Science:

Q1 Can the project team provide a more detailed explanation of the challenge of characterizing beams for drift scan telescopes at the requisite level of precision for EoR science? A pedagogical approach would be welcomed by the panel.

A well-characterized (or at least well-constrained) beam pattern is of critical importance to arrays targeting the cosmological 21-cm signal, but we would like to emphasize the required level of characterization depends on an experiment’s strategy for separating bright foreground emission from the faint cosmological signal. Some approaches reduce the need for absolute calibration in exchange for engineered constraints on spatial or spectral smoothness; others can be more agnostic about beam performance, so long as it is replicated with high fidelity between different antennas in an array. This unfortunately makes it difficult to define a universal specification. However, more strategies become viable with improved beam characterization, with results that translate to clear science gains.

Several factors contribute to the difficulty of precisely measuring an antenna’s beam response at low frequencies. Foremost is the fact that, at the level that impacts foreground leakage into the cosmological signal, beam responses are quite sensitive to the surrounding environment. For example, simulations suggest that a HERA element embedded in an array differs from one in isolation at the -10 to -15 dB level (Fagnoni et al. 2019), far exceeding the -50 to -60 dB dynamic range between foregrounds and the expected 21-cm reionization signal. Even identically constructed antennas can exhibit significant variation on the basis of their position within the array.

As a result, calibration and characterization efforts must be performed on elements in situ. This, however, comes with its own set of complexities. The design of some elements (e.g. HERA) do not support pointing to reposition sources of emission within the beam and therefore must rely on, e.g., sky rotation or drone-suspended calibration sources to compare responses in different directions. Various approaches hold promise, but each present challenges that remain to be overcome. Steerable elements are unlikely to solve the problem because the orientation of an antenna in a dense array alters the beam response.

Our community recommends support for beam characterization with a variety of approaches that could include drones, RF reflectometry, EM simulations, improved foreground models, and improved calibration algorithms. We also suggest supporting design studies that explore ways to reduce coupling between elements and improve the repeatability of beam responses in an array context.

Q2 How might the different science goals of a $z < 12$ focused “EoR Imager” and a $z > 12$ focused “Cosmic Dawn Array” translate to different instrumental parameters if both were ultimately built? (A qualitative discussion would be informative even if a quantitative analysis is not yet possible.)

Relative to the targeted cosmological signal, sky noise increases at the low frequencies targeted by a Cosmic Dawn Array. A post-HERA instrument targeting $z>12$ will be starved for sensitivity, yielding measurements with SNR < 1 on individual power-spectral modes. As such, a future Cosmic Dawn Array will likely target increased per-element collecting area with a dense array configuration that yields repeat mode measurements (e.g. Parsons et al. 2012a). This approach pairs well with foreground-avoidance techniques in the vein of those applied to PAPER and HERA.

A post-HERA EoR Imager, by contrast, will be aiming to expand the number of independent modes measured, along with an expanded field of view that might increase overlap with other high-redshift probes for cross-correlation science. Designs suitable for this are likely to rely on a large number of simple elements in an expansive array configuration, although much work remains to pin down the key design principles of such an array.

The major difficulty in a dual EoR Imager/Cosmic Dawn Array design is producing an element with a 5:1 bandwidth response that is simple enough to permit imaging-level calibration while yielding the collecting area for Cosmic Dawn sensitivity. That said, it is easy to imagine that these two arrays could rely on similar correlation, calibration, computing, and site infrastructure. Eventually, the differing needs of these instruments will require different element designs, but we plan to keep these two communities together as long as possible, and there is much to be shared even with separate physical instruments.

Technical/Risk/Cost/Schedule/Management:

Q3 Is HERA on schedule, and is the initial experiment expected to be complete by the end of 2023? Does the project team already anticipate extending its operating lifetime to 2025 or beyond, perhaps as a testbed for technology improvements?

HERA is currently one year behind schedule and has de-scoped to two years of observing with the full array instead of three. We remain committed to completing the experiment by the end of 2023, although a no-cost 1-year extension could be considered. Degrading hardware will make it difficult for HERA to perform as a science instrument beyond 2025, but we do anticipate it being a valuable platform for the international community to use for exploring and developing next-generation designs and technology.

Q4 Would access to SKA1-low datasets help support the scientific aspirations of the U.S. H I cosmology community in a significant way?

The consensus in our community is that SKA1-low is a risky endeavor at the targeted level of investment. Considerable uncertainty remains in the science requirements and how they flow down to technical specifications. Should SKA1-low prove successful, data access would absolutely support the HI cosmology community in a significant way. If not, the usefulness of SKA1-low data for foreground modelling would not be significant enough to warrant the investment. Given the risks, we advocate for the staged development presented in our whitepaper which aims to retire key risks before moving to higher levels of investment.

Should SKA1-low data access come in trade for access to other US-led investments, we still have concerns. Data access to a risky project cannot take the place of the staged development plan we outlined, but as a supplement, it could be valuable. We are also concerned that investing in SKA1-low could stall progress in the field by diverting resources from less risky investments and by creating the perception that SKA1-low by itself represents a sufficient investment in HI cosmology instrumentation.