PROCEEDINGS OF SCIENCE

Towards IceCube-Gen2: Plans for the in-ice radio array

A. Nelles[a,b,*] **for the IceCube-Gen2 Collaboration**

[a] *Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany*

[b] *Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Center for Astroparticle Physics (ECAP), Nikolaus-Fiebiger-Str. 2, 91058 Erlangen, Germany*

E-mail: anna.nelles@desy.de

Building on the success of IceCube at the South Pole, the next generation experiment IceCube-Gen2 is taking shape. Next to an extension of the optical array, further developing the optical detector learning for the IceCube-Upgrade currently in preparation, IceCube-Gen2 is planned to feature a large in-ice radio array targeting neutrinos beyond PeV energies. This radio array will build on heritage from many former and existing radio neutrino experiments. It will dominate the sensitivity of IceCube-Gen2 at EeV energies, improving at least an order of magnitude in sensitivity over existing arrays. IceCube-Gen2 will also feature a much enlarged surface array, including in-air radio antennas targeting air showers. This contribution will highlight the current status of IceCube-Gen2 with a focus on the in-ice radio array.

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*Speaker

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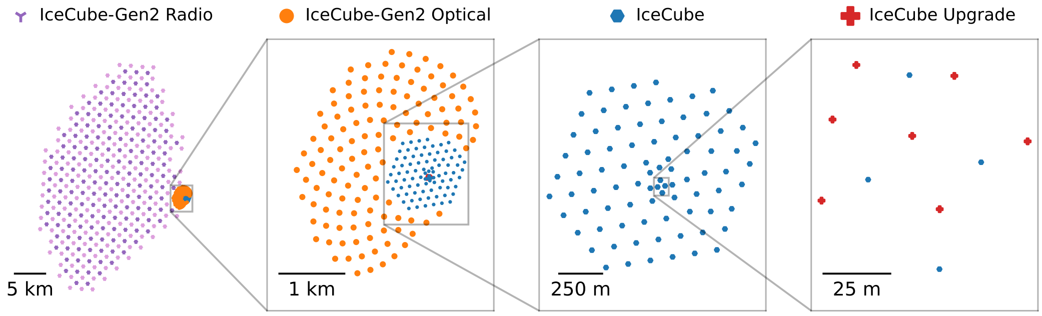

Figure 1: Top view of the detector illustrating the different length-scales. From left to right: Positions of the individual stations of the in-ice radio array of IceCube-Gen2, the positions of the strings of the optical array of IceCube-Gen2, IceCube, and IceCube Upgrade.

1. Introduction

The IceCube Collaboration is currently in the process of constructing the IceCube Upgrade at South Pole [1]. The Upgrade adds additional strings in the center of IceCube to target lower energy neutrinos [2]. These strings are also equipped with a variety of calibration instruments that will be used to obtain a better ice model [3], which in turn will allow a re-calibration of the existing IceCube data set. Beyond the IceCube Upgrade, the collaboration is planning to construct IceCube-Gen2.

2. IceCube-Gen2 Overview

IceCube-Gen2 is planned to pursue a number of main science objectives (see [4] for details).

- Resolving the high-energy neutrino sky from TeV to EeV energies, answering the question: What are the sources of high-energy neutrinos detected by IceCube?
- Understanding cosmic particle acceleration through multi-messenger observations.
- Revealing the sources and propagation of the highest energy particles in the Milky Way and the Universe.
- Probing fundamental physics with high-energy neutrinos and cosmic rays.

IceCube-Gen2 consists of different components to address these science objectives (see Figure 1). The optical in-ice component of IceCube will be extended by 120 strings, at a spacing twice as large as IceCube's spacing with novel optical sensors. This array will improve the point source sensitivity by at least a factor of 5 and increase the collection rate of neutrinos by almost an order of magnitude. The increased collection rate is particularly important for the detection of transient sources. On top of every string an enhanced surface array to conduct precision measurements of cosmic rays will be constructed, consisting of scintillators and radio antennas (see [5] for details). Essential to these science objectives is the vastly improved sensitivity at PeV to EeV energies, which will be enabled through an in-ice radio array, making use of the Askaryan emission following a neutrino interaction.

