# Design status of next-generation levitated dipole experiment Tahi

*T. Berry*[a], C.S. Chisholm[a], D. T. Garnier[a,b], T.E. Simpson[a], R. Mataira[a], T. Wordsworth[a], G. Wallace[b], J. Wright[b]*

[a] OpenStar Technologies, Wellington, New Zealand
[b] Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA, USA
*thomas@openstar.nz

## 1. Introduction

Levitated dipole experiments have demonstrated successful plasma confinement and validated fundamental magnetospheric physics in laboratory settings. However, these experiments have lacked the heating power density required to achieve fusion-relevant plasma conditions leaving their performance as fusion devices yet to be experimentally investigated. Following the completion of OpenStar Technologies' first device "Junior," the next-generation machine "Tahi" is designed to achieve dense, hot thermal ion populations to investigate their performance in this plasma regime and provide the stepping stone necessary for the development of future higher-performance devices. Planned for construction by 2027, Tahi offers significant upgrades to previous levitated dipole experiments in its heating systems, magnet performance, and plasma diagnostics.

## 2. Tahi Objectives

### Science Objectives

1. Confine a fusion-relevant plasma:

⟶
- **Achieve a fusion triple product on the order of $10^{19}$ keV s m$^{-3}$**
- **Hot ions ~ 1 keV**

2. Develop empirical scaling laws for dipole plasma performance: Tahi will be a flexible device capable of testing different heating methods and plasma geometries, which will enable investigation of key parameters for reactor design.

⟶
- **What is the power flow through the edge and how does it scale?**
- **What is the optimal divertor design?**

3. Verify the turbulent pinch in the ion population. Electron turbulent pinch was observed in LDX and RT-1, but has yet to be verified in the ion population due to the lack of ion heating.

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- **Do we observe the marginally interchange stable stationary profiles in the ion population with sufficient heating?**

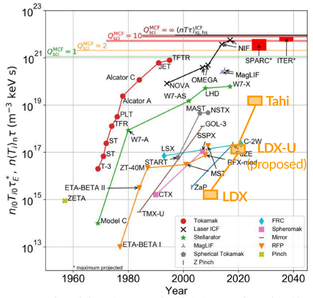



Figure adapted from S.E. Wurzel and S. C Hsu, Phys. Plas. **29**, 062103 (2022)

### Engineering Objectives

1. Design and construct a magnet on the frontier of stress limits (~1 GPa)
   a. Keep Tahi magnet the same size as the Junior magnet but increase field strength

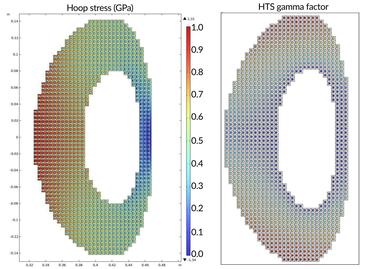
⟶
- Move to HTS cable-based magnet design
- Increase current output of HTS power supplies (flux pumps)

   b. Magnet must enable plasma performance requirements from the science objectives

⟶ Optimize magnet to give maximum plasma performance at a given size and stress limit

2. Develop and test prototype cryogenic system to be used in future reactors

⟶ Reduce docking time of the magnet to achieve a high duty cycle



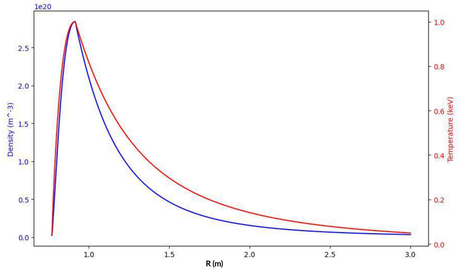

## 3. Operational scenarios

### Primary Reference Discharge

The primary reference discharge (PRD) is our flagship operational scenario we hope to achieve with Tahi. This scenario must meet our primary science objectives. Specifically, it should achieve a triple product >$10^{19}$ keV s m$^{-3}$. This scenario may require multiple heating sources and methods to achieve the desired equilibrium.

Pre-conceptual values for the PRD are shown in the adjacent table. Final parameters will be the result of more in-depth modelling. The values shown here are computed from equilibria using the Dipoleq Grad-Shafranov solver [1], with kinetic profiles then computed from the pressure equilibrium.

[1] Physics of Plasmas 6, 9, 3431–3434, (1999); 10.1063/1.873601.




| Parameter | Value (pre-conceptual) |
|---|---|
| Vacuum vessel diameter | 6 m |
| Peak magnet field strength | 18.2 T |
| Magnet major radius | 0.39 m |
| Pressure peak location | R = 0.915 m |
| \|B\| at the low field side peak | 0.467 T |
| Peak pressure | 9.21 x $10^4$ Pa |
| Maximum local beta | 1.06 |
| Peak temperature | 1.0 keV |
| Peak density | 2.84 x $10^{20}$ m$^{-3}$ |
| Edge temperature | 49 eV |
| Plasma stored energy | 191 kJ |
| Edge density | 3.2 x $10^{18}$ m$^{-3}$ |
| Neutron rate (DD) | 7.67 x $10^{11}$ s$^{-1}$ |
| Neutron flux on first wall | 5.34 x $10^5$ n/s/cm$^2$ |
| Neutron flux on magnet cryostat | 3.12 x $10^4$ n/s/cm$^2$ |
| Neutron power density on magnet cryostat | 0.019 W/m$^2$ |

### Heating

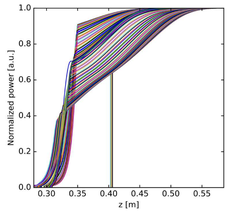
We plan to use multi-frequency ECH for start up and for forming a target plasma for neutral beam injection or ion cyclotron resonance heating (or both). We are working with the MIT PSFC (ICRH) and General Atomics (NBI) to investigate the feasibility of these heating methods for use in Tahi.

