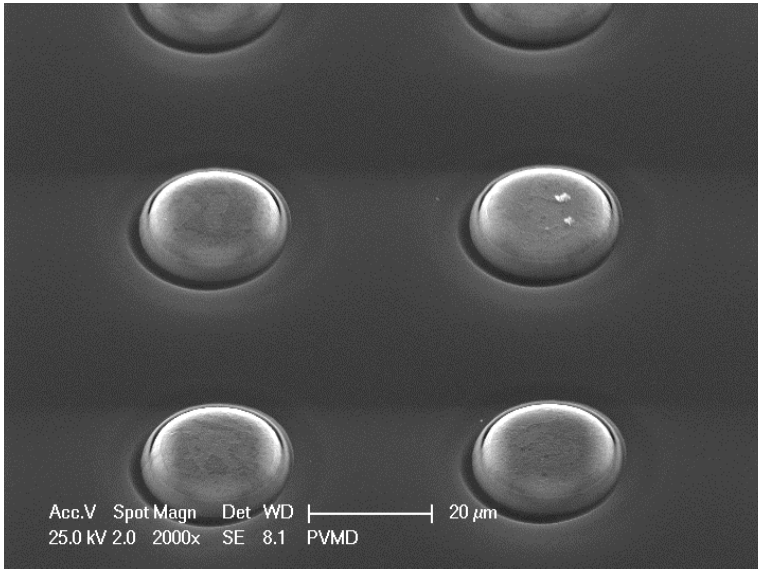


New material in Micro Electronic Mechanical System MEMS technology from GridPix and MEMBrane projects:

MEMBrane: vacuum electron multiplier: Tipsy, Trixy

SiNitride
SiCarbide
Alumina Al_2O_3





Developments in new MEMS materials:

- Chemical Vapor Deposition: Low Pressure and Plasma Enhanced:
  - LP CVD, PE CVD
  - sputtering
  - Atomic Layer deposition
    - Al_2O_3
    - MgO
    - TiN
    - BX ?

Availability of pixel chips: TimePix 3, TimePix 4, TimePix 10

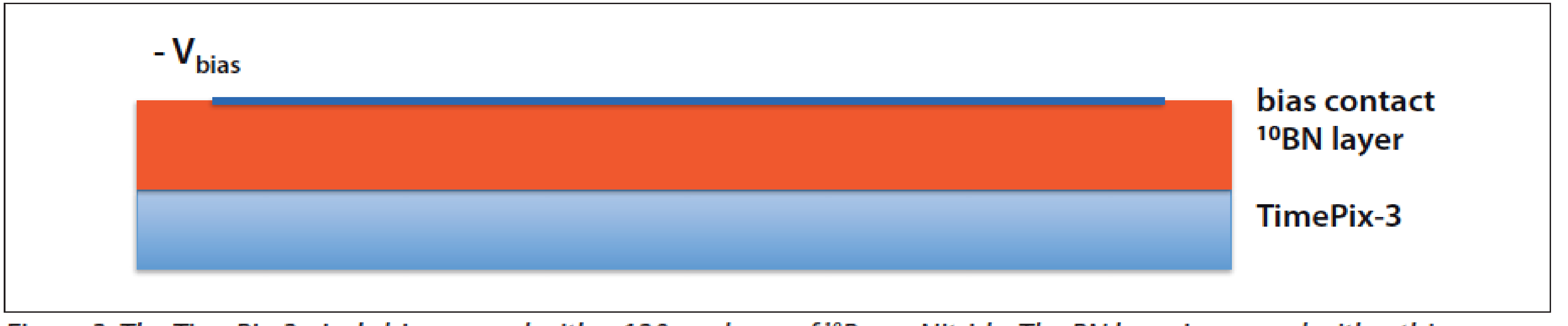


Figure 3. The TimePix-3 pixel chip covered with a 120 µm layer of ^{10}BoronNitride. The BN layer is covered with a thin conductor put at a bias potential.

For a 95 % efficient detector we need a layer of 120 µm BN

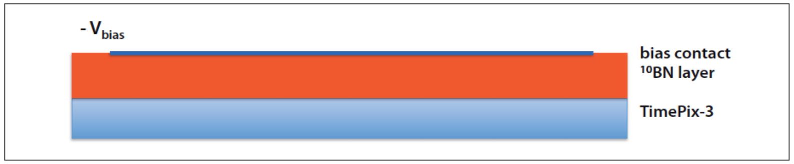


Figure 3. The TimePix-3 pixel chip covered with a 120 µm layer of ^{10}BoronNitride. The BN layer is covered with a thin conductor put at a bias potential.

