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Custom Silicon Detectors To Enhance Jet Neutral Particle Analysers For DT Operations

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JET neutral particle analysers (NPA) need to operate under demanding conditions. The main difficulty is the overlap between true ion signals and neutron-induced background. We have improved the background rejection dramatically by developing thin, custom silicon detectors optimised for ion detection on JET NPAs. The detectors have a silicon-on-insulator structure with the active layer ground to only a few microns but supported by a thick substrate to create a robust detector with an active thickness of 5 μm or 25 μm initially[1] and recently down to 3 μm. Although designed for JET, these detectors could find use in other fusion machines as well.

With the first batch of detectors, the JET high energy NPA has been upgraded and its performance demonstrated in high-power DD campaigns. With 5 μm detectors, there is essentially no overlap between ion signals and background, and with 25 μm detectors the signal and background are better separated due to improved pulse-height response. With the second batch, the aim is to upgrade also the low-energy NPA. We will also discuss MCNP results on the anticipated performance in DT conditions.

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1. JET neutral particle analysers

Neutral particle analysers are unique diagnostics because they are the only one capable of measuring plasma ions deep in plasma. In principle, their operation is simple: some of the plasma ions are first neutralised in the plasma, releasing them from the magnetic confinement, and these neutrals are measured after escaping the plasma. However, the analysis of neutralisation and reionisation are often challenging problems on their own. The measured signals are integrals along the line-of-sight through entire plasma.

JET has two neutral particle analysers (NPA): the high-energy NPA (KF1, Fig. 1) has a vertical line-of-sight through the plasma core. It is predominantly used for measuring fusion products and RF-accelerated ions. For hydrogenous ions it can operate typically from 250 keV to 1-1.5 MeV and up to 3 MeV for helium ions. The low-energy NPA (KR2) has a horizontal, radial line-of-sight through the plasma core. It can be configured for various energy ranges starting from 5 keV up to 750 keV for hydrogen. It is ultimately intended for the measurement of the plasma isotope composition profile, however, achieving this has proven rather difficult due to the highly non-thermal ion population present in typical JET plasmas.

Both JET NPAs have a similar operating principle: neutrals escaping the plasma are first re-ionised by a thin carbon foil (40 nm), then dispersed spatially; first in momentum by a electromagnet followed by a transverse deflection by an electrostatic field separating different ion species. Ions are detected by a set of detectors arranged as a single row in KF1 and three rows in KR2. KF1 needs to be tuned to specific ion species whereas KR2 detects all hydrogenous species simultaneously. As ion species and energies are dispersed spatially, the ion detectors effectively only act as counters.

As there is generally little need for spectroscopy, detectors have so far been thin CsI(Tl) scintillators coupled to photomultipliers (PMTs), with highly nonlinear response. However, some

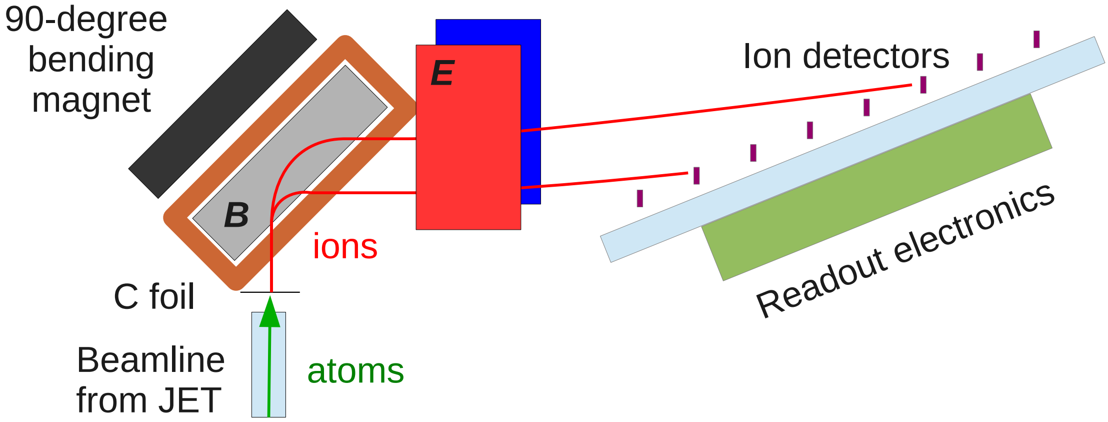

Figure 1: Schematic view of the JET high energy NPA KF1. Neutrals enter the diagnostic along a vertical beamline, are ionised by a thin carbon foil, bent through 90° by an electromagnet, and off-the-plane by electrostatic plates. Finally, ions enter a detector chamber with detectors lined along an angled flange. Readout electronics are mounted directly on the air-side of the flange.

