2D Hall Arrays for High Resolution Tokamak Magnetic Field Imaging

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Background

'AtomCraft' is an undergraduate student-led initiative to design, build and commission a tokamak at the University of New South Wales in Sydney, Australia. The device is a small, spherical tokamak featuring conventional magnets and relying on electron cyclotron resonance heating (ECRH), influence primarily by the Danish NORTH tokamak (which is Tokamak Energy's ex-ST40). The device has been dubbed SOUTH: Student Operated Undergraduate Tokamak with rf Heating. Unlike most Tokamaks, SOUTH's focus is primarily pedagogical. The AtomCraft project seeks to train the next generation of fusion-ready multidisciplinary engineers and physicists by engaging students in complex and impactful fusion engineering research from as early as their second undergraduate year[1].

As a student project, AtomCraft operates on an extremely tight budget, with an extremely low tolerance for risk (to ensure student safety and project viability), and the need to fundraise operating costs from philanthropic institutions and the fusion industry. This funding requirement makes producing easily communicable and exciting results a priority. The project also suffers from a tyranny of distance associated with Australia's geographical isolation from the fusion industry, which restricts access to expertise and potential collaborators. (Note: If you are reading this and work for a national lab, fusion company, university exe and want to collaborate, please reach out to us.)

These circumstances – a tight budget, a low appetite for engineering risk, and a need to produce communicable results – led to the development of the Hall array concept. This high-resolution, fast, magnetic field 'camera' can photograph the field produced by SOUTH's magnets well before the R&D has progressed towards introducing a plasma. This device will identify potential technical issues in the magnet system early, as well as assist in research and development. The device's easily digestible visual outputs can also be used for outreach, fundraising and educational purposes.

Methodology/Device Design

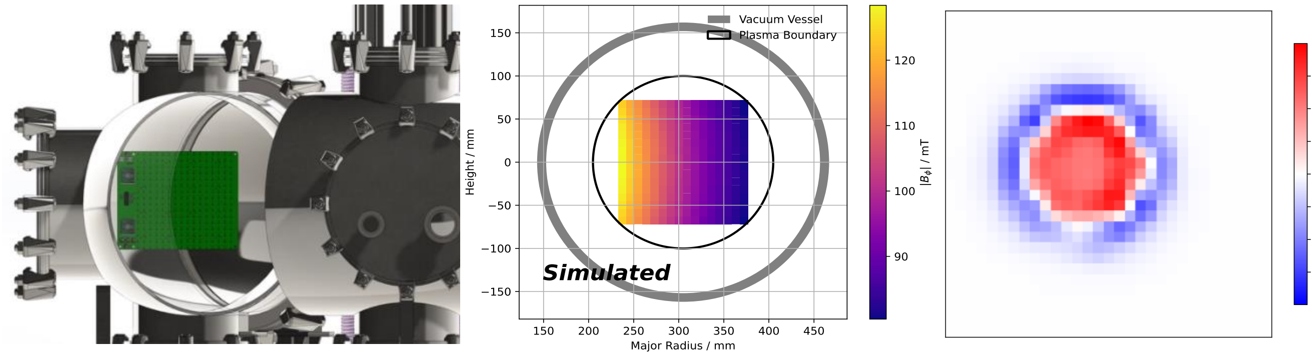
Hall arrays are not themselves a novel concept, with similar devices being proposed proposed as general novelties[2], consumer electronics interfaces[3], non-destructive testing of ferrous metals and for the detection of metallic objects (à la airport security)[4], but none of these devices are suitable for fusion applications.