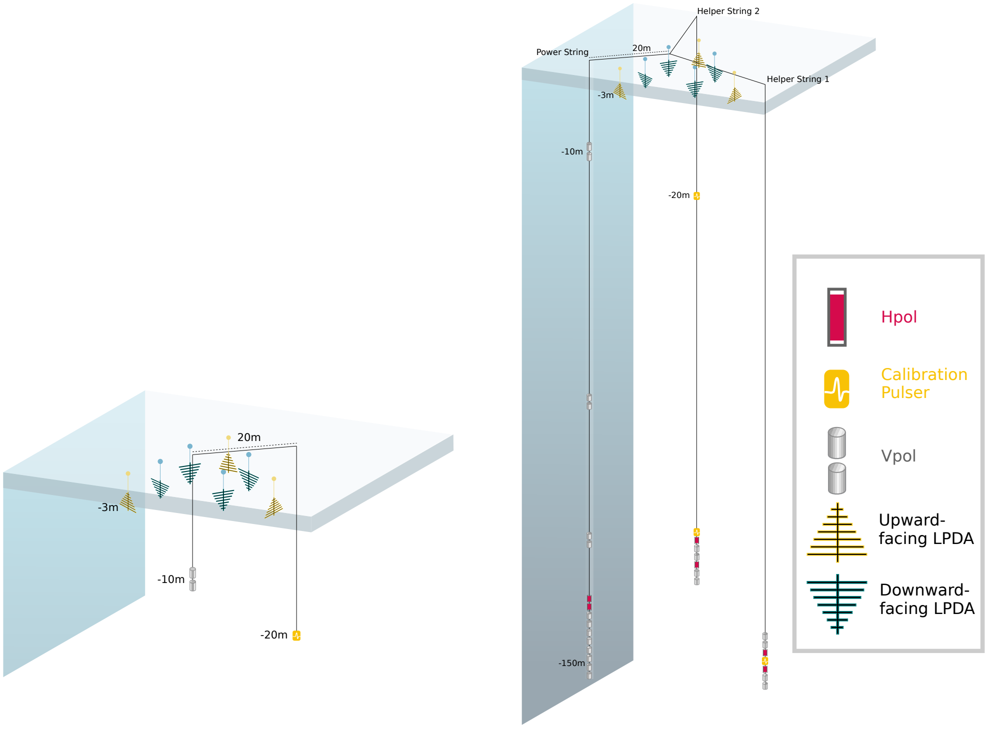

Figure 2: Two types of IceCube-Gen2 radio stations: Left: Shallow-only station, right: hybrid station. The shallow component is identical in both station types.

3. IceCube-Gen2 Radio Array

The IceCube-Gen2 radio array builds on the foundations laid by RICE [6], ARA [7], ARIANNA [8], and ANITA [9] and lessons learned from various air shower arrays. The reference design is a combination of different aspects in order to build a robust discovery experiment.

3.1 Design Considerations

Ice and its decreasing index of refraction towards the surface is dominating the rationale of what one wants to build for the in-ice array of IceCube-Gen2. The deeper an antenna, the larger its field of view and the larger the resulting effective volume. On the other hand, shallow antennas are easy to deploy (no drilling), allow flexibility in antenna design (high gain in all polarizations due to large size), and provide self-tagging of air showers. Within the (currently large) uncertainties there is a similar sensitivity-to-cost ratio for both types of approaches. This results in a strategy for the complete array: Mitigate risks for a large scale detector (both in installation and different detection components) and use complementary advantages by combining deep antennas with shallow antennas.

The spacing between two in-ice radio stations is defined by a desired ratio of 10% coincidences events at EeV energies. A denser spacing will lead to more coincidences with likely better reconstruction of neutrino properties, but will reduce the overall effective volume of the detector.

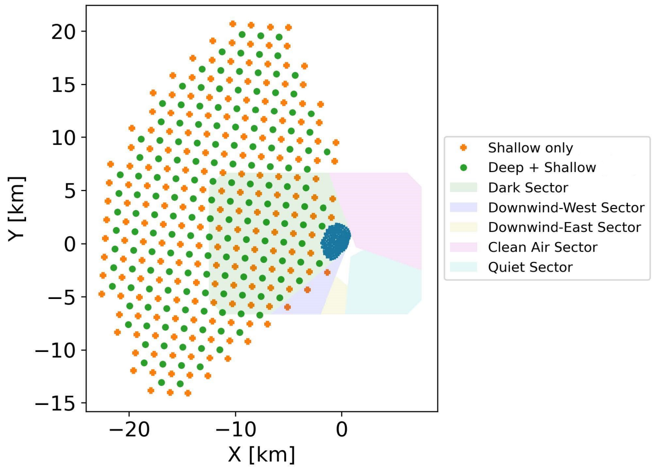

Figure 3: Reference array layout of the in-ice radio array of IceCube-Gen2. The shape of the array is determined by the desired spacing between different types of stations and the requirement to stay in the so called dark sector as defined by South Pole regulations.

For shallow antennas, this rationale leads to a smaller spacing than for antennas at 150 meters depth. Therefore, in combining shallow and deep antennas, two types of stations are being used: hybrid stations (combining deep and shallow antennas in a single station) and shallow-only stations as shown in Figure 2. They are interspersed into a tight array as shown in Figure 3. With this approach there is no loss of combined effective volume (coincidence fraction does not increase significantly), better air shower detection capabilities with the resulting smaller array spacing, a compact array which is advantageous for installation, and finally a cross-check for systematic uncertainties.

3.2 Technology

The reference technology will lean heavily on what is currently installed as part of RNO-G [10] at Summit Station in Greenland (see [11] for current status).