If a suitable material would be found:

- 2D spatial resolution:	arbitrary
- time resolution	down to 40 ps
- efficiency	if thick layer: 95 – 99 %
- discrimination against gammas	yes: pulseheight discrimination
- rate capability	yes: TPX-3
- (neutron) radiation hard	yes: Si shielded by sensor

The starting point for the pixelised detector will be the TimePix-3 pixel chip [1], which is the latest incarnation of a generic chip widely used in radiation detectors (see Figure 1 & 2) and was developed at CERN. In order to be used as a charged particle detector, the TimePix-3 chip must be covered by a bump-bonded pixelized Si layer. If the passage of an ionising radiation creates electron-hole pairs in the (depleted) Si layer, a charge pulse activates the TimePix pixel circuitry and the time and amplitude of the pulse are registered.

On top of the Si we will apply a 1 µm thick layer of ^{10}B. This will absorb thermal neutrons the following nuclear reaction:

$$^{10}B + n \rightarrow {}^{7}Li + \alpha + \gamma_{0.48MeV}$$

where the energy of the ^{7}Li recoil nucleus is 0.84 MeV, and the energy of the α particle 1.47 MeV. The ^{7}Li and α particle will strongly ionise the ^{10}B in which they will be created, and with a very high probability the Si layer as well, leading to recordable charge pulses. Besides the realization of a the ^{10}B-covered Si pixel detector, Task 1.2 includes:

the realisation of an operational readout system for the TimePix-3 chip (using the available SPIDRE readout system and the FitPix TPX-3 readout system), including DAQ and chip control software;

test of the performance in terms of efficiency, noise, spatial resolution, time resolution by comparing with (Monte Carlo) simulations

determination of the sensitivity for background γ's.

investigation of ageing effects induced by radiation.

Since its advent Neutron Scattering has become a critical analytical tool for materials science leading to new scientific fundaments and the development of scientific, industrial and consumer products worldwide. The increasing demand for more and ‘better’ neutrons resulted in the planned European Spallation Source (ESS), which entered its construction phase in 2014, in Lund, Sweden. The optimum use of the advanced instrumentation of the ESS, and of the existing neutron facilities such as the European High flux reactor at the Institute Laue Langevin (ILL, France) or the spallation source ISIS (UK) require neutron detectors that outperform the state-of-the-art. We aim to realize a leap forward in this direction and develop a neutron detector with unprecedented performance in terms of (2D) spatial resolution, time resolution, rate capability and radiation hardness. We propose to develop a new detector based on a pixel chip, covered with a Boron-based neutron absorber/convertor. Our first choice material is Boron Nitride (BN) because of its known semiconductor properties.

Based on the results above, the next step will be to cover the TimePix-3 chip with a 120 µm thick layer of ^{10}BN (preferred, but possibly another B containing compound can be envisaged). In this layer, 94% of neutrons with a wavelength of 0.2 nm will be absorbed and the efficiency will approach 100 % for longer wavelengths. The resulting total ionisation energy of the ^{7}Li and α’s of 2.31 MeV will be deposited in a small volume (~10 µm^3) in the bulk ^{10}BN. An added conducting layer on top of the ^{10}BN will allow the application of a bias electric field, under the influence of which, ~300 k electrons and holes will move in opposite direction towards and away from the pixel input pads of the TimePix-3 chip. With a charge separation of 1.2 µm, an induced charge pulse of 6 k e– will appear on the pixel input pad, comfortably larger than the equivalent input noise (100 e–), although the initial positive and negative charge clouds will be reduced due to recombination. With an assumed electron mobility of cubic-BN of 200 cm^2/Vs and a bias electric field of 10 kV/cm, this charge pulse will be theoretically created within 5 ns. In reality, however, electrons and holes are trapped by vacancies, and crystal boundaries, which effectively slows down and limits the charge signal. Therefore the following properties of the ^{10}BN containing layer need to be taken into account to determine the detector response: band gap, determining the number of electron-hole pairs; lifetimes of electrons and holes in the conduction band; bias current as a function of bias voltage (noise); charge transport properties related to the crystal quality of the material.