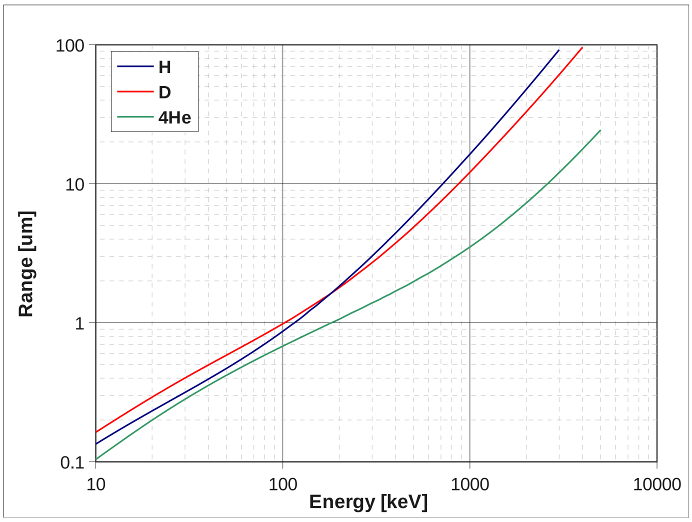

Figure 2: Range of hydrogenous and helium ions in Silicon, derived from tables in SRIM[3].

spectroscopic performance is desired in practice. First, discrimination between ions and neutron-induced background is essential. Second, the electromagnetic dispersion is unable to separate ions with equal charge-to-mass (q/m) ratio, like deuterons and alphas. The ability to measure both separately is important for DT operations. The CsI(Tl) detectors also suffer from slow response (3 μs decay constant) and PMT stability issues. These factors have led to the enhancement projects to develop custom Si detectors for the use in NPAs.

2. Custom silicon detectors

The use of silicon detectors for NPAs to improve the performance has been proposed long ago. However, commercially available detectors are typically much thicker (order of 100 μm) than the ion ranges at the relevant energies (Figure 2). At the typical energies, the necessary detector thickness is only a few μm. The excess detector volume is only harmful by detecting background and increasing the effects of radiation damage; another problem with commercial detectors.

The issues with commercial detectors and access to semiconductor fabrication facilities at VTT/Aalto Micronova[2] led to the development of custom detectors aimed for JET NPAs with potential use of ITER also kept in mind. To match the ion range with the active detector volume while producing mechanically robust detectors, Silicon-on-Insulator (SOI) structure was chosen (Figure 3). These are manufactured by bonding a high-resistivity p-type active wafer to technical grade substrate wafer and grinding the active wafer to the desired thickness. In the initial batch[1], detectors with active thickness of 5 μm and 25 μm were made, the former at the limit-of-technology and the latter close to the range of the highest energy protons.

Internally, the detectors are split into strips which act as independent sub-detectors. In the initial batch, the active area was 7 by 10 mm in 64 strips (110 μm pitch). The strips are insulated from each other by a p-stop barrier which prevents charge from spreading into neighbouring strips. Splitting the detector into strips also helps to reduce the capacitance and drastically reduces pile-up.

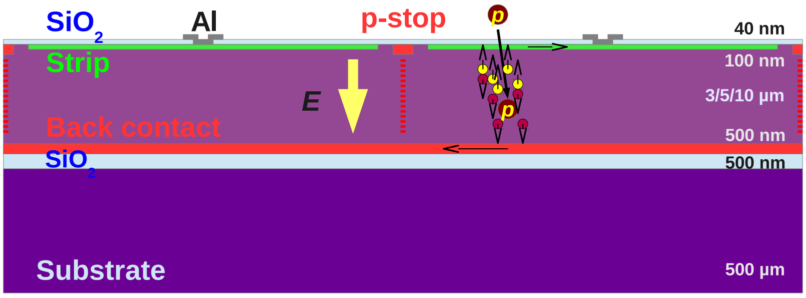

Figure 3: Schematic structure of the SOI thin ion detectors.