The following key adaptations were required to make hall arrays viable for use in the context of fusion:

- **Sensitivity and Range:** This device is required to measure large magnetic fields just in excess of 100 mT. This range is in part achieved by the analogue frontend, which references the ADC and all the Hall sensors from a heavily regulated power rail, and the value of a zero field is encoded as Vcc/2, keeping it well within the linear ranges of all the component.
- **Bandwidth and Sampling:** Because of a short expected pulse duration of 100 ms, the array samples at over 40 kHz per sensor, achieving an analogue bandwidth of 20 kHz, just enough to provide some qualitative measure of ripple. This very high sampling rate requires high-speed multiplexing, and eight parallel ADCs operated simultaneously by an FPGA.
- **Miniaturisation:** The entire array fits through SOUTH's standard ports (with a diameter of about 150mm;). this necessitated separate analogue and digital boards, which are connected with a high-bandwidth FPGA connector that supports 8-lane SPI communications at 80 MHz.
- **Environmental:** The device features a more comprehensive active filtering system – consisting of a single stage Sallen-Key filter and a second active RC filter/ADC driver – superior to comparable devices to ensure functionality in the noisy vacuum vessel environment. Mu-metal shielding is used over the ADCs, and the power rail is well filtered.

Preliminary Results

The final device has a dynamic range exceeding ±150 mT, with an effective sensitivity of ~0.19 mT, representing exceptional performance for this application. While the full bandwidth capability requires an FPGA, a microcontroller can achieve approximately 1 kSPS and use hardware oversampling to decrease both bandwidth and noise. The microcontroller setup offers exceptional portable and accessible, allowing live interaction with the device and a hugely reduced net cost.



L) Array position in torroidal configuration inside SOUTH; **C)** Simulated reconstruction of Torroidal Field; **R)** Actual device image of Apple MagSafe phone charger.

[Click here to see a video of the device being used interactively in live-plotting mode with a microcontroller [https://youtu.be/roVHeTKtLwU].](https://youtu.be/roVHeTKtLwU)

The device performs generally well in operational testing and can effectively image a range of everyday objects, although testing still needs to be done to measure linearity in the presence of strong fields (>50 mT). So far, the device has been calibrated using a one-point calibration in a zero-field environment; ideally an MRI machine – with its strong, uniform and large field cross section – could be used to provide a linear calibration but accessing one has proved extremely difficult. An alternate method using a bar magnet and a jig is being investigated, but the datasheet linearity values for the individual sensors can be in leu of a more complex calibration process.

Impact and Future Work

The scope of the 2D Hall array in this form is inherently limited to small, spherical tokamaks where the array dimensions can be reasonably comparable to the toroidal conferment region of interest. Furthermore, such devices would be unnecessary given sufficient engineering confidence or the absence of budgetary constraints that preclude more comprehensive field mapping solutions. Similar devices are therefore best suited for small-scale, student-level projects in plasma physics and related fields.

The device demonstrates significant pedagogical potential, servings as essentially a digital version of magnetic viewing film. It could be used for lower-level undergraduate instruction in general physics and introductory electromagnetism courses, where it could enable direct observation of fundamental concepts like the magnetic fields produced by current carrying wires. The visual and interactive nature of the device make it particularly suitable for outreach activities.

This project represents the current practical limit of what can be done with off-the-shelf technologies. Custom Hall sensors could provide increase analogue bandwidth and field range, but for much increased cost and complexity. We anticipate developing novel applications of this device to support the research, development, manufacturing and commissioning of SOUTH over the next 12-24 months.

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[1] Another presentation, titled "AtomCraft: Training the fusion workforce by delivering the first tokamak entirely designed, built and operated by undergraduate university students" has been submitted to the student paper competition, and provides a more comprehensive look at AtomCraft (the organisation) and SOUTH (the device).

[2] Peter Jansen. A Third, High-Speed Magnetic Imager Tile — Details — Hackaday.io. en. Dec. 2018. url: https://hackaday.io/project/project/18518-iteration-8/log91551-a-third-high-speed-magnetic-imager-tile

[3] Rong-Hao Liang et al. "GaussSense: Attachable Stylus Sensing Using Magnetic Sensor Grid". In: Oct. 2012. doi: 10.1145/2380116.2380157.

[4] Jiangwei Cai et al. "A High-Resolution Magnetic Field Imaging System Based on the Unpackaged Hall Element Array". MDPI Applied Sciences (Jan. 2024).