ECH has been successfully used in all previous levitated dipole experiments and enables a peak density slightly above the cutoff density due to the turbulent pinch phenomenon. The RT-1 device at the University of Tokyo has previously used ICH with mixed results [2].

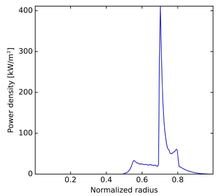
[2] AIP Conference Proceedings 1689, 040002 (2015); 10.1063/1.4936485.

### Electron Cyclotron Heating

Figures are computed using Petra-m with an 84 GHz wave with injection angle of -80°, 4.65° half-width-half-max for the cone, and launched at a location of R=0.5 m and z = 1.0 m. Figures courtesy of G. Wallace.




Normalized power along the ray showing total absorption for all rays. The vertical lines at $z$ = 0.4m indicate dramatic absorption at that height for a few rays, possibly due to a few rays near the edge of the cone failing to cross the LCFS showing as a sudden drop in power.

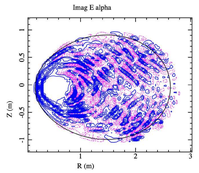



Power deposition profile. R = 0 is the magnetic axis (center of the floating coil) and R = 1 is the LCFS. The FCFS is around 0.5, and the peak density and temperature are around 0.7.

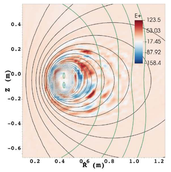
### Ion Cyclotron Heating

- Modeling work underway with MIT (Greg Wallace + John Wright)
- Adapted existing tokamak codes to work with dipole topology (TORIC/AORSA)
- Designing around a 10 MHz fast wave with He3 minority heating in a deuterium plasma

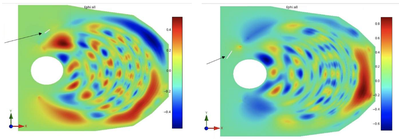
Figures courtesy of G. Wallace and J. Wright.




AORSA-computed component of the wave field normal to the magnetic field (D(H), 1.5 MHz fast wave).




AORSA wave fields at 10MHz along with resonances in green



Petra-M wave fields at 10 MHz with two different antenna locations.

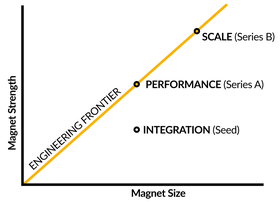
## 4. Diagnostics

The Tahi diagnostic suite can be broken into three categories:

1. Diagnostics required for plasma formation and control
2. Diagnostics required for measuring the reactor performance
3. Diagnostics required to understand the plasma physics for the design of future reactors

Dipoles are unique in their ability to easily accommodate many diagnostic systems due to their largely uninterrupted vacuum vessel surface area. We are actively looking for collaborations to develop our diagnostic suite.

| Objective | Measurement | Diagnostic | Purpose |
|---|---|---|---|
| **Function** Plasma formation and control | Neutral pressure | Ion gauge | Discharge control |
| | Equilibrium Profiles | Magnetics + kinetic measurements | Equilibrium reconstruction |
| | Radiation Dose | X-Rays and neutrons | Personnel safety |
| | Plasma density | Interferometer | Measure density profile |
| | Core Magnet Position | Magnet flight system + video | Levitation control |
| **Performance** Demonstrate confinement of a fusion relevant plasma | Peak Ion Temperature | Neutron spectroscopy | Measure ion temperature |
| | Core Electron Temperature | Thomson scattering | Core plasma physics |
| | Core Electron Density | Interferometry | Core plasma physics |
| | Ionization at Edge | D-alpha emission | Confirm fully ionised plasma |
| | Input Power | Heating diagnostics | Measure absorbed heating power |
| | Zeff | Bremsstrahlung photometer | Impurities |
| **Scaling** Develop the necessary dipole scaling laws to design future reactors | Radiated power | Bolometry | Power balance |
| | Turbulent pinch | PCI / collective TS | Transport in plasma |
| | SOL power | Thermometry + probes | Wall power deposition |
| | Density profile inside peak | MW Reflectometry | Confinement inside the peak |
| | Temperature inside peak | Thomson Scattering | Confinement inside the peak |

## 5. Future work

Significant scientific and engineering work is still required to take Tahi from the pre-conceptual to the conceptual design phase. There has been little to no work done modelling the edge region and the effect that a separatrix could have on the equilibrium, or modelling of the core transport. We are interested in collaborating on both our modelling and experimental efforts!