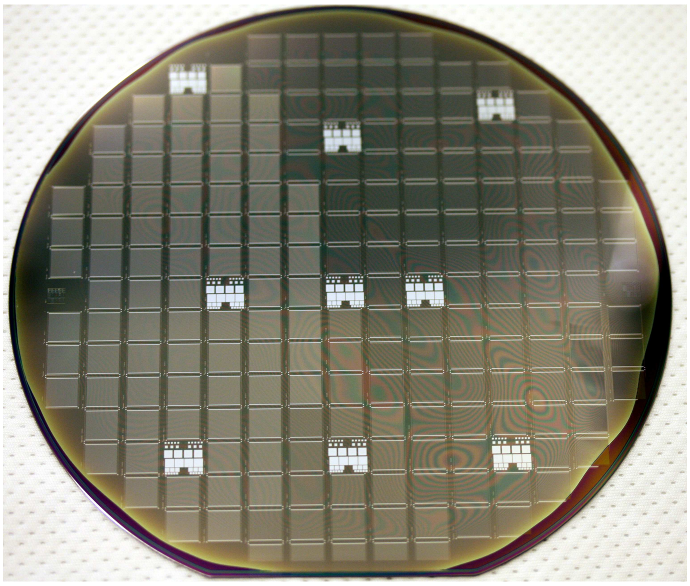

Figure 4: Completed wafer of the recent batch. Note the interference fringes visible in front of the wafer, these are caused by minute thickness variations of the top layer. In addition to detectors there are test structures at different radii.

If high capacitance and pile-up can be tolerated, strips can be read-out in parallel. In NPAs the strip structure is not needed for spectroscopic purposes. However, in other applications these detectors could possibly be used as linear profilers for ions, low-energy X-rays or optical emission.

In the second batch, just completed, the detector size has been changed to 7 by 7 mm in 32 strips (Figure 4). These are aimed for the low-energy NPA, so emphasis has been on making the top layer as thin as possible. In the new batch there are detectors with 3, 5, and 10 μm thickness.

3. High energy NPA upgrade

As the first step, the JET high energy NPA was upgraded with detectors from the initial batch. With only eight detectors in a simple linear arrangement this was seen as relatively simple process.

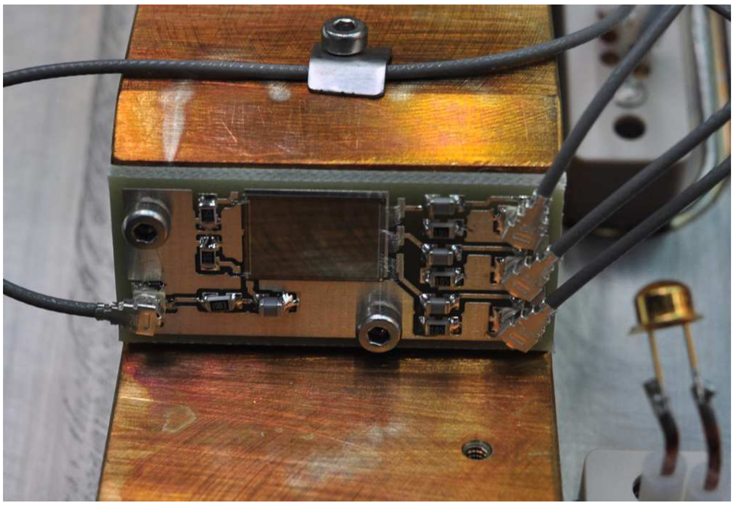

Figure 5: A 5 μm detector mounted on a printed circuit board as installed on the KF1 vacuum flange prior to installation on the machine. Hirose U-FL-series ultra-miniature connectors are used for bias (left) and AC-coupled signal connections (right). The detector is read-out as three banks of 20 strips. An IR LED for artificial excitation of the detectors is seen at lower left.

Nevertheless, the entire data acquisition chain was redesigned at the same time. As silicon detectors have no intrinsic gain (unlike PMTs) much more sensitive preamplifiers were needed.

For the two lowest energy channels 5 μm detectors were installed (see Fig. 5) and 25 μm detectors were used for the remaining six channels. To reduce complexity, the thin detectors are read-out as three bundles of 20 strips and the thick ones as a single bundle. In total, there are 12 data acquisition channels. Each channel has a preamplifier, differential line driver, twisted-pair signal transmission from the machine to diagnostics hall, and a 14-bit 2 MS/s digitiser. The signal is digitised for the entire JET pulse and the ion events are located by numeric processing afterwards.