The same mechanical drilling technology will be used to obtain boreholes to 150 m depth. The array will use the same or a next generation of the DAQ electronics, amplifiers, Vpol and Hpol antennas, RF over fibre, and phased array trigger. It is likely that it will be transitioned to mass production LPDAs for stream-lined costs and construction time, as opposed to off-shelf LPDAs as used for RNO-G and ARIANNA. Possibly a dedicated ASIC will be used for the instrument, replacing the LAB4D chips of RNO-G, and the goal is to build a modular DAQ that can accommodate both shallow and hybrid stations. The RNO-G site in Greenland may be used to test elements that are made dedicatedly for IceCube-Gen2. However, the infrastructure will be different in terms of power and communication. As the South Pole has a very strict policy on radio-quietness, a custom LTE network as used by RNO-G is unlikely to get permission. Similarly, satellite communication is discouraged. Therefore, the IceCube-Gen2 in-ice radio array will be cabled for communication. Since this already involves trenching, it was decided to also power the array centrally, to allow for year-round operation. RNO-G attempts to run year-round in Greenland on renewable power sources, but the wind-turbine technology has not yet been stable enough to achieve such operations.

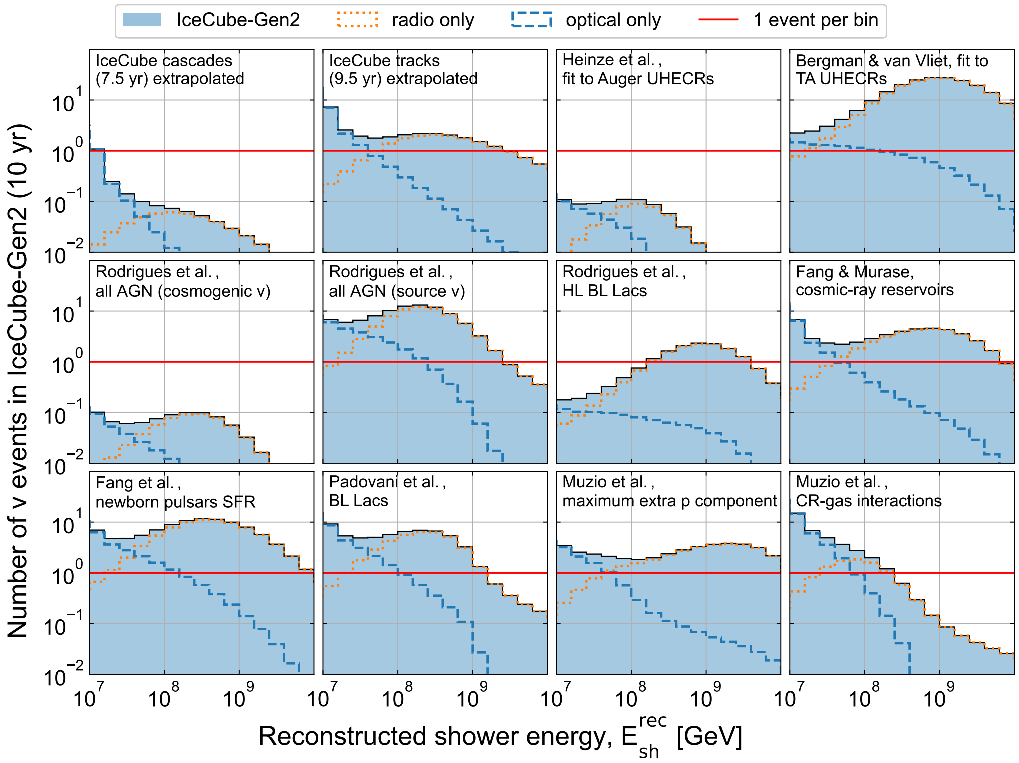

Figure 4: Indicator of the performance. Average expected number of events in IceCube-Gen2, after 10 years of operation, for different predicted diffuse UHE neutrino flux models. From left to right, top to bottom: two extrapolated IceCube measurements [12, 13], four cosmogenic predictions [14–17], and six astrophysical predictions [16, 18–21]. Shown are the event numbers for optical and radio-only, as well as the total number. The red line highlights one event per energy bin of this analysis. (To appear in the IceCube-Gen2 Technical Design Report; figure inspired by [22].)

The longer polar night at South Pole, in combination with fewer days with winds, amplifies the challenge.

4. Performance

The predicted event numbers for the highest energies are shown in Figure 4. The sensitivity of IceCube-Gen2 will probe all but the most pessimistic model with the detection of a significant number of neutrinos. This in turn implies that if IceCube-Gen2 fails to detect neutrinos at $> 10^7$ GeV, many light(er) cosmic ray compositions and favorable source evolutions will be ruled out.

It is expected that the energy resolution of the in-ice radio array of IceCube-Gen2 will be similar to what is expected for RNO-G [23, 24], meaning that it will be dominated by the unknown energy fraction transferred by the neutrino into the shower. The angular resolution is still being studied, but highly depends on the number of antennas triggered. For a subset of high-quality events, it will be better than 5 square degrees [25–27].

5. Conclusions

IceCube-Gen2 is planned beyond the IceCube Upgrade at the South Pole. It consists of an extended optical array, an enhanced surface array and a large in-ice radio array. Roughly a factor of 10 larger than RNO-G, it will complement it on the Southern Hemisphere and will be the ultimate discovery experiment beyond 10 PeV.

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