Sample pulse-height spectra of the new detecors during a high-power JET DD discharge are shown in Fig. 6. With no internal gain, pulse-height is proportional to energy. Hence, low-energy channel Ch1 has the lowest typical pulse-height and the high-energy channel Ch8 the highest.

The thick detectors show an exponential component at low energies. This is caused by neutron-induced background, predominantly by Compton electrons and X-rays. Nevertheless, this component is well-separated from the ion signal apart from a slight overlap with Ch3. Hence, the radiation background has little impact on the analysis of the spectra.

Background rejection is even more remarkable with the thin detectors which show hardly any neutron-induced background at all. This improvement is far more than would be expected from the reduction of thickness alone because background mainly originates from particles which are not stopped by the active layer. Hence, background counts are not proportionate to active volume, but the pulse-height is roughly proportionate to thickness and the count-rate is likely independent of thickness. The thinner the detectors are, the easier it is to discriminate background from true ion events. During DT operation, the situation becomes more complex due to (n,p) and (n,α) reactions in silicon.

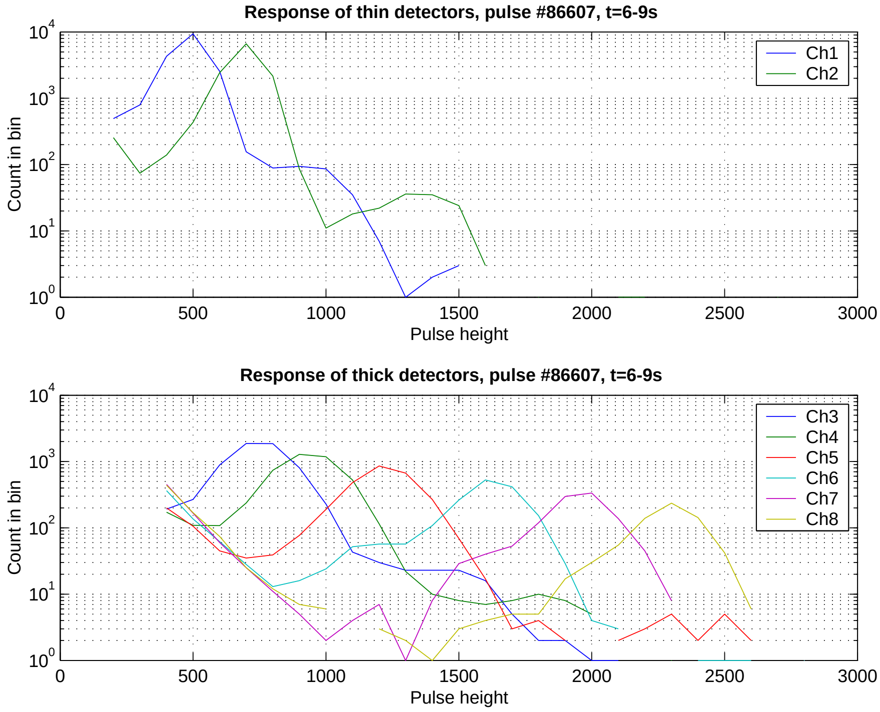

Figure 6: Time-integrated pulse-height-spectra of thin (top) and thick detectors of in JET pulse 86607 (binned data with bins of 50 ADC 'units', roughly 25 keV). At low pulse-heights, an exponential component caused by neutron-induced background is seen with thick detectors. This is nearly absent with thin detectors.

4. Low energy NPA upgrade

The excellent background rejection of the thin detectors in the high energy NPA upgrade, was a decisive factor in launching the upgrade of the low-energy NPA. This task is presently ongoing. The expected detector response has been modelled by MCNP, suggesting tolerable background even in full DT conditions. Due to the more refined mechanical structure, this upgrade is much more challenging than for the high-energy NPA. The readouts will also be implemented using multi-channel readout chips to avoid the high capacitance from paralleling many strips together.

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References

[1] J. Kalliopuska *et al.*, *A novel silicon detector for neutral particle analysis in JET fusion research*, Nucl. Inst. and Meth., Vol. **A591**, pages 92-97, (2008).

[2] See http://www.micronova.fi/

[3] *SRIM - The Stopping and Range of Ions in Matter* software available at http://www.srim